Bioremediation: Recent Advances in Site Characterization

High-Resolution Site Characterization

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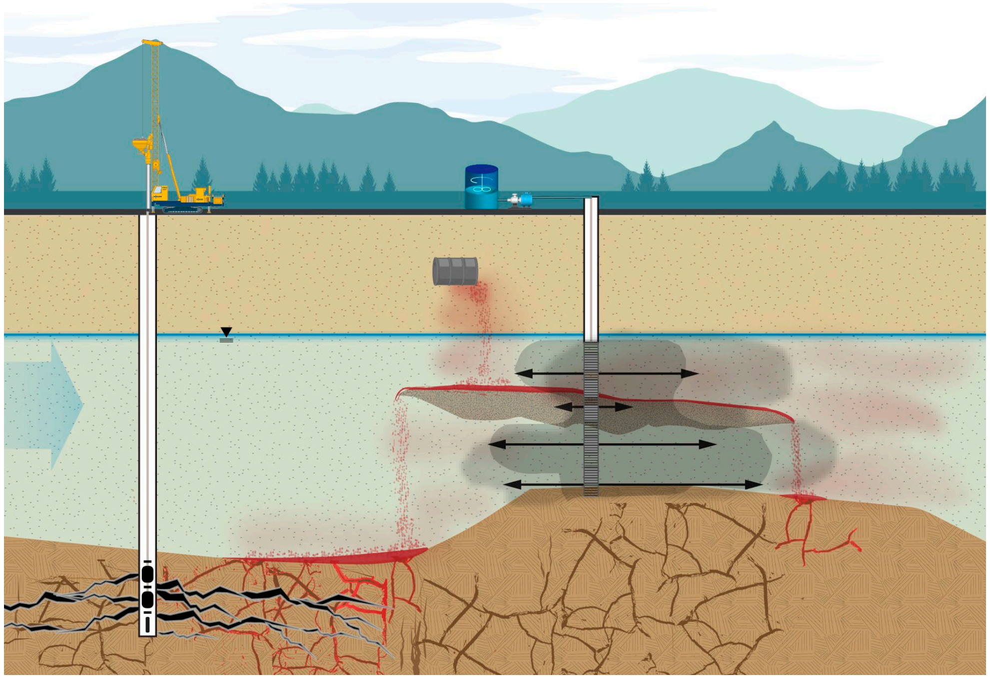
Challenges with Bioremediation

- Success is driven by efficient amendment delivery
- Heterogeneity in aquifers causes fluid bypass to preferential pathways
- Multiple/persistent sources affect mobility/treatment time
  - DNAPL
  - Sorption
  - Matrix back diffusion

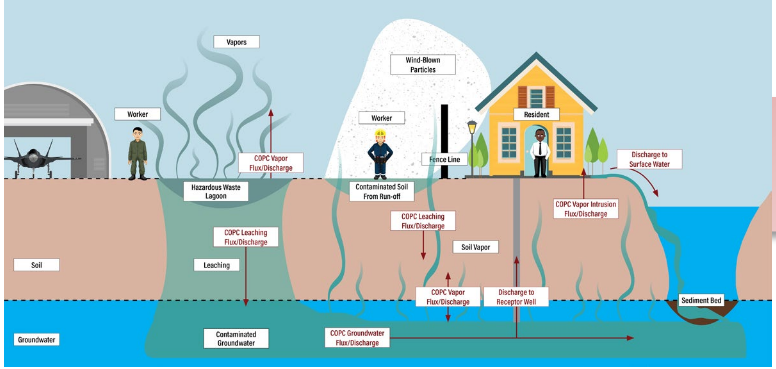


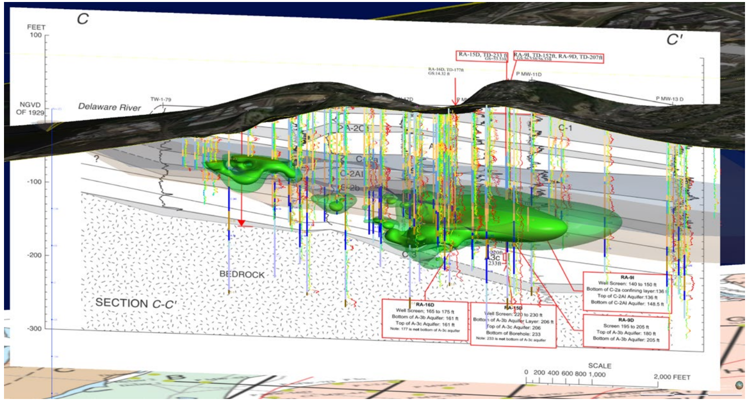
Conceptual Site Model Resolution

Develop a conceptual site model at an appropriate scale to account for site heterogeneity to characterize:

