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ENVIRONMENTAL SEQUENCE STRATIGRAPHY (ESS) AND PFAS SITE CHARACTERIZATION:
RETHINKING THE APPROACH TO REMEDIAL INVESTIGATIONS

October 2023

Remediation Technologies Symposium | Fairmont Banff Springs

Colin Plank, Rick Cramer, Mike Shultz, and Brian Hoye

Agenda

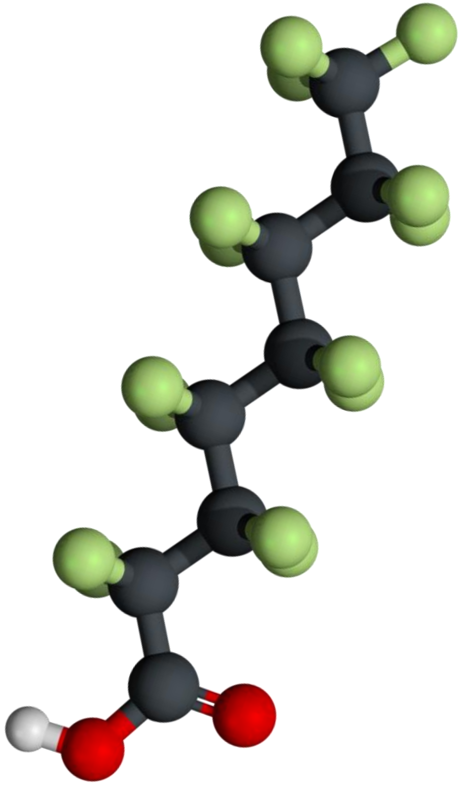
1 Introduction –The Challenge of PFAS

2 The Challenge of the Subsurface

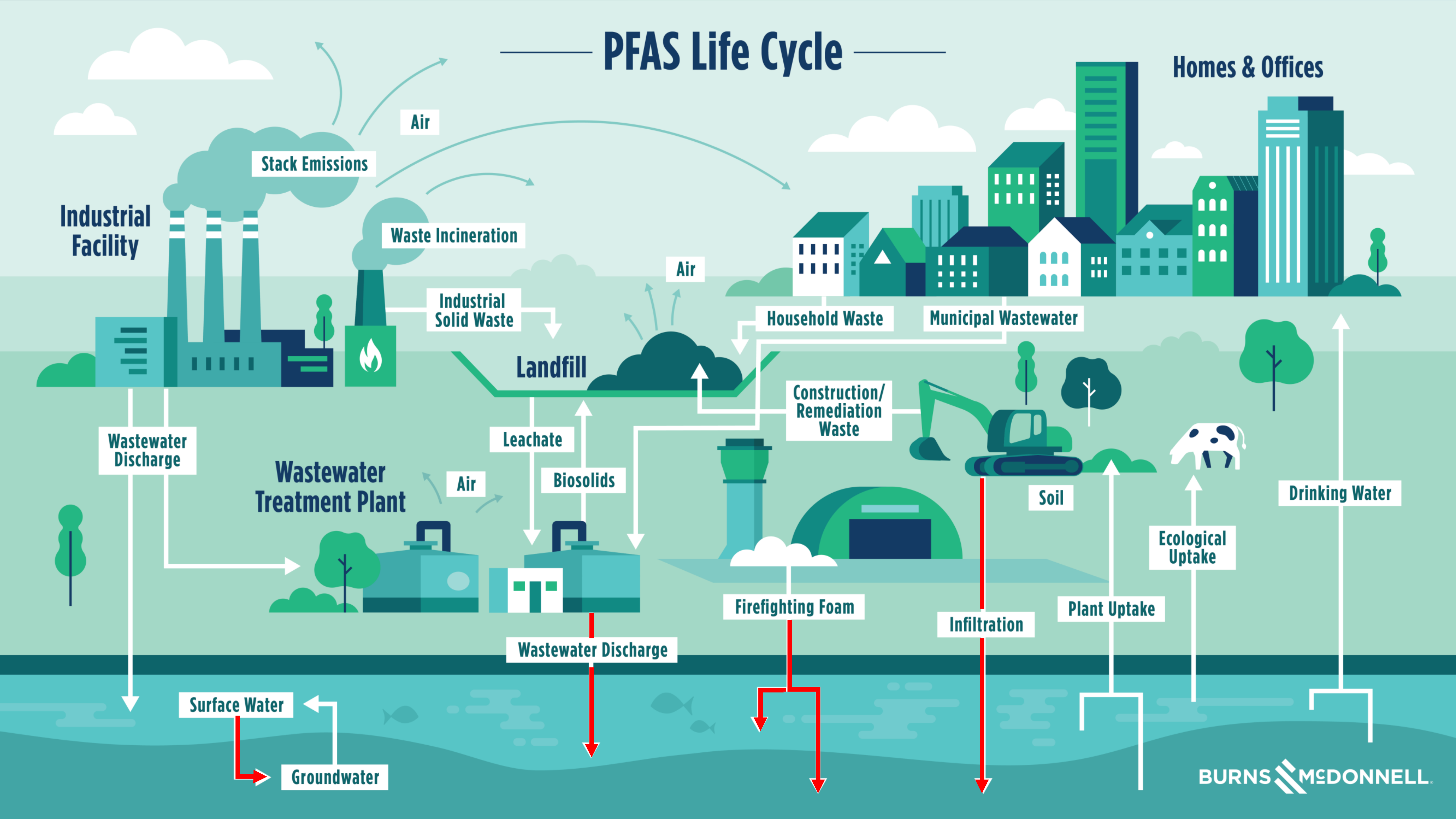
3 Environmental Sequence Stratigraphy (ESS)

4 Site Example

5 Q&A



https://pfas-1.itrcweb.org/2-2-chemistry-terminology-and-acronyms/



PFAS Life Cycle
Homes & Offices
Industrial Facility
Air
Stack Emissions
Waste Incineration
Industrial Solid Waste
Air
Landfill
Household Waste
Municipal Wastewater
Construction/ Remediation Waste
Wastewater Discharge
Leachate
Wastewater Treatment Plant
Air
Biosolids
Soil
Drinking Water
Ecological Uptake
Firefighting Foam
Infiltration
Plant Uptake
Wastewater Discharge
Surface Water
Groundwater
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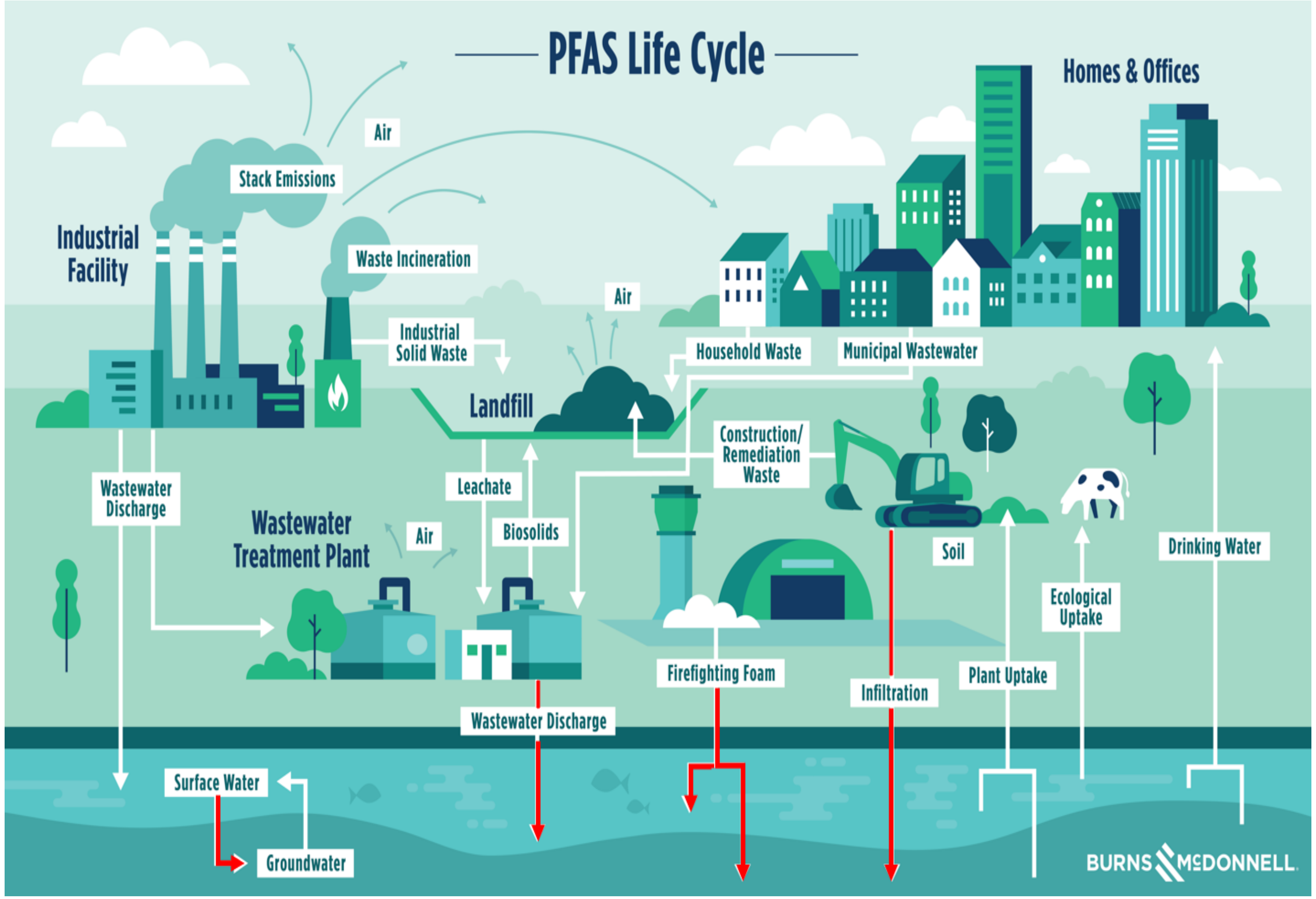
PFAS Presents New Challenges

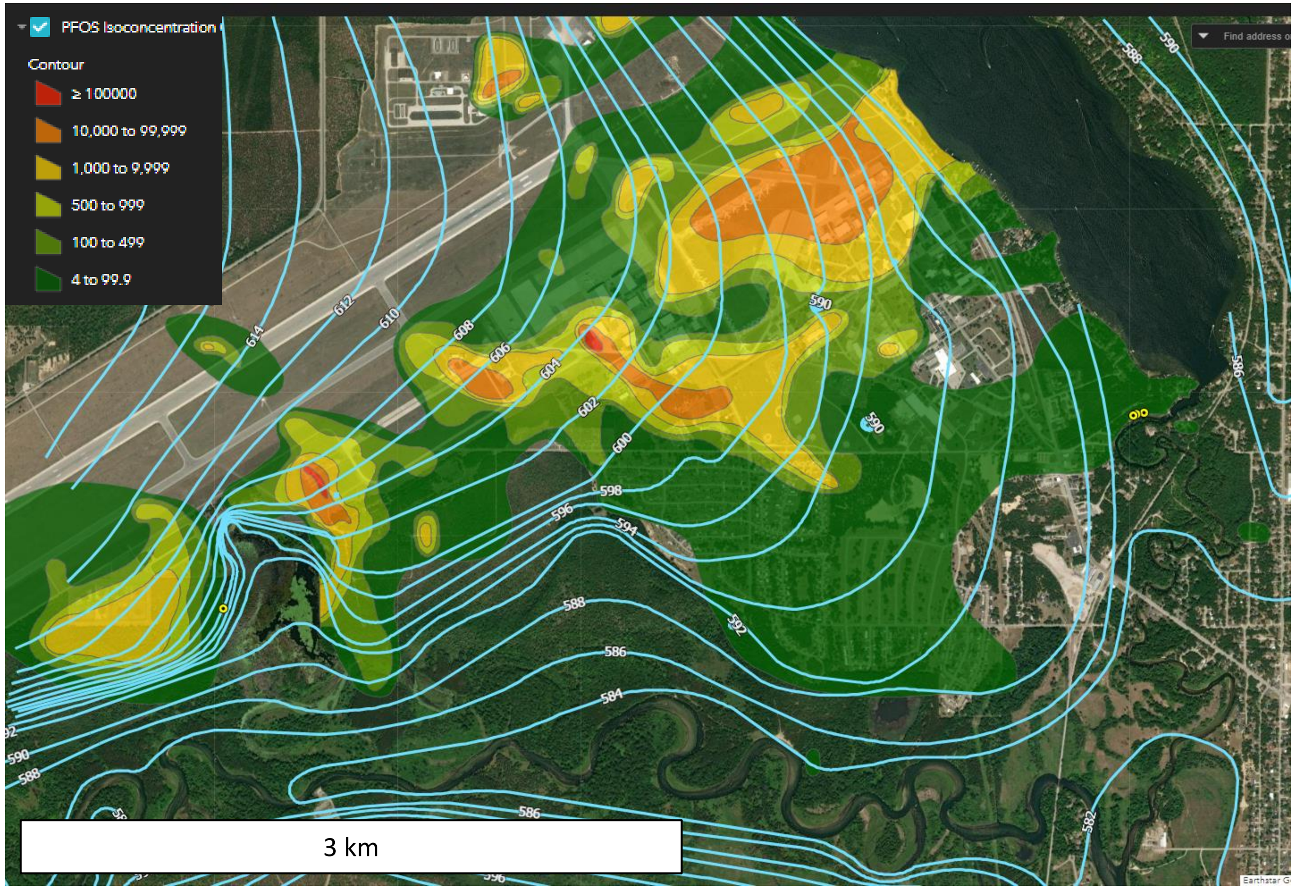
- **Persistence** – Extremely resistant to environmental and metabolic degradation
- **Mobility-** Readily transported long distances in air and water
- **Diversity**- A wide range of potential sources

- Very low regulatory screening concentrations, *e.g. parts per trillion (pptr.)*
- In U.S. we are dealing with Residential Screening Levels (RSLs) as low as 4 pptr.



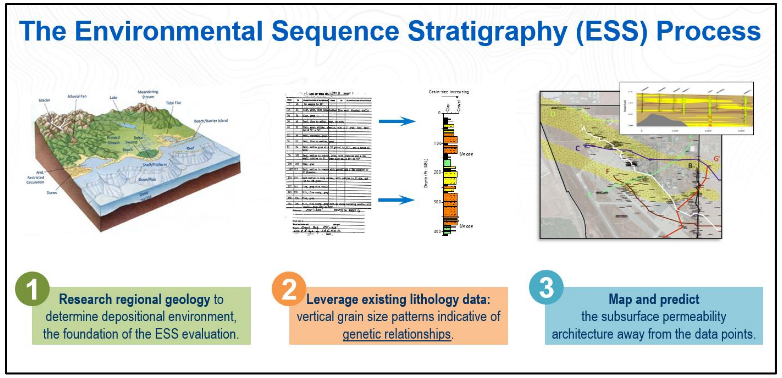
What Does This Mean for PFAS Groundwater Investigations?

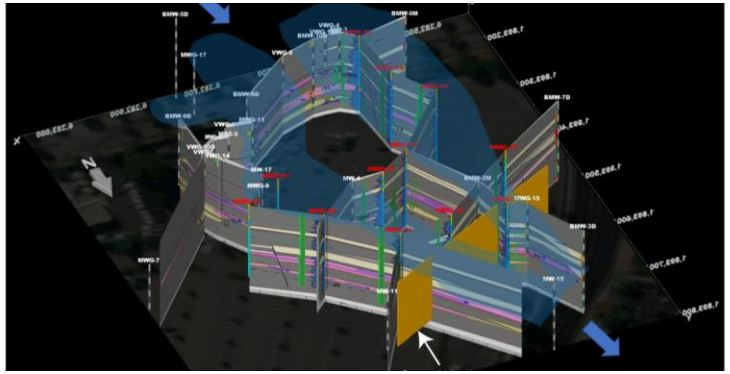
- We are tasked with defining large and dilute groundwater plumes
  - Groundwater plumes ~10 km^2 in area
  - Multiple potential sources encompassed.
- Support of Interim Remedial Actions
- The industry standard "Step-out" approach, guided by concentration is inefficient and expensive.
  - May not provide key data targeted with respect to subsurface heterogeneity necessary for remedial alternatives analysis

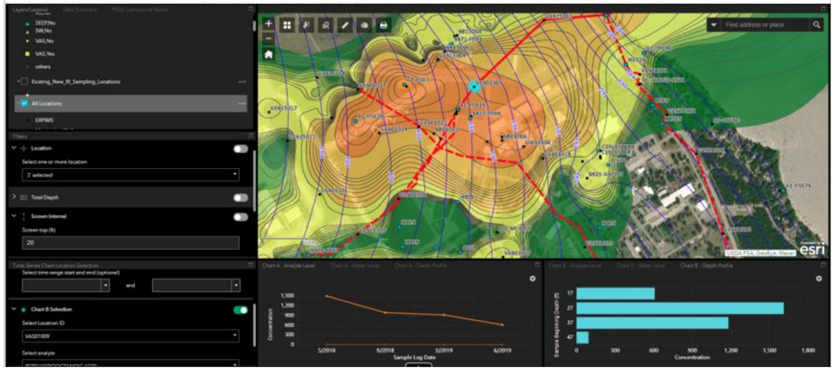


PFAS Requires a More Advanced Approach To Groundwater Investigation

What Does An Advanced Approach Mean?







Advanced Methods of Stratigraphic Correlation:

- ▶ Environmental Sequence Stratigraphy
  - ESS brings facies models back to future
  - Sequence strat. principles guide correlation of subsurface permeability

Advanced Methods of Data Interrogation and Visualization:

- ▶ Mapping Software and Database Management
  - Increased use of legacy and regional data
- ▶ 3D visualizations of HRSC data constrained by stratigraphic data:
  - Fence Diagrams and “dummy points”

Advanced Methods of Delivery:

- ▶ Digital CSMs
  - Web-Application approaches
  - XYZ data and Strat Surface Files
  - Increasing direct connectivity with numerical modeling approaches

ESS is *Step 1* in an advanced approach to groundwater remediation

The Challenge of the Subsurface

Geologic complexity is a recognized impediment to progress .

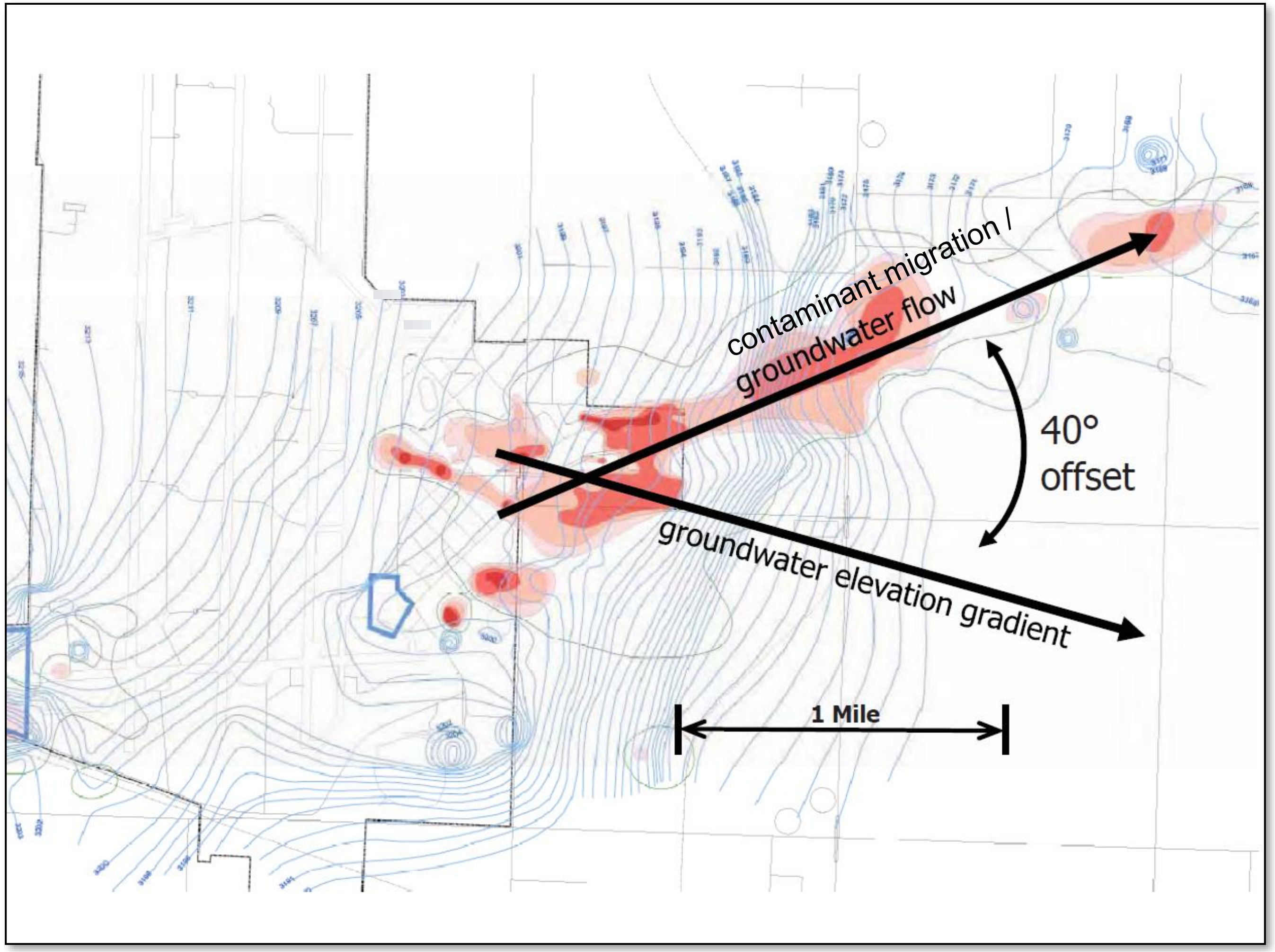
- National Academy of Sciences defined **12,000** groundwater remediation sites as “complex”
- And concluded that “…. Due to **inherent geologic complexities**, restoration within the next 50-100 years is likely not achievable

Alternatives for Managing the Nation's Complex Contaminated Groundwater Sites
National Academy of Sciences Committee on Future Options for Management in the Nation's Subsurface Remediation Effort, 2013

Why Advanced Methods of Stratigraphic Correlation Are Key:

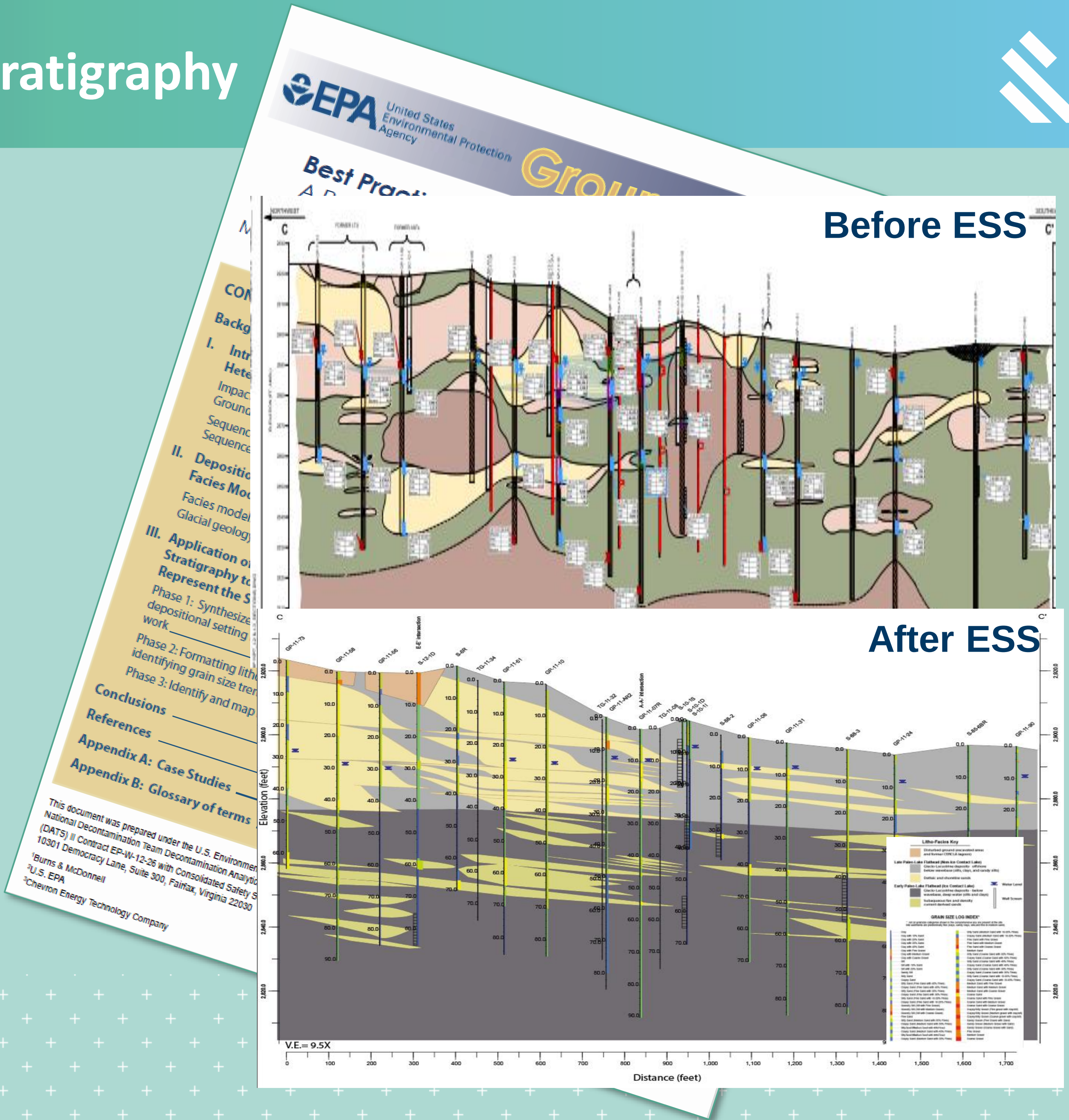
The groundwater gradient is not the principal control on flow, *the stratigraphy is*.