- Physical properties
- Chemical of concern (COC) distribution
- Fate and transport

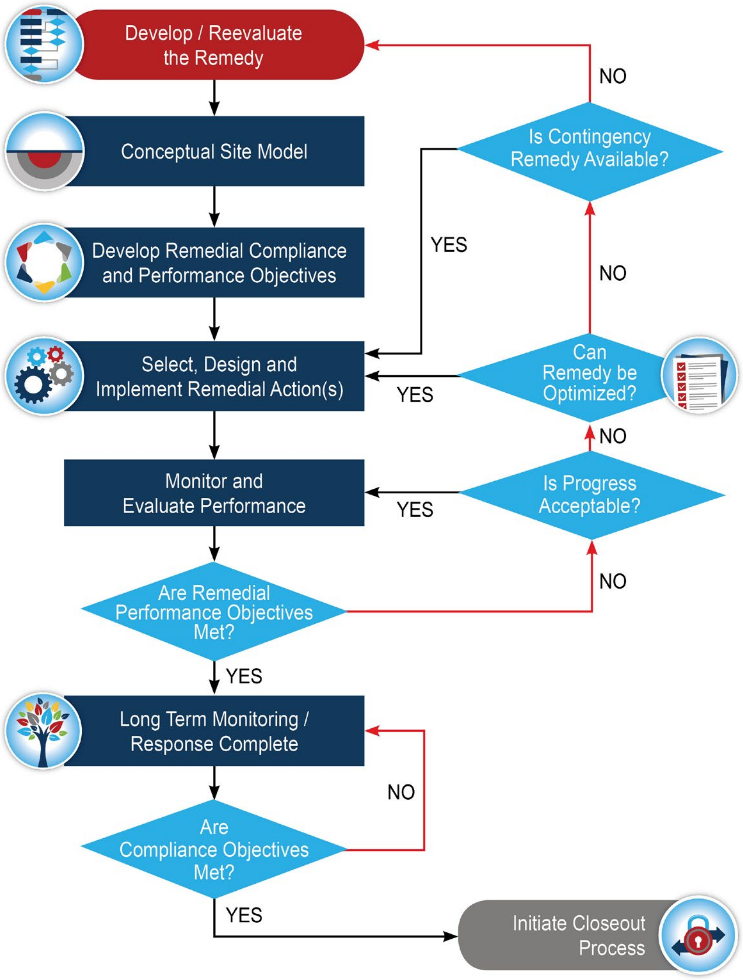
High-resolution site characterization tools collect data on relatively small scales with a greater data acquisition rate than conventional characterization tools and approaches.



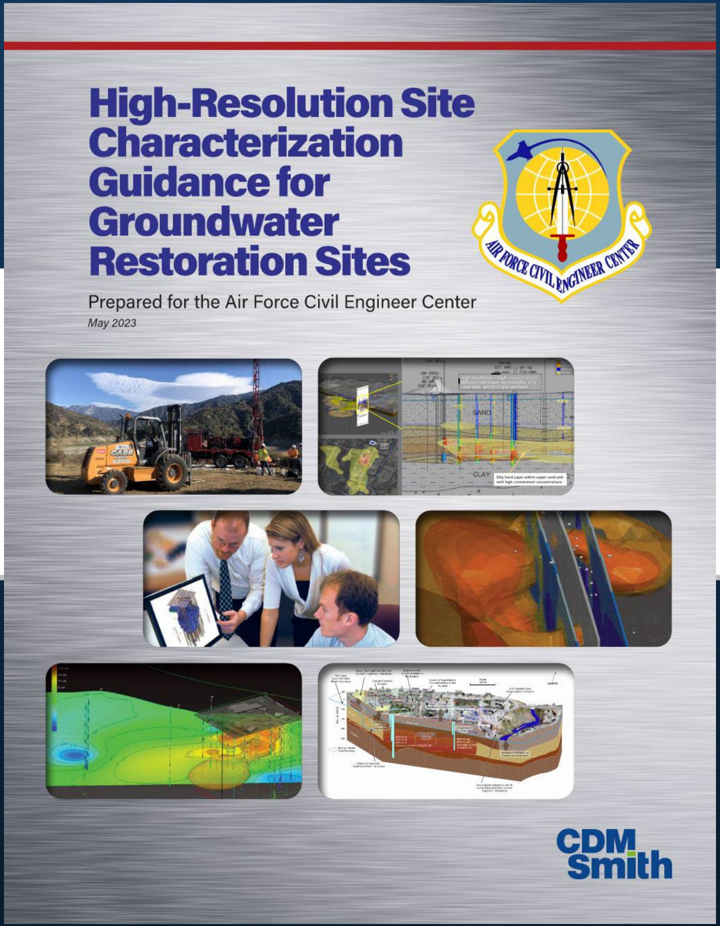


HR-CSM During the Site Life Cycle

- HRSC to Improve Site CSM
- HRSC to Support Remedial Objectives
- HRSC to Support Technology Selection and Design
- HRSC for Remedy Optimization and Closure