- Critical to recognize these types of nuance and tackle them head on.
- Site geology provides The Conceptual Site Model's (CSM) foundation: *The Plumbing*



ESS- A Best Practice Approach to Stratigraphy

- Based on principles and a knowledge base developed in the world of petroleum exploration
- Emphasis on moving past your "postage stamp" of data
  - Context and research that allows you recognize key observations in lithologic logs
  - Utilize spatial distribution of grainsize trends
  - Create geologically defensible correlations



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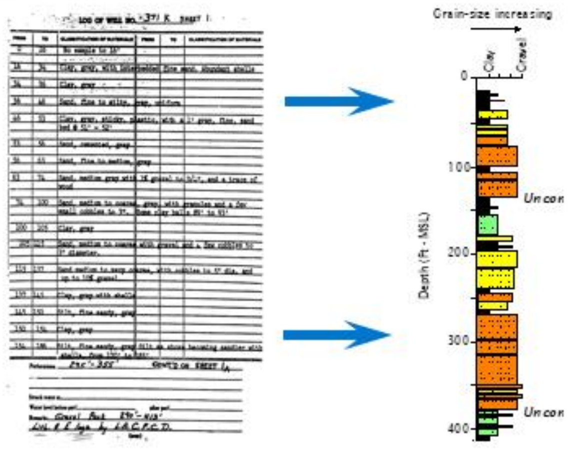
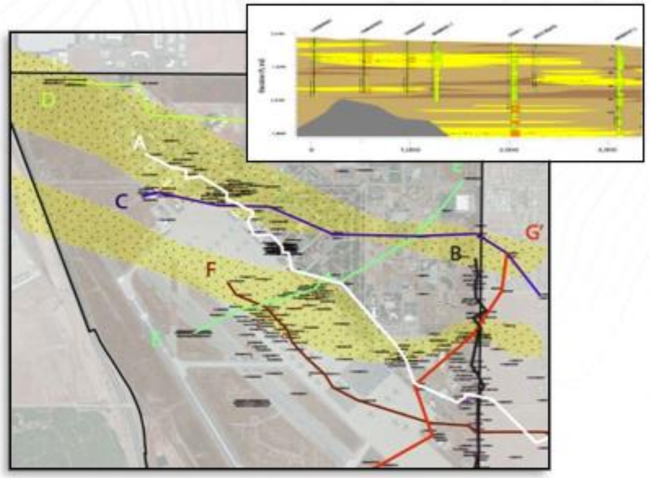
The Environmental Sequence Stratigraphy (ESS) Process



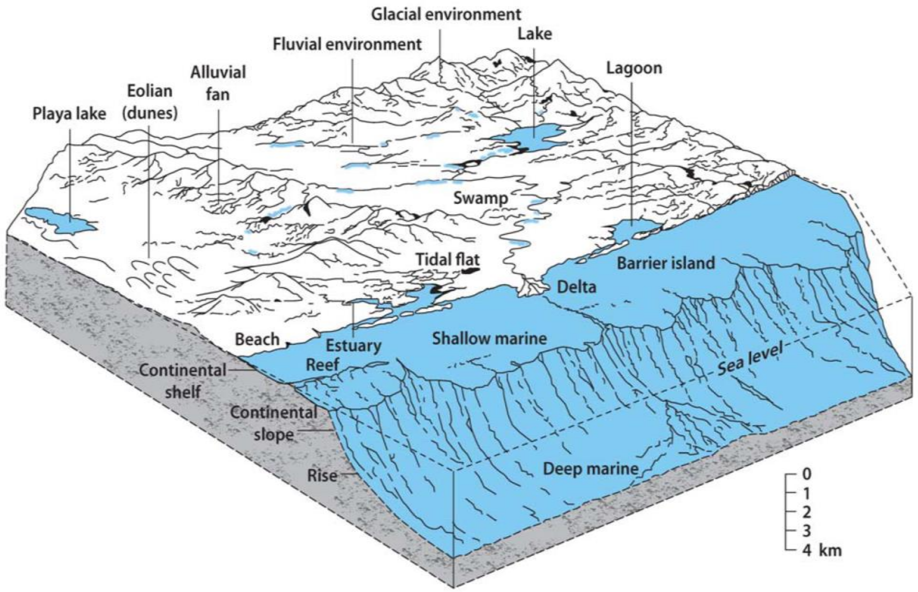


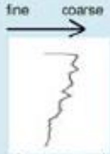
1 **Research regional geology** to determine depositional environment, the foundation of the ESS evaluation.

2 **Leverage existing lithology data:** vertical grain size patterns indicative of genetic relationships.

3 **Map and predict** the subsurface permeability architecture away from the data points.

Depositional Models and Modern Analogues

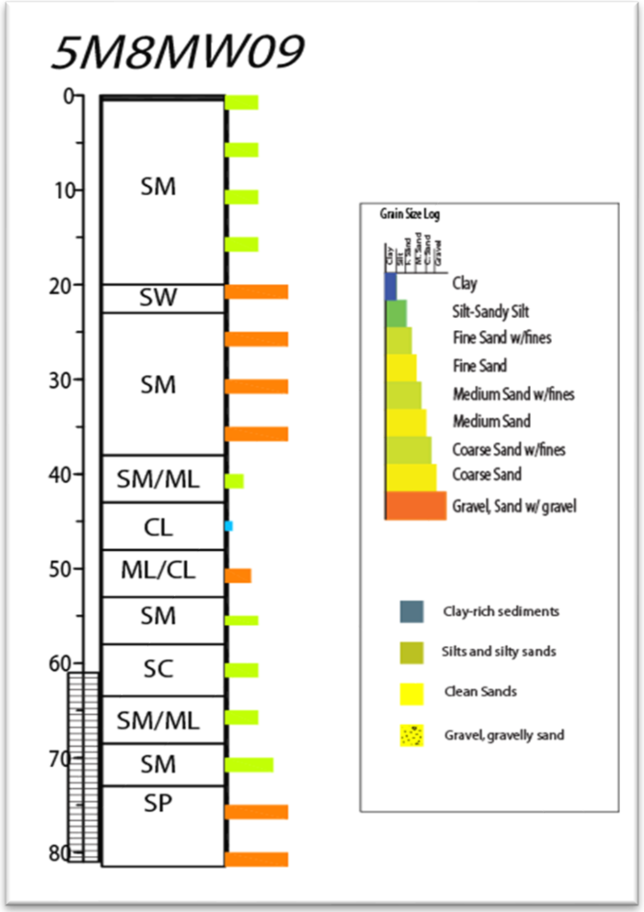


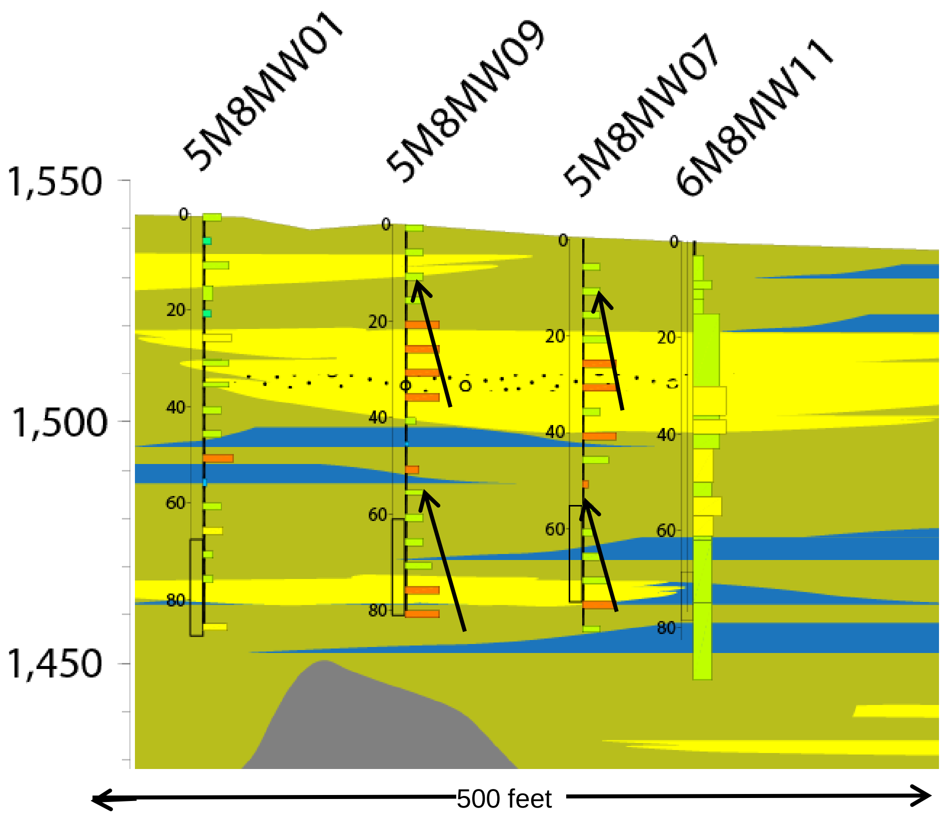
Depositional environment and typical grain size profile	Major aquifer elements and their common dimensions	Major aquitard elements and their common dimensions	Impact on CSM	Data resolution needs
Alluvial Fan  coarsening-upward	Proximal fan channels, mid-fan sheet sands, distal fringe sands X: 10^2 m – 10^4 m Y: 10^1 m – 10^3 m Z: 10^{-1} m – 10's m	Playa lake deposits or paleosol formations commonly vertically separate fans. Debris-flow deposits also commonly clay-rich. X: 10^2 m – 10^3 m Y: 10^2 m – 10^3 m Z: 10^{-1} m – 10's m	Laterally extensive paleosol or playa lake deposits may be thin (10's of cm to meters), but can vertically compartmentalize aquifers. Such thin aquitards may not be recognized by non-continuous sampling methods due to their thin nature. Fans have a primary stratigraphic dip basinward at 1-6 degrees, and are laterally offset stacked ("shingled"). Fans are constructed primarily by channels encased in sheet-flood deposits. Channels are radial from a point source and represent permeable pathways. Channel density decreasing down-fan.	High in vertical sense, need for lateral resolution decreases down-fan where channels are less predominant.
Meandering Fluvial  fining-upward	Channel axial fill, point bar, crevasse splays X: 1 m – 10's m Y: 10^2 m – 10^3 m Z: 10^{-1} m – 10 m	Floodplain deposits, levee deposits, clay drapes on lateral accretion surfaces, plugs filling abandoned channels. X: 10^2 m – 10^3 m Y: 10^2 m – 10^3 m Z: 10^{-1} m – 10's m	Channel and point-bar deposits are encased in fine-grained floodplain deposits and represent the groundwater flow pathways. Traditional potentiometric surface maps are poor predictors of specific groundwater flow paths and contaminant migration pathways. Coarse-grained "lags" at the bases of channels and point bars represent high-permeability pathways. Lateral accretion drapes can form 'shingled' aquifer units. Clay plugs filling abandoned channels ("oxbow lakes") common and provide barriers to groundwater flow and contaminant fate and transport.	High both laterally and vertically
Braided Fluvial  blocky	Channel axial fill, bar complex X: 1 m – 10^1 m Y: 10^1 m – 10^2 m Z: 10^{-1} m – 10^1 m	Floodplain deposits, silt and clay plugs filling abandoned channels. X: 10^2 m – 10^3 m Y: 10^1 m – 10^2 m Z: 10^{-1} m – 1's m	Low-sinuosity high-permeability streaks encased within an overall permeable matrix may dominate groundwater flow and contaminant migration. Laterally discontinuous silt and clay units may be significant at the plume scale, and are more continuous in the down-channel direction compared to the cross-channel direction.	High both laterally and vertically, greater lateral resolution required perpendicular to depositional axis (i.e., cross-channel transects) versus parallel to depositional axis (down-channel)

Depositional environments have distinctive vertical grain size distributions

Applying the Basic Methodology

- ► Reformat existing data to represent vertical grainsize trends
- ► Pay attention to log details (rounding, sorting, biological indicators)
- ► Examine grainsize trends spatially and use facies model to constrain scale and geometry