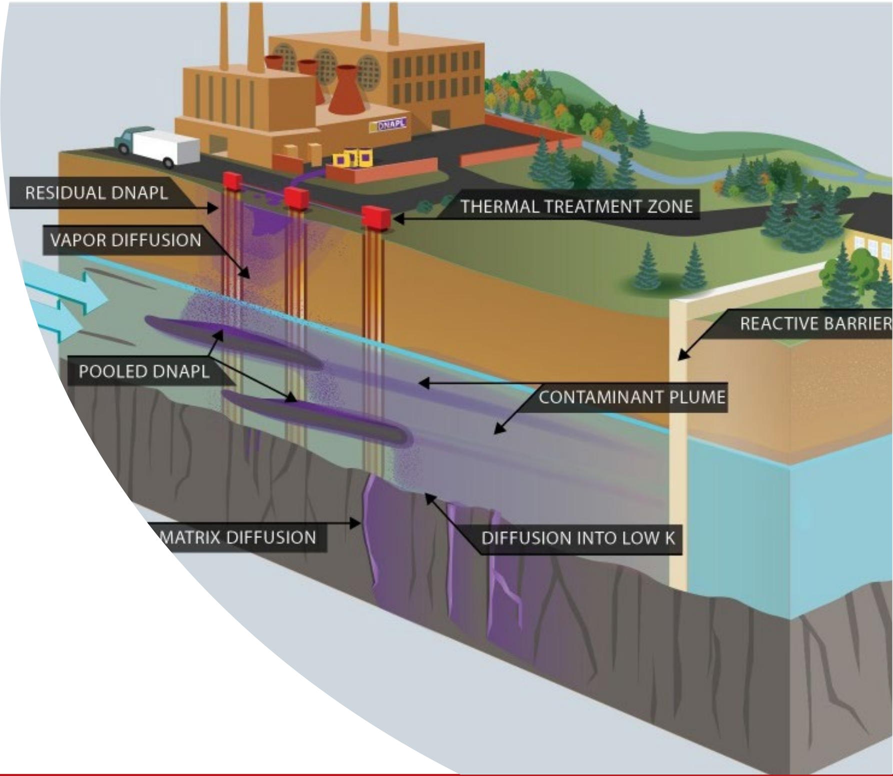


AFCEC BAA-704: HRSC Guidance Document and Tool



HRSC Guidance Purpose

- Developing robust CSMs
  - Incorporating site complexities = essential to remedy design, implementation, optimization
- Fill data gaps and fulfill site objectives
  - Uses a combination of HRSC and standard tools
- HRSC tools are more available
  - More tools = increased awareness of how site condition heterogeneities and complexities impact CSM development
- HRSC tools can re-evaluate failed remedies
  - Lack of site understanding = remedies more likely to fail



Guidance Outline

Section 1: Introduction

Section 2: Building a Conceptual Site Model

- Elements of a Conceptual Site Model

Section 3: High Resolution Site Characterization Tools

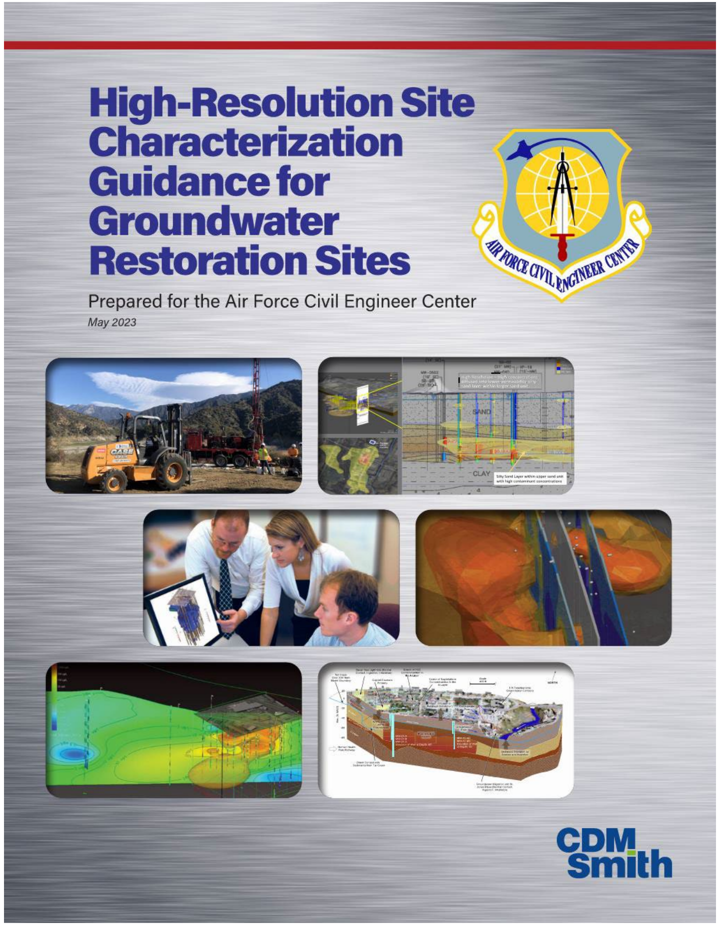
- Definition and Description of HRSC Tools
- Conventional Tools Applied at High Resolution

Section 4: High Resolution Conceptual Model Role is Site Life Cycle

- Definition of Site Life Cycle
- Utilizing HRSC Tools at each Step of the Site Life Cycle

Section 5: Implementing this HRSC Guidance and Tool

Section 6: Demonstration Case Study



Using the HRSC Guidance

HRSC TOOL SELECTION TABLE

HRSC TOOL SELECTION PROCESS

TOOL SELECTION CRITERIA INPUTS

Step 1: Identify Site Characteristics (select one item per group)

Component of the CSM*		Formation Type*	
Aquifer Properties		Unconsolidated	
Chemical Distribution		Bedrock	
Chemical Attenuation			

Step 2: Identify Type of Parameter/Data Required (multiple selections permitted)

Geology		Hydrogeology		Chemicals		Chemical Attenuation	
Lithology		Depth to Water Table		LNAPL		Biotic Degradation	
Lithologic Contacts		Water Content		DNAPL		Abiotic Degradation	
Primary Porosity		Hydraulic Conductivity		Groundwater COC Concentration		Sorption	
Secondary Porosity: Fractures		Preferential Flow Paths		Geochemical Tracking		Diffusion	
Structural Faults		Groundwater Discharge		Soil COC Concentration			
Competence		Borehole Flow		COC Flux			
		Borehole Condition					
		Fracture Connectivity					

Step 3: Identify Level of Data Quality (select at least one item)

Data Quality*	
All	
Screening-level	
Qualitative	
Semiquantitative	
Quantitative	

Minimum selections have not been made. Please select one item for input groups with an asterisk.