Example from GW site in S. CA, USA

Applied at Over 60 United States Dept. of Defense Locations

Groundwater Monitoring & Remediation 43, no. 3/ Summer 2023/pages 79–92

Groundwater Monitoring&Remediation

Leveraging Sequence Stratigraphy to Accelerate Site Remediation: Pliocene Citronelle Formation, Eglin Air Force Base, Florida, USA

by Mike Shultz, Colin Plank, Mark Stapleton, Leo Giannetta and Rick Cramer

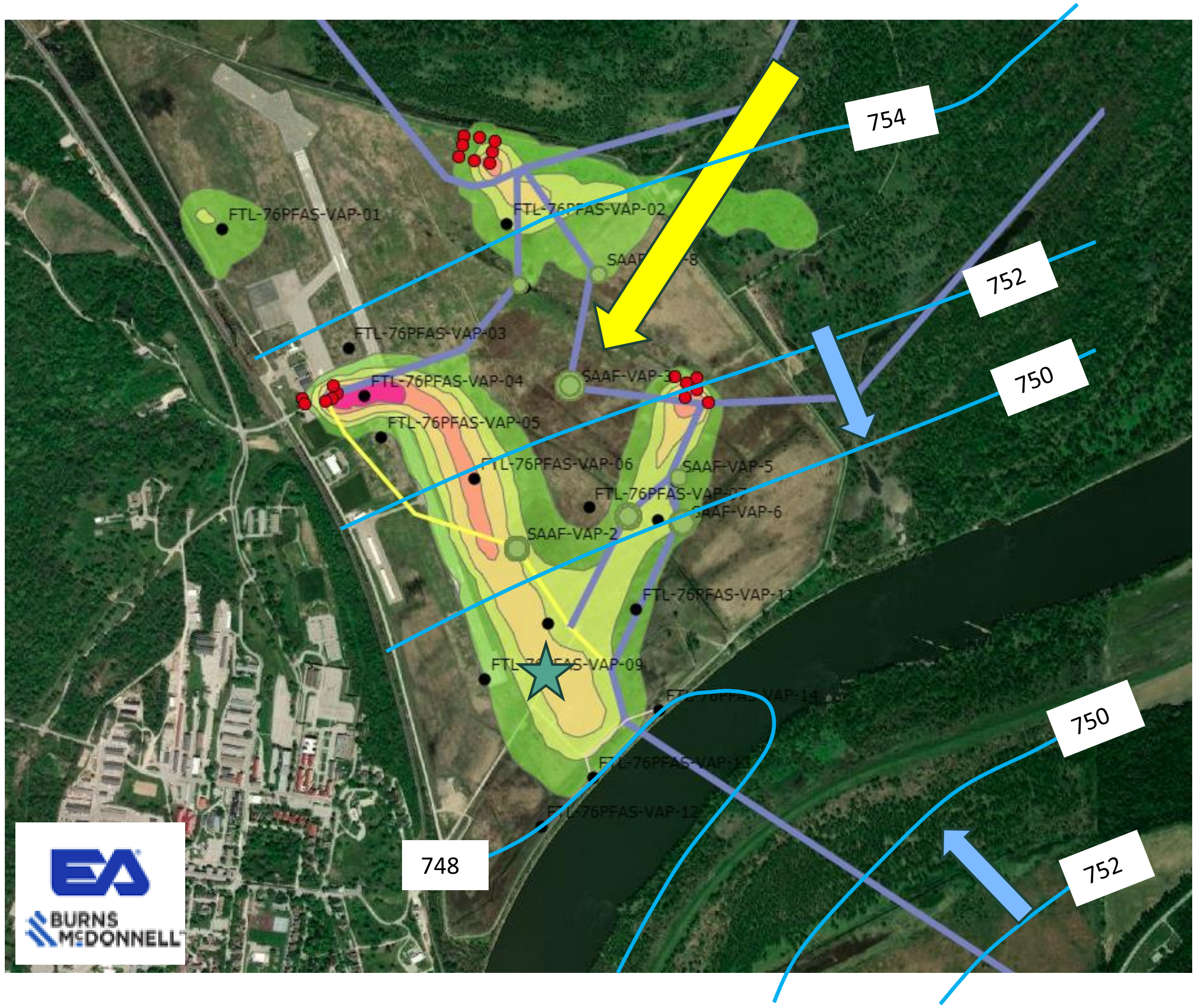
- Installations with Completed CSMs
- Installations with Newly Awarded and Ongoing CSMs

PFAS Remedial Site Investigation Guided By ESS

- Task: Create CSM to guide remedial Investigation
  - Direct Push- Vertical Aquifer Profiling (VAP) and Electrical Conductivity /Hydraulic Profiling Tool (EC-HPT)

- Goals: PFAS delineation, planning of “final” monitoring well network

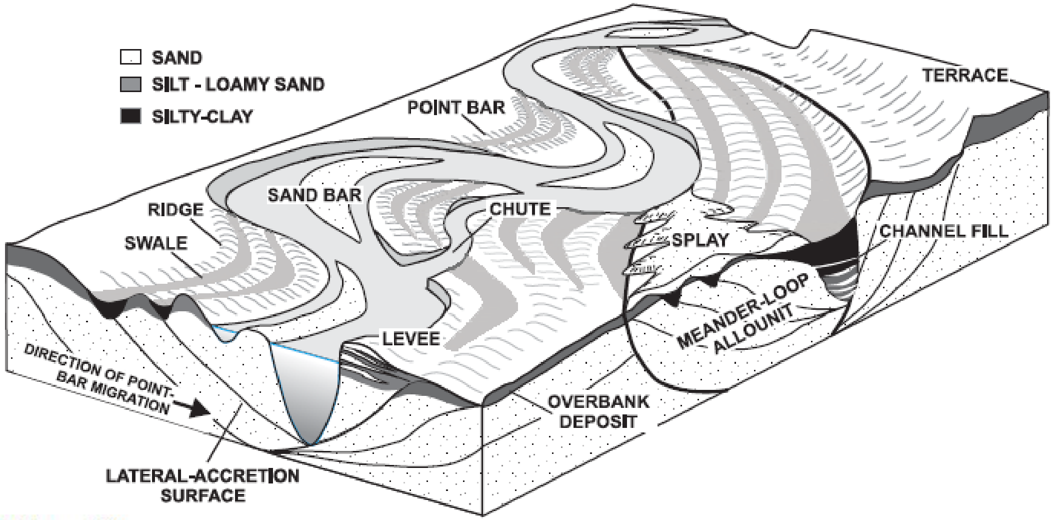
- The unusual plume geometry initially presented in a preliminary site assessment suggests stratigraphic heterogeneity



Fluvial Analogue and Facies Models: Evolution from Braided Fluvial to Meander Belt

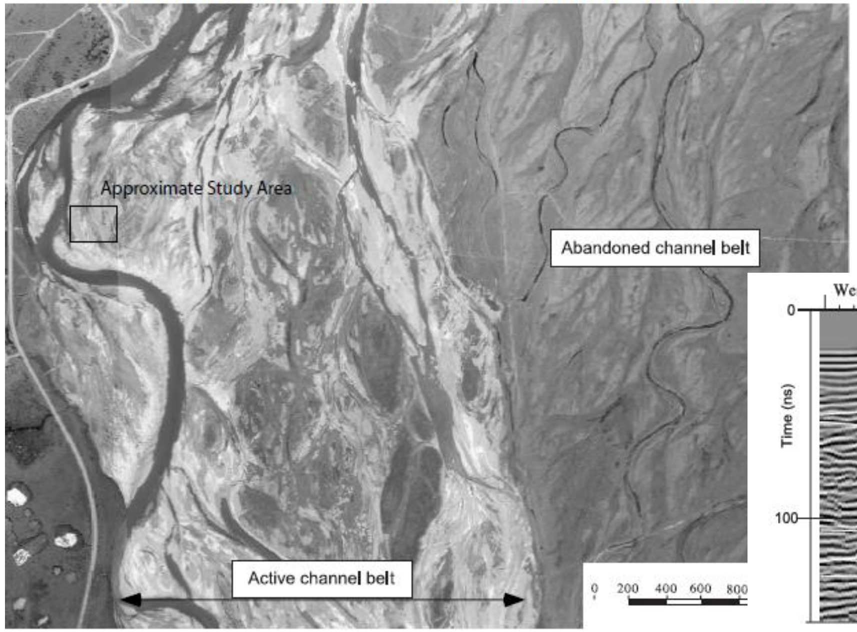
- Ample cause to expect heterogeneity shallow and coarser grainsizes at depth.
- Clay-plugs, levee silt, and point bar sands in upper 25 ft.
- Complex bars of sand and gravel with discontinuous silts from 25 ft to bed Rock

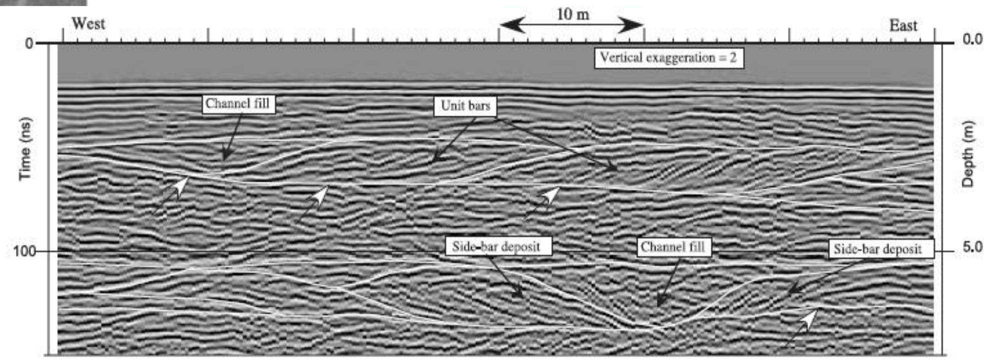
Sedimentary facies model:
fluvial meander belt sedimentation



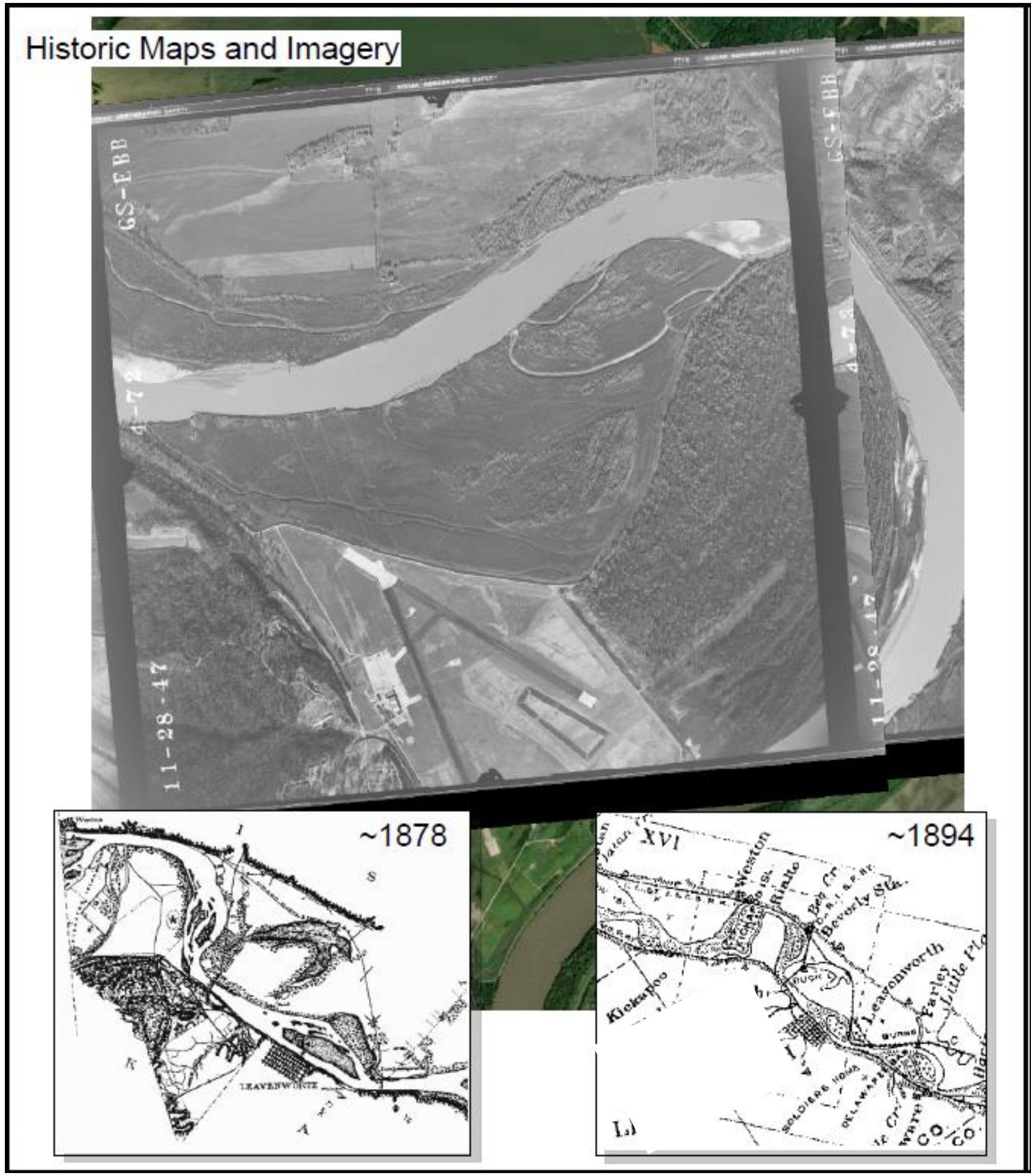
Distribution and orientation of grain sizes
and bedding within meandering river deposits.
Loam refers to a combination of fine sand, silt, and clay.