DEVELOP A HRSC DATA COLLECTION PROGRAM

COMBINING HRSC TOOL AND CONVENTIONAL TOOLS

TOOLS TO VISUALIZE AND INTERPRET HRSC DATA

Too
Sur

Method/Tool	Relative Cost	Data Type/Data Quality Objectives	Advantages/Applications	Disadvantages/Limitations
Dipmeter References ▪ ITRC 2015 ▪ USEPA 1993, 2004, 2016 ▪ Williams 1990	▪ $$ ▪ $1.00–2.00 per foot ▪ $2,500 – 5,000 per day*	▪ Physical – geologic structure (fractures and bedding planes) ▪ Four downhole logs of resistivity and two caliper traces provides quantitative measurement of location and orientation of fractures and bedding planes	▪ Radius of investigation near borehole surface ▪ Can only be used in open borehole 6 to 20 inches in diameter in the saturated zone ▪ Used in both bedrock and unconsolidated soil/sediment; more accurate measuring bedding planes ▪ Logging rate 8 to 20 feet per minute	▪ Minimum borehole diameter of 6 inches for accurate measurement of bedding planes and fractures ▪ Under most conditions the acoustic televiewer provides more accurate measurements of fractures ▪ Cannot be used concurrently with other probes
Induction Resistivity (Conductivity logging) References ▪ ITRC 2015 ▪ USEPA 1993, 2004, 2016 ▪ Williams 1993	▪ $$ ▪ $1.00 – 2.00 per foot ▪ $2,500 – 5,000 per day*	▪ Physical – lithology and water content ▪ Chemical – salinity ▪ Downhole log of conductivity measurements provides semi-quantitative information on lithology, salinity of formation water, and water content	▪ Radius of investigation 30 inches ▪ Can be used in open or cased (PVC) borehole 5 to 20 inches in diameter in the vadose and saturated zones ▪ Used in both bedrock and unconsolidated soil/sediment ▪ Logging rate up to 60 feet per minute ▪ Not sensitive to borehole diameter	▪ Results are low resolution (as they are averaged over 1-2 meters) ▪ Interferences due to metallic minerals or objects ▪ Low signal and resolution in low conductivity environments ▪ Cannot be used concurrently with other probes
Nuclear Magnetic Resonance (NMR) References ▪ Baker 2015 ▪ ITRC 2015 ▪ Vista Clara 2020 ▪ USEPA 1993, 2004	▪ $$ ▪ $1.50 – 3.00 per foot ▪ $2,500 – 5,000 per day*	▪ Physical – water content (above water table) and porosity, grain size distribution, hydraulic conductivity (below water table) ▪ With confirmation samples lithology and geology can be determined ▪ Measurements of hydrogen provide a semi-quantitative downhole log of physical parameters	▪ Diameter of investigation 5 to 10 inches ▪ Can be used in open or cased (PVC) borehole 2 to 9 inches in diameter in the vadose and saturated zones. ▪ Limited availability of a tool capable of deployment in 2-inch boreholes ▪ Used in both bedrock and unconsolidated soil/sediment ▪ Logging rate 0.5 to 3 feet per minute ▪ NAPL identification in progress	▪ Quantitative measurements limited to unconsolidated sandy sediments and require other information to calibrate (e.g. slug or aquifer tests) ▪ Insensitive to individual fractures (porosity must be above 3 percent) ▪ Not widely used concurrently with other probes
Magnetometric Resistivity (MMR) References ▪ Asten 1988 ▪ ITRC 2015 ▪ Willowstick 2016	AquaTrack ▪ $$$ ▪ $100,000 – 300,00 per survey	▪ Physical – groundwater flow paths, lithology, geology, and structure ▪ Measurements of the magnetic field provide a qualitative 2-D or 3-D map of groundwater flow paths, lithology, geology, and structure	▪ Radius of investigation dependent upon survey configuration and electrode spacing ▪ Can be used in open or cased (PVC) borehole in the vadose and saturated zones ▪ Used in both bedrock and unconsolidated soil/sediment	▪ Not widely commercially available, proprietary version AquaTrack available only through Willowstick Technologies ▪ Results dependent upon the electrical connectivity in the subsurface ▪ Cannot be used concurrently with other probes

Tool Comparison Summary (10 page)

Surface Geophysics

Downhole Geophysics: Hydrogeologic Properties

In Situ Logging

Downhole Geophysics: Hydraulic Properties

Subsurface Contaminant Profiling

Attenuation

Conventional Tools*

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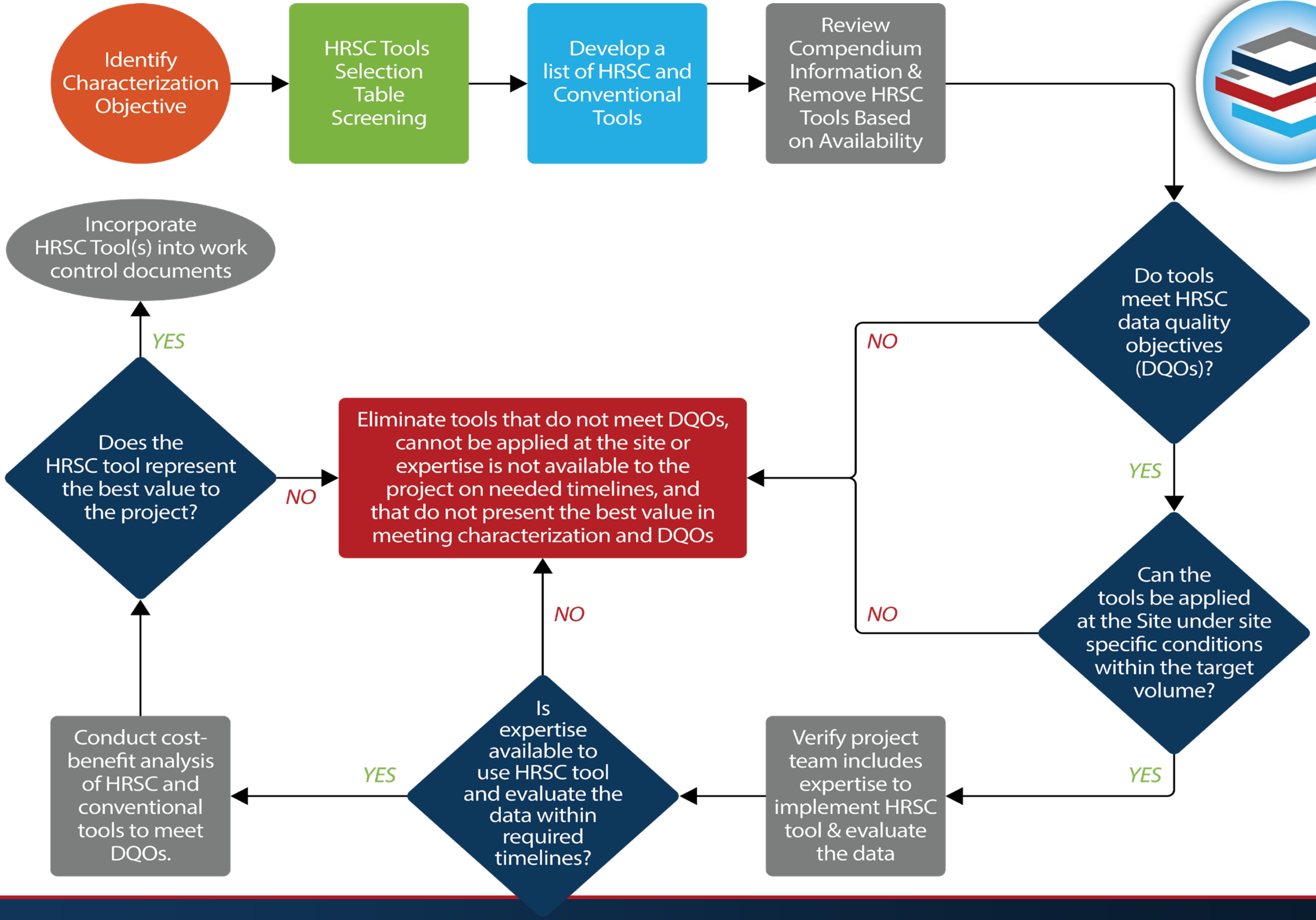
CDM Smith