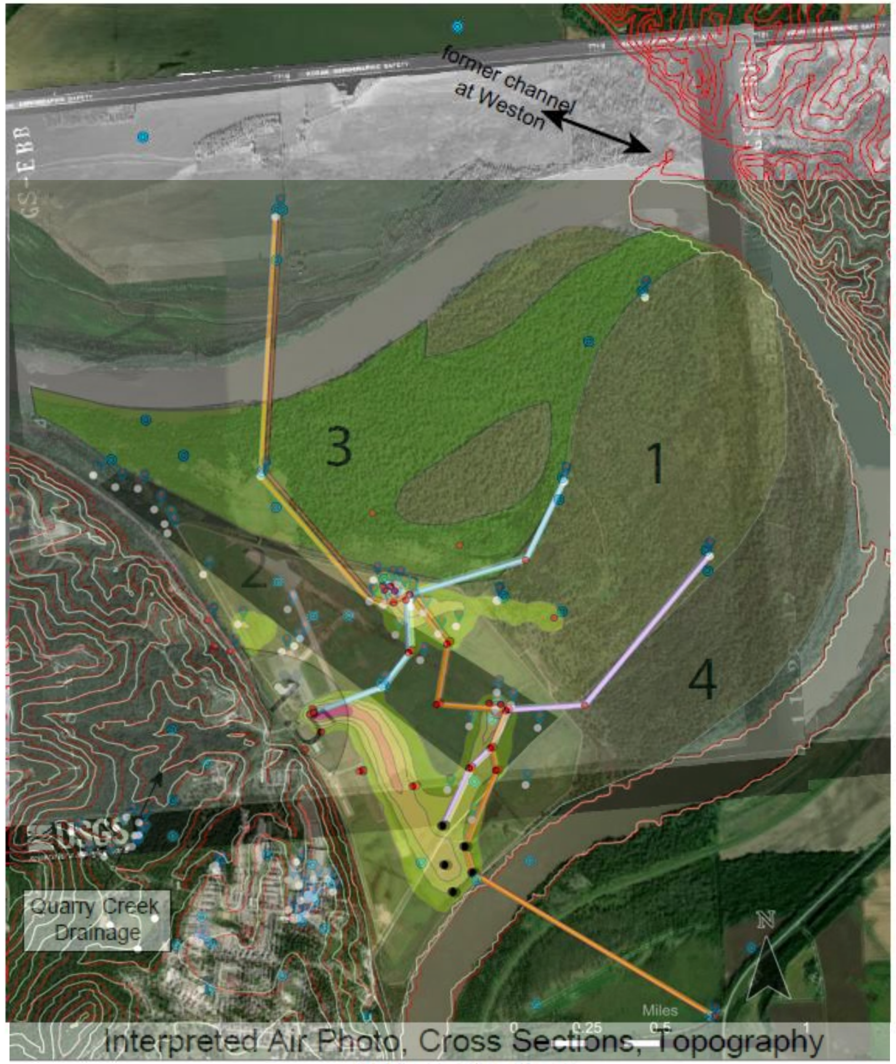
Modern Braided Fluvial Analogue- Sagavanirktok River, AK





Historical Analysis Provides the Answer (For Upper 25 ft…)

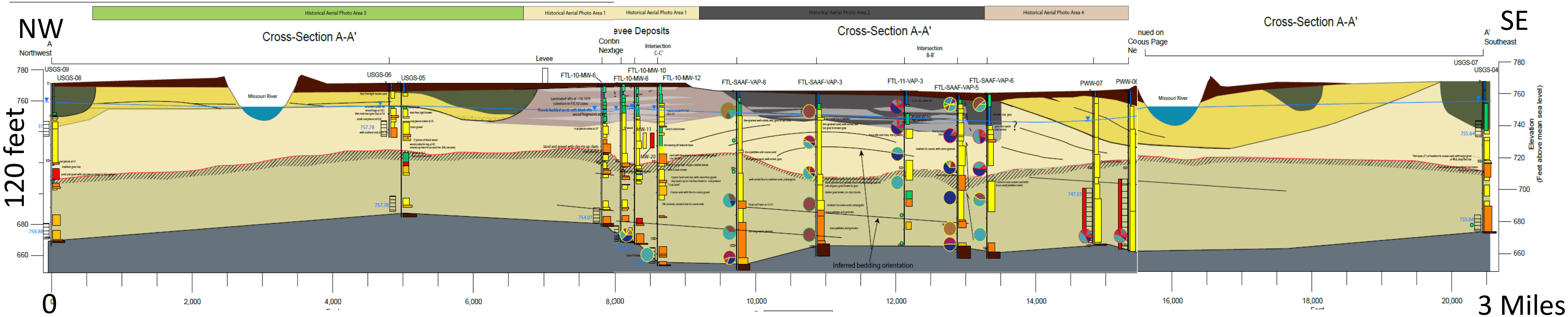




Interpreted Air Photo, Cross Sections, Topography and Well Distribution

1. Relict Meander Point Bar "Core"
1.5. Quarry Creek Fan
2. Abandoned Chute Area
3. Braided Meander -Contraction
4. Braided Meander - Translation

Overview Of Site Stratigraphy and Initial CSM Elements



Low K, Heterogeneous Facies (Storage Zones)

K	
	HSU 5: Meander Belt - Levee and Overbank Deposits
~ 0.3-13 ft/d	overbank silt and clay levee sands
	HSU 4: Meander Belt - Chute Channel and Bars
~ 0.3-13 ft/d	clay plug sands and silty sands
	HSU 3: Quarry Creek Fan
~0.03 ft/d	Distal Proximal and Channel

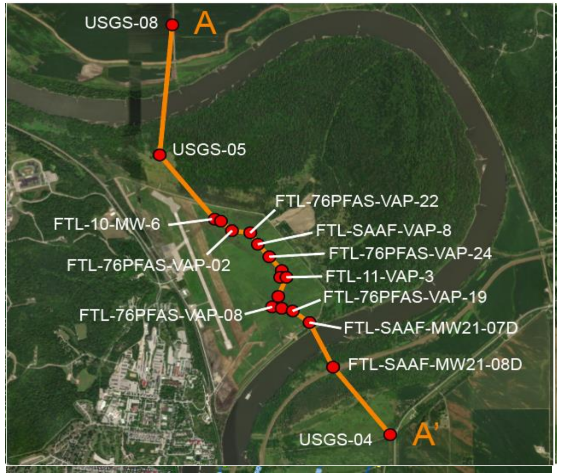
High K, Bedded Coarse Facies (Transport Zones)

K	
	HSU 6: Braided Meander-
~ 13 to 50 ft/d	Clay Plugs Sandy Bar deposits
	HSU 2: Meander Belt- Point bar and Channel sands
13 to 50 ft/d	
	HSU 1: Braided Fluvial- Bar and Channel Deposits
120-600 ft/d	

Bounding Units

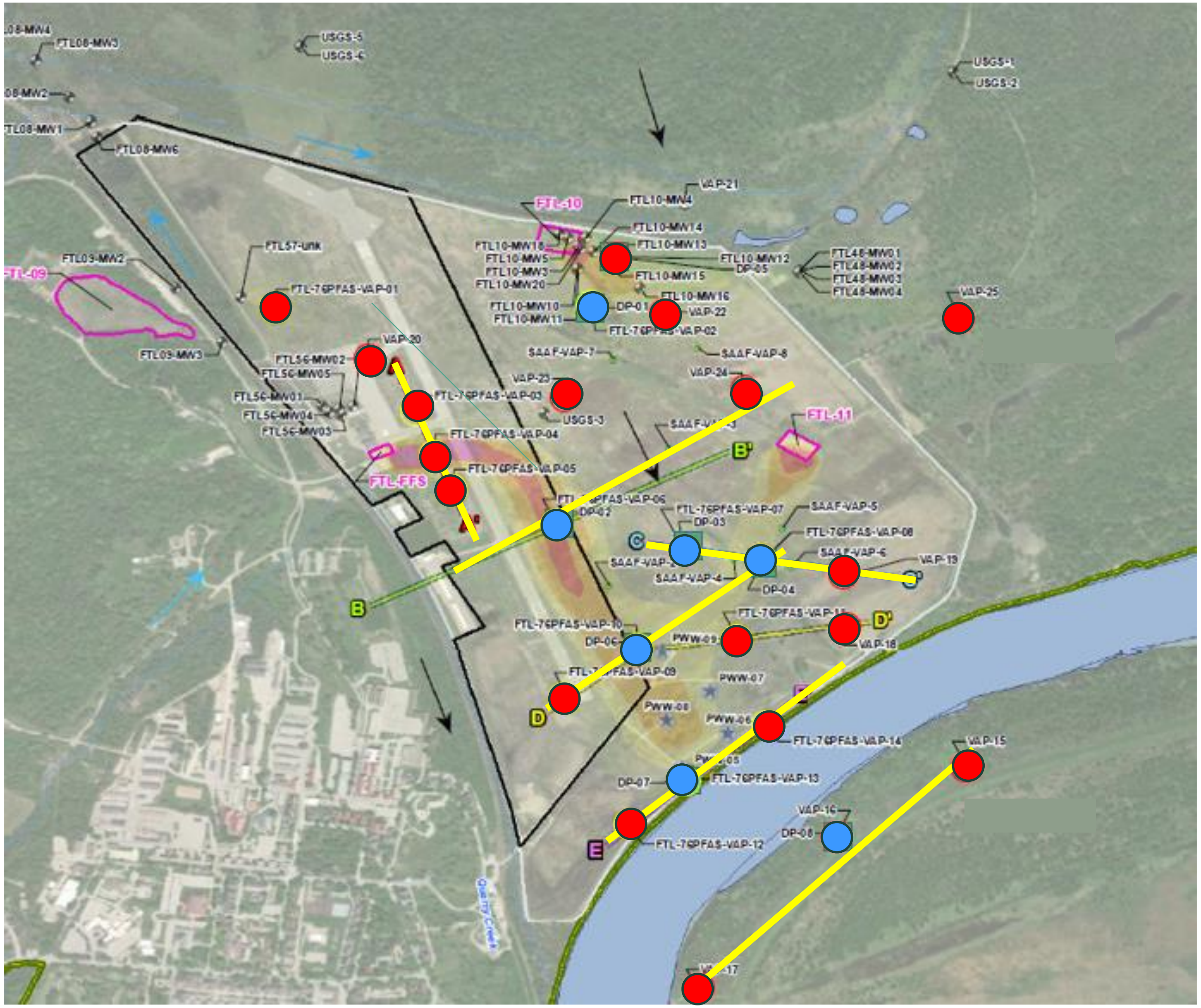
Modern Floodplain

Bedrock: shale encountered in borings

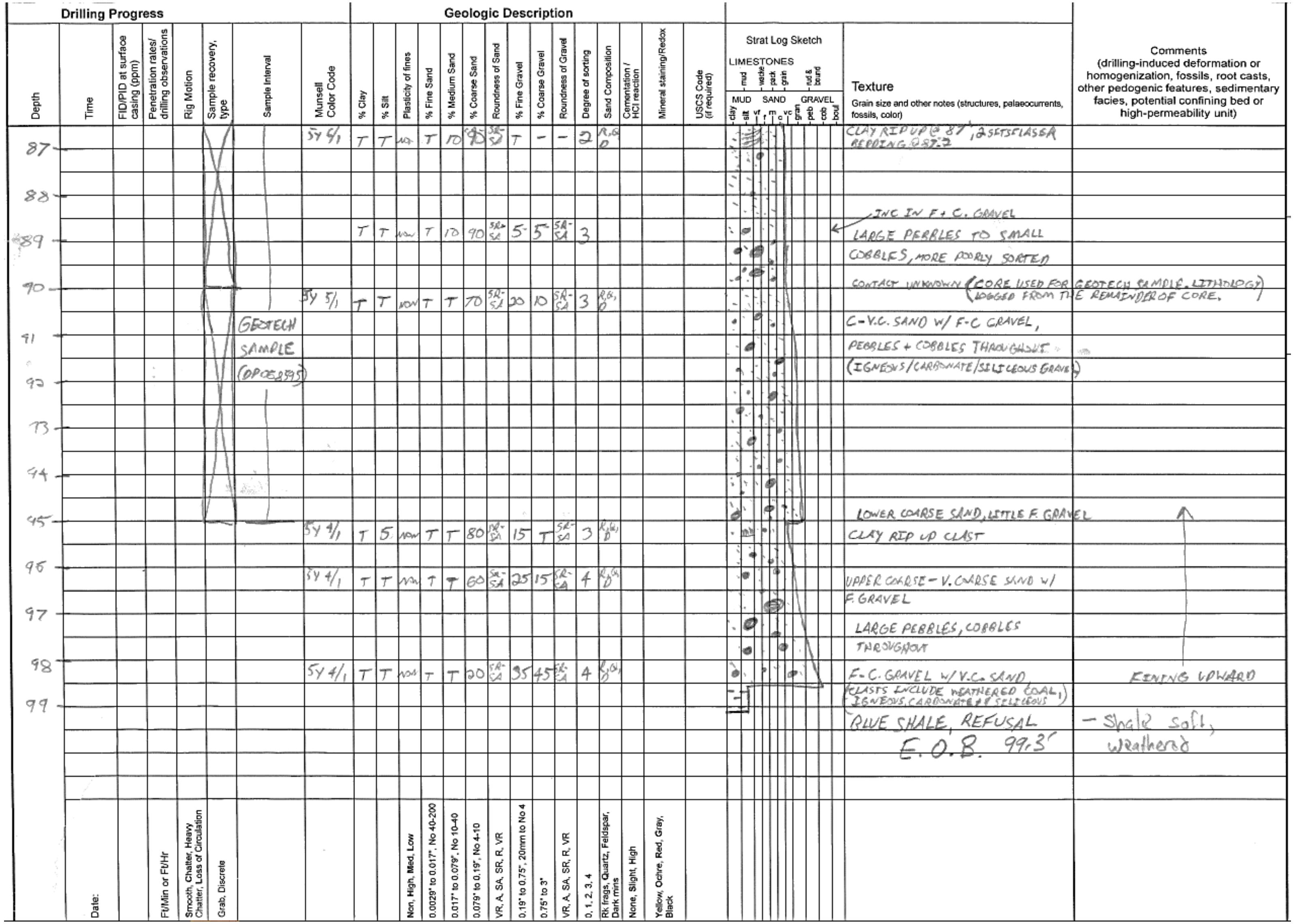


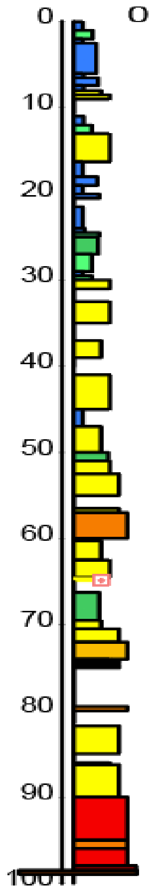
Planned RI Investigation

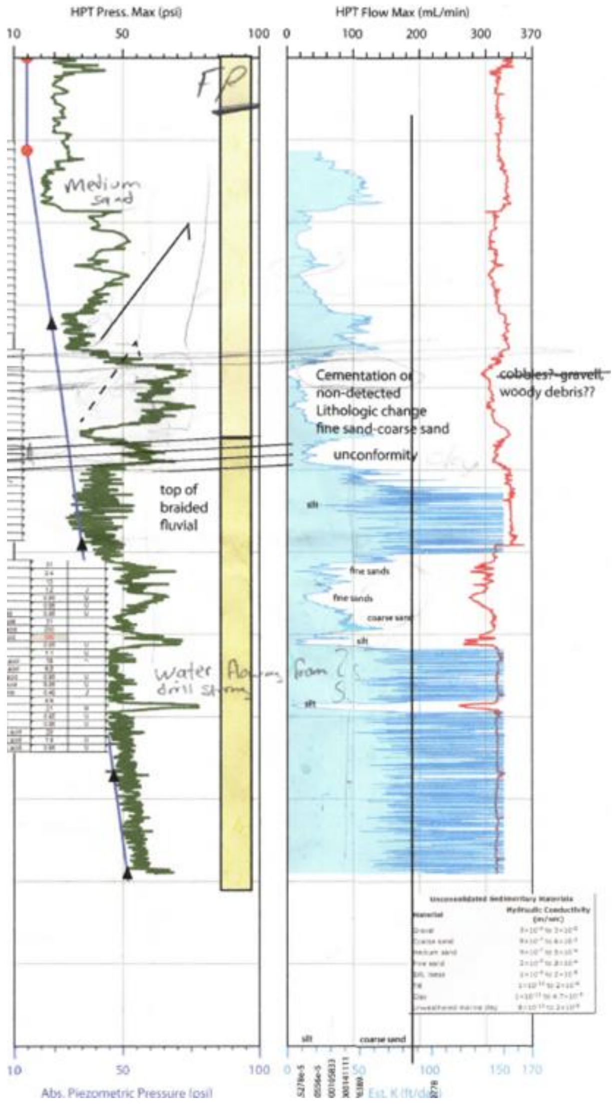
- 25 Investigation Locations
  - 2 phases
  - EC-HPT data collected first
  - 8 with detailed ESS lithologic logging to calibrate, test CSM
  - VAP groundwater grabs at all locations with depths based on findings
  - Point distribution supports flux transect approaches (yellow)