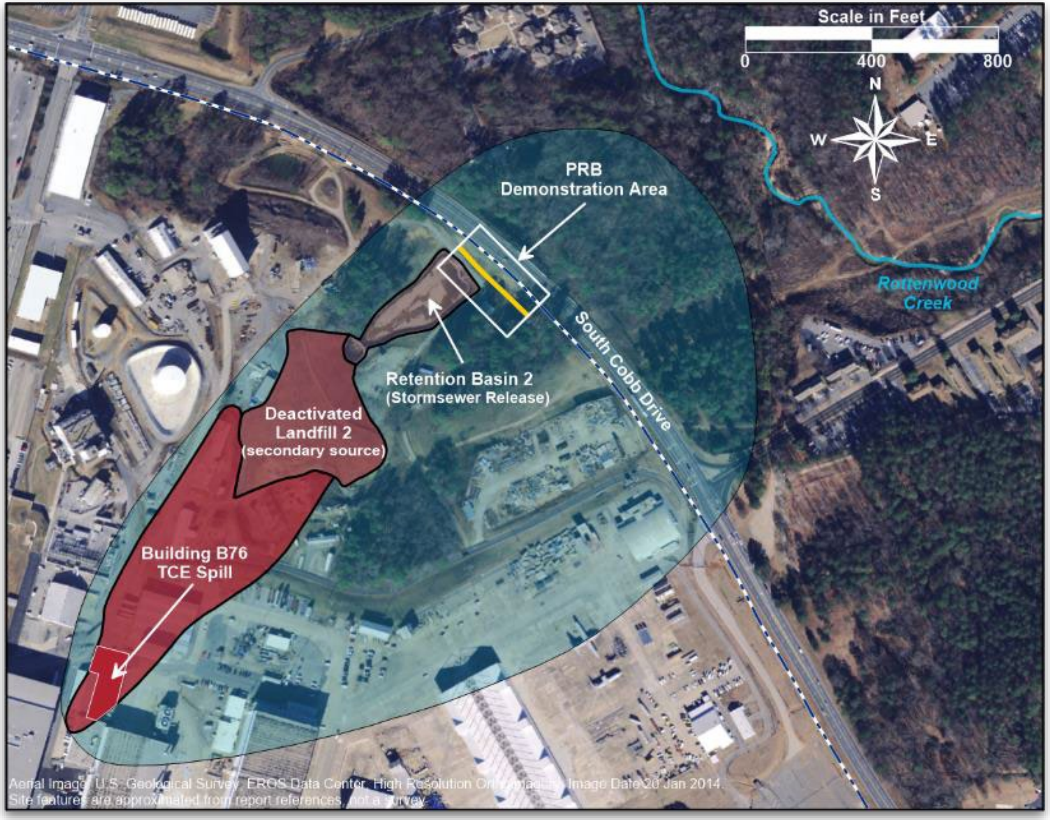
HRSC Decision Process



Demonstration Case Study
Air Force Plant 6

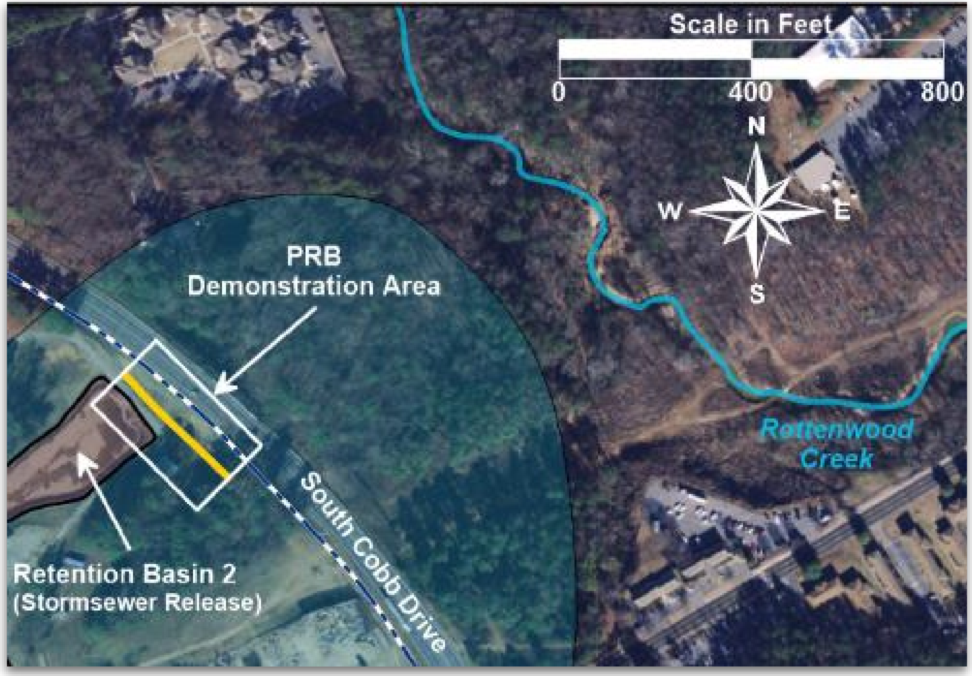
B04 Area History

- Minor historic spills/ releases suspected
- 1983 Building B76 TCE spill, ~13,000 lbs.
  - Entered storm sewer and flowed to retention basin
  - Suspected DNAPL
- Possible waste oil/solvent disposal in Landfill 2



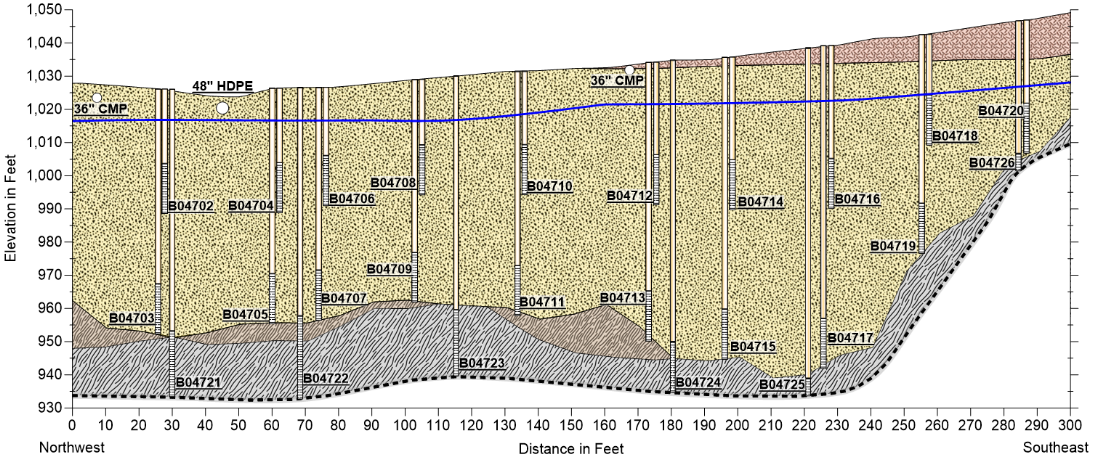
Remedy: Permeable Reactive Barrier (PRB)