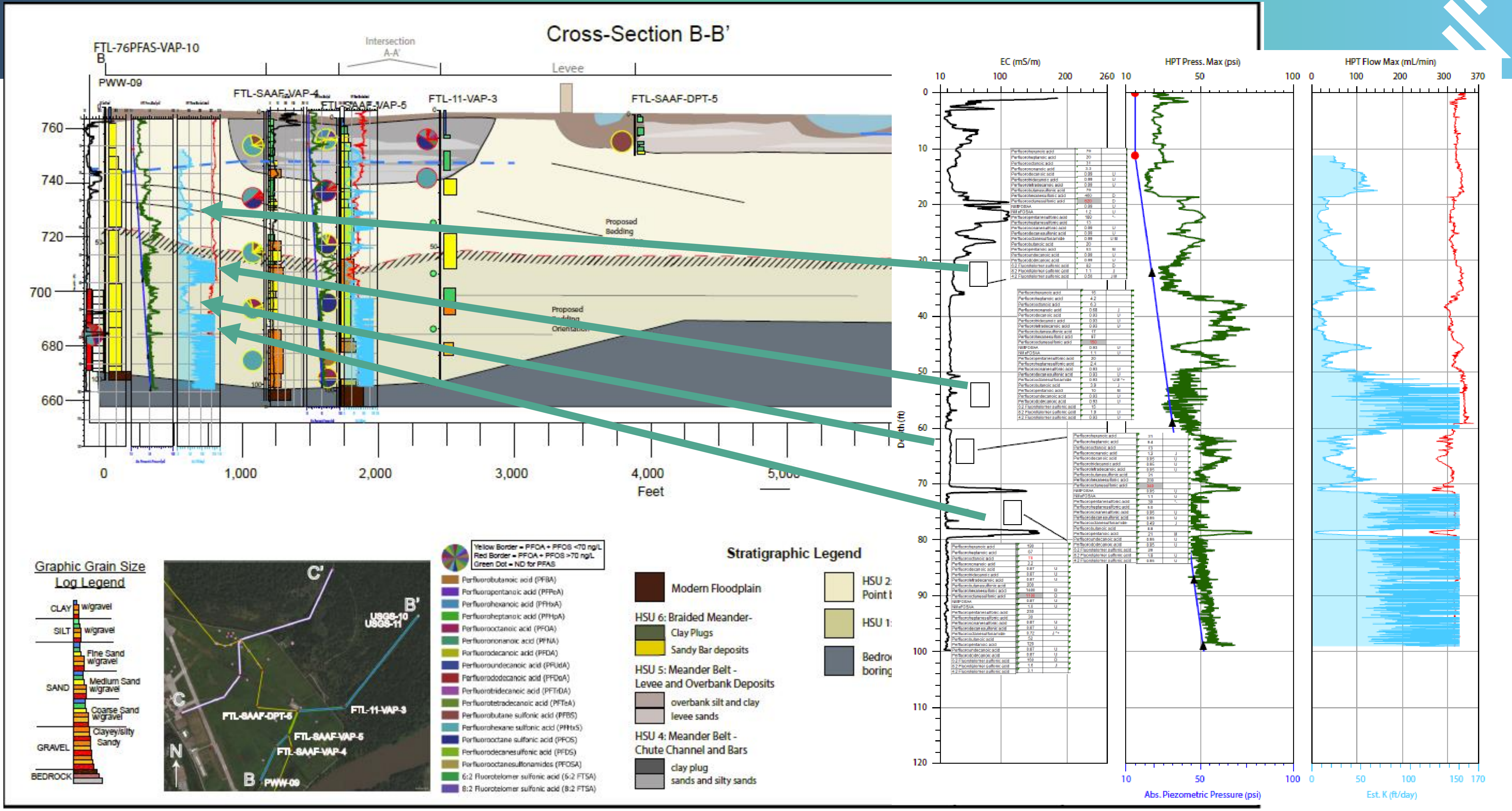


ESS –Graphical Approaches to Core Logging



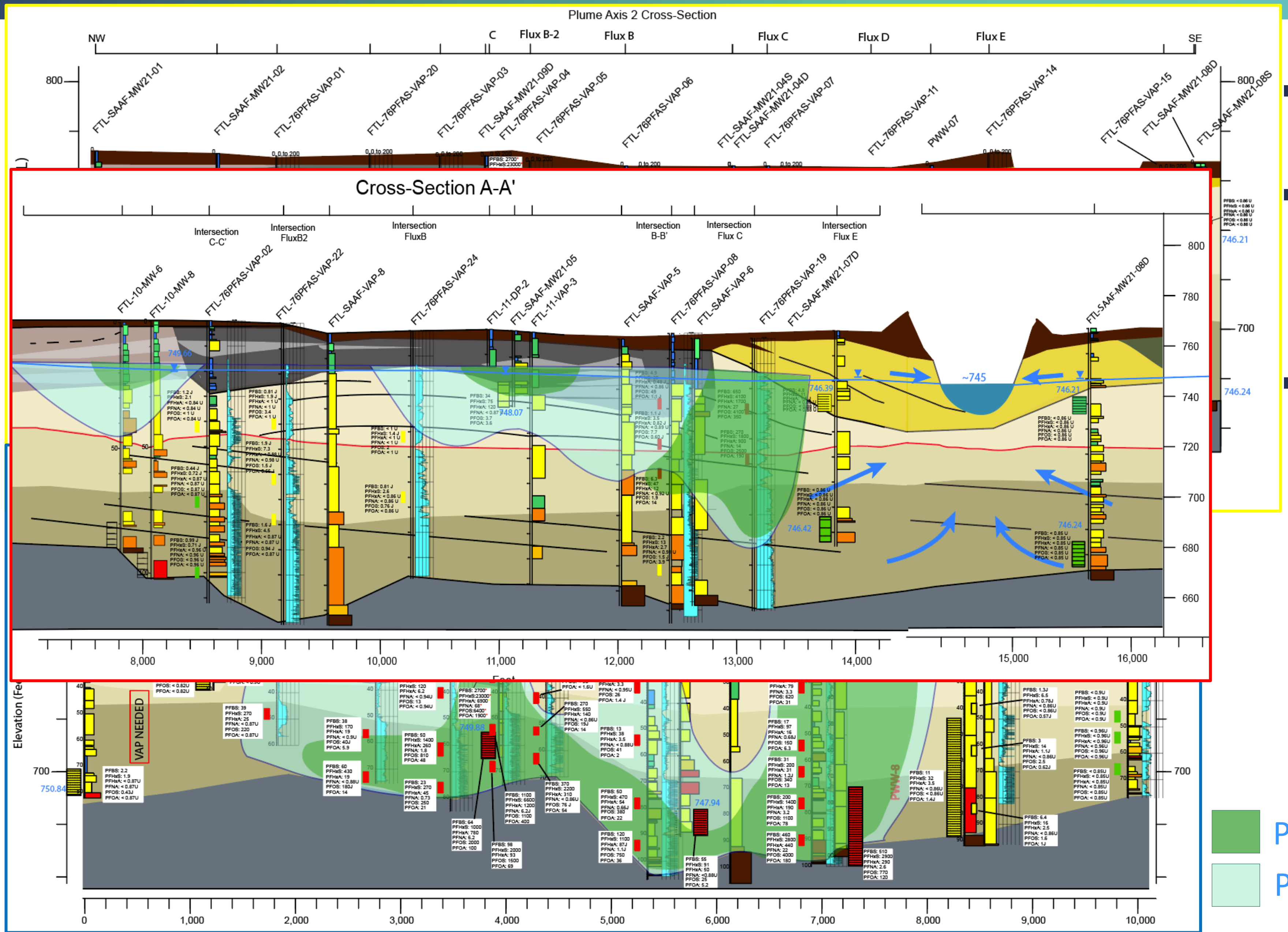




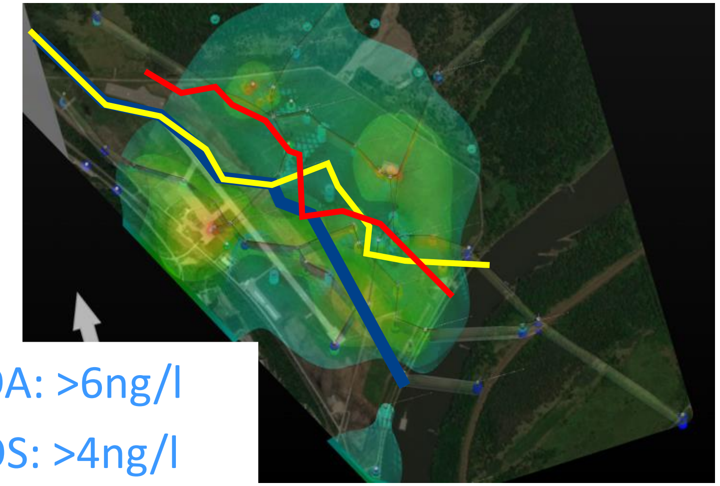


Cross-Section B-B'
FTL-76PFAS-VAP-10
B
Intersection
A-A'
Levee
PWW-09
FTL-SAAF-VAP-4
FTL-SAAF-VAP-5
FTL-11-VAP-3
FTL-SAAF-DPT-5
760
740
720
700
680
660
Proposed Bedding
Proposed Bedding Orientation
0
1,000
2,000
3,000
4,000
Feet
EC (mS/m)
HPT Press. Max (psi)
HPT Flow Max (mL/min)
Abs. Piezometric Pressure (psi)
Est. K (ft/day)
Depth (ft)
Graphic Grain Size Log Legend
CLAY w/gravel
SILT w/gravel
SAND
Fine Sand w/gravel
Medium Sand w/gravel
Coarse Sand w/gravel
Clayey/silty Sandy
GRAVEL
BEDROCK
C'
B'
USGS-10
USGS-11
C
FTL-SAAF-DPT-5
FTL-11-VAP-3
FTL-SAAF-VAP-5
FTL-SAAF-VAP-4
N
B
PWW-09
Yellow Border = PFOA + PFOS <70 ng/L
Red Border = PFOA + PFOS >70 ng/L
Green Dot = ND for PFAS
Perfluorobutanoic acid (PFBA)
Perfluoropentanoic acid (PFPeA)
Perfluorohexanoic acid (PFHxA)
Perfluoroheptanoic acid (PFHpA)
Perfluorooctanoic acid (PFOA)
Perfluorononanoic acid (PFNA)
Perfluorodecanoic acid (PFDA)
Perfluoroundecanoic acid (PFUdA)
Perfluorododecanoic acid (PFDoA)
Perfluorotridecanoic acid (PFTrDA)
Perfluorotetradecanoic acid (PFTeA)
Perfluorobutane sulfonic acid (PFBS)
Perfluorohexane sulfonic acid (PFHxS)
Perfluorooctane sulfonic acid (PFOS)
Perfluorodecanesulfonic acid (PFDS)
Perfluorooctanesulfonamides (PFOSA)
6:2 Fluorotelomer sulfonic acid (6:2 FTSA)
8:2 Fluorotelomer sulfonic acid (8:2 FTSA)
Stratigraphic Legend
Modern Floodplain
HSU 6: Braided Meander-
Clay Plugs
Sandy Bar deposits
HSU 5: Meander Belt - Levee and Overbank Deposits
overbank silt and clay
levee sands
HSU 4: Meander Belt - Chute Channel and Bars
clay plug
sands and silty sands
HSU 2
HSU 1
Bedrock boring

Updated ESS Cross Sections and Conclusions



- HSUs modified to reflect HPT results
- Right hand turn in plume controlled by drainage and contact with high K braided fluvial deposits at depth
- Plume appears to rise to river, with easterly flow in absence of pumping

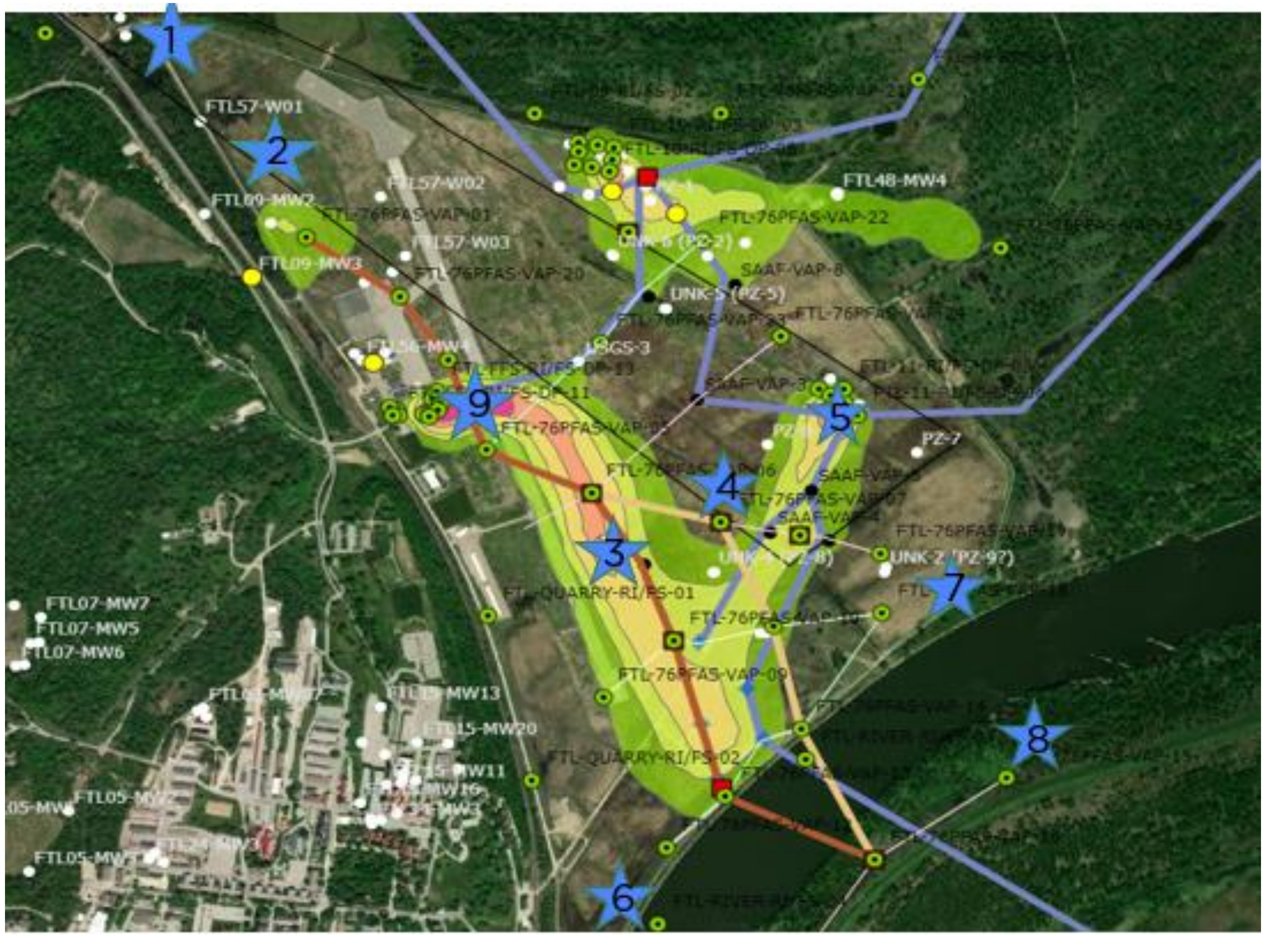


PFOA: >6ng/l

PFOS: >4ng/l

The Outcome: Targeted Well Placement

- Confirmed impact of Clay plug on isolating/deflecting GW shallow
  - PFAS Plume Drawn under during pumping
  - Shallow Migration eastward in absence of pumping potentially facilitated by relict chute channel
- 11 Wells Located During Working Sessions of RI Team
- Approximate Position Of Proposed Wells



General Conclusions

- ESS is an established best practice for improved CSM development
- The three-step process is possible to implement with the types of lithologic data traditionally available in the environmental industry
- An ESS CSM creates a predictive framework and improved context that can guide a more efficient and effective PFAS investigation

https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=341373&Lab=NRMRL

EPA/600/R-17/293
September 2017

EPA United States Environmental Protection Agency **Groundwater Issue**

Best Practices for Environmental Site Management:

A Practical Guide for Applying Environmental Sequence Stratigraphy to Improve Conceptual Site Models

Michael R. Shultz[1], Richard S. Cramer[1], Colin Plank[1], Herb Levine[2], Kenneth D. Ehman[3]

CONTENTS

This document was prepared under the U.S. Environmental Protection Agency National Decontamination Team Decontamination Analytical And Technical Service (DATS) II Contract EP-W-12-26 with Consolidated Safety Services, Inc. (CSS), 10301 Democracy Lane, Suite 300, Fairfax, Virginia 22030

[1]Burns & McDonnell
[2]U.S. EPA
[3]Chevron Energy Technology Company

BACKGROUND

This issue paper was prepared at the request of the Environmental Protection Agency (EPA) Ground Water Forum. The Ground Water, Federal Facilities, and Engineering Forums were established by professionals from the United States Environmental Protection Agency (USEPA) in the ten Regional Offices. The Forums are committed to the identification and resolution of scientific, technical, and engineering issues impacting the remediation of Superfund and RCRA sites. The Forums are supported by and advise Office of Solid Waste and Emergency Response's (OSWER) Technical Support Project, which has established Technical Support Centers in laboratories operated by the Office of Research and Development (ORD), Office of Radiation Programs, and the Environmental Response Team. The Centers work closely with the Forums providing state-of-the-science technical assistance to USEPA project managers. A compilation of issue papers on other topics may be found here:

http://www.epa.gov/superfund/remedytech/tsp/issue.htm

The purpose of this issue paper is to provide a practical guide on the application of the geologic principles of sequence stratigraphy and facies models (see "Definitions" text box, page 2) to the characterization of stratigraphic heterogeneity at hazardous waste sites.

Application of the principles and methods presented in this issue paper will improve Conceptual Site Models (CSM) and provide a basis for understanding stratigraphic flux and associated contaminant transport. This is fundamental to designing monitoring programs as well as selecting and implementing remedies at contaminated groundwater sites. EPA recommends re-evaluating the CSM while completing the site characterization and whenever new data are collected. Updating the CSM can be a critical component of a 5 year review or a remedy optimization effort.

THANK YOU

FOR YOUR TIME

A Major Obstacle For Performance : The Inherent Complexity of the Subsurface

Complexity Consists of:

Lithologic Heterogeneity

- Scale of detection vs. reality

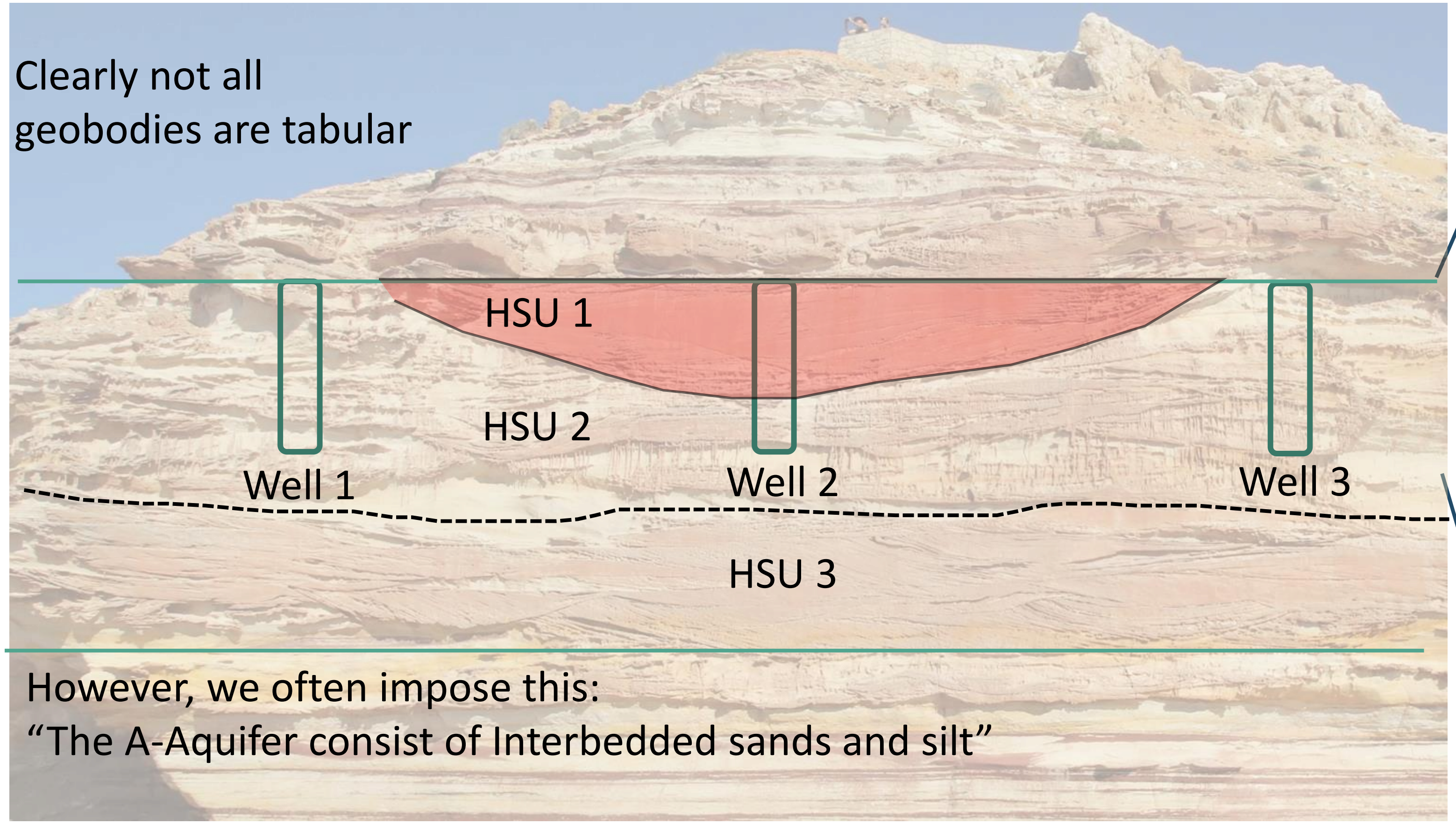
Stratigraphic Geometry

- Real vs. Interpreted Hydrostratigraphic unit continuity

Van Etten Creek, Oscoda, MI

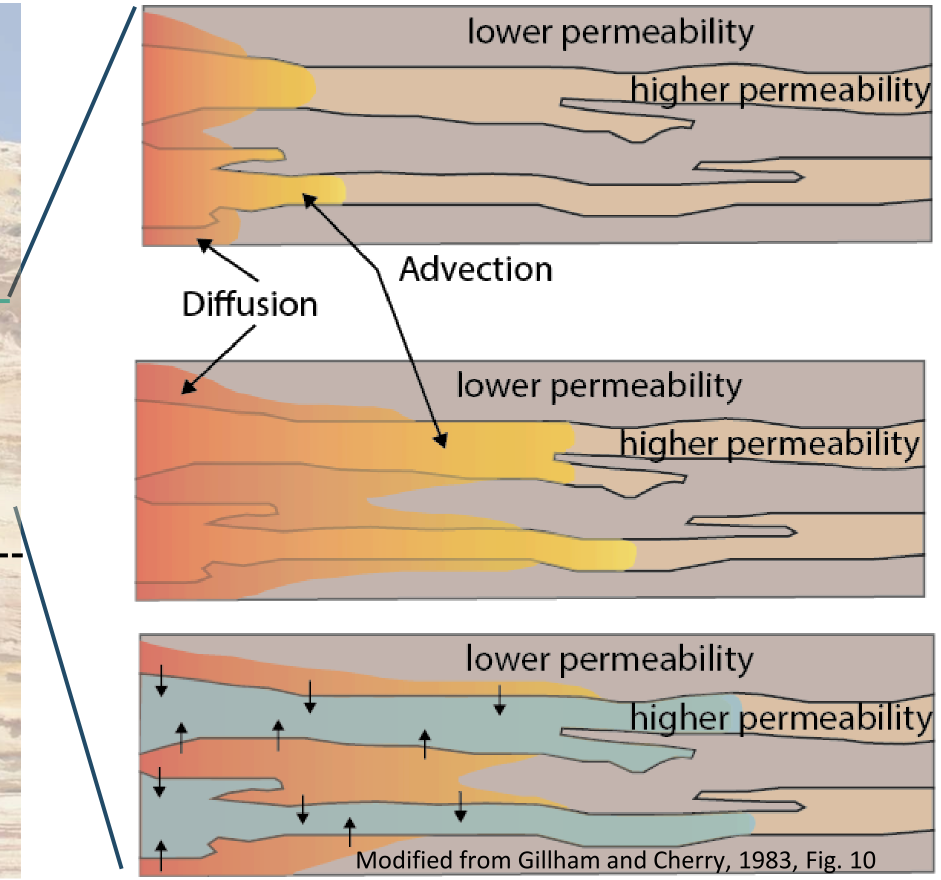
Geologic Complexity: Geometry and Heterogeneity

Geometry



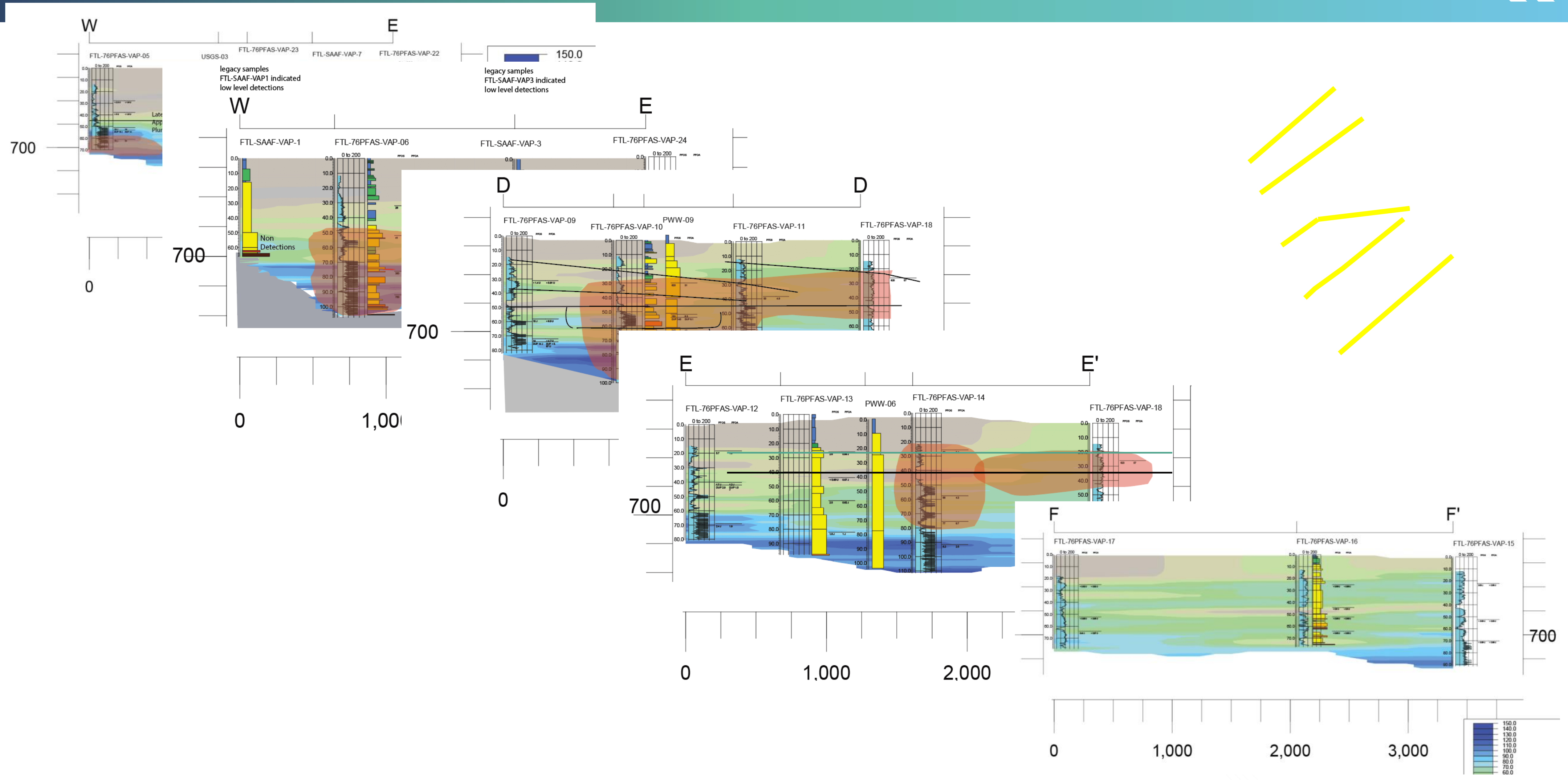
Depositional geometry of HSU's can significantly impact hydraulic connectivity, well performance, and/or amendment efficacy and so must be addressed.

Heterogeneity

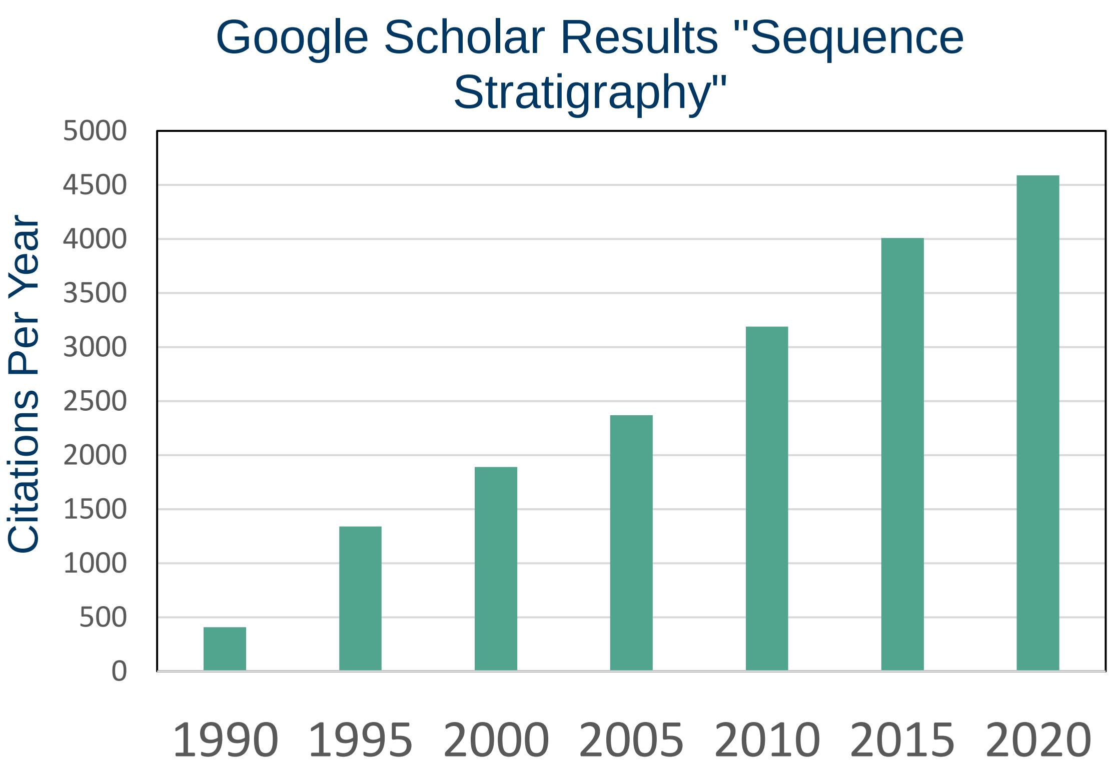


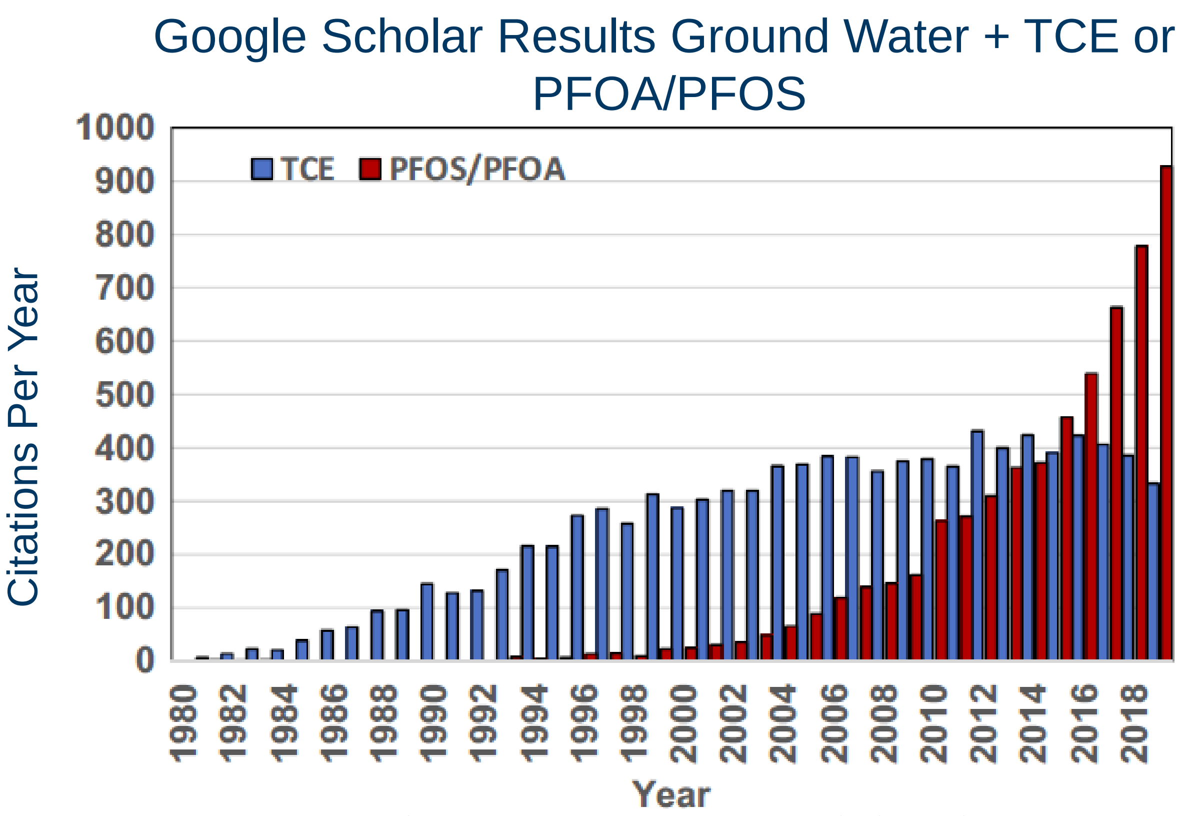
Diffusion of mass into fine-grained storage zones can lead to back diffusion and prolonged remediation time frames

Preliminary Relative Flux Transects :



Growing Interest in Stratigraphic Analyses and PFAS





(Newell et al.,2020, Remediation (30), 7-26)

- 2013 Battelle Program: “Geology” not found
- 2022 Battelle Program: “Geology” 70X, Stratigraphy 35X