- Reduce onsite volatile organic compounds (VOC) mass so monitored natural attenuation (MNA) results in offsite compliance
- Cleanup to Groundwater Protection Standards-MCLs
- PRB Treatment Objective: >300 ug/L TCE
  - 70% VOC mass flux reduction across the PRB to stabilize/shrink the offsite plume and support MNA



B04 PRB Construction

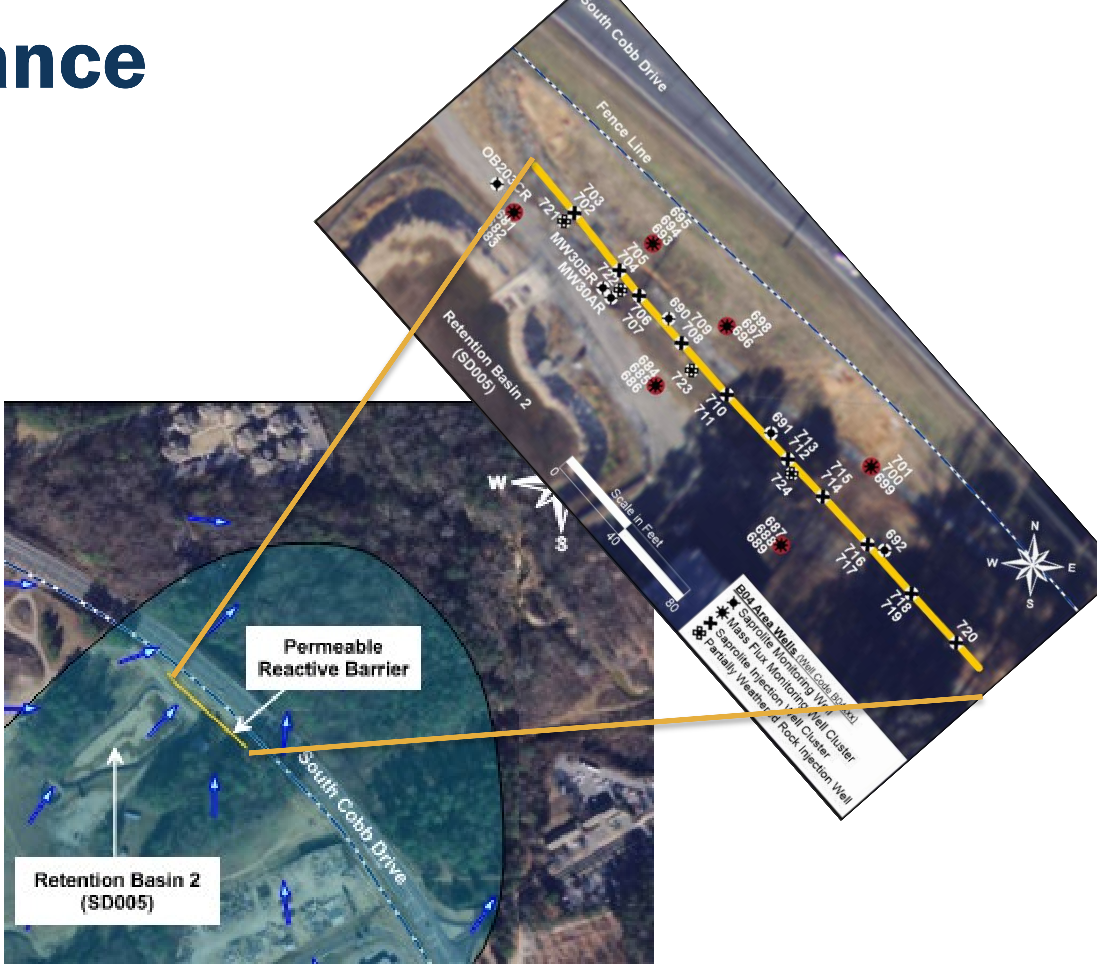
- PRB trench
  - 300 feet long and 2.5 feet wide and up to 90 feet deep
- Backfill
  - Backfilled with fine- to medium-grained sand and biopolymer
- Injection well installation
  - Installed deep (9) and shallow (10) saprolite injection wells in the PRB trench
  - Installed 4 PWR injection wells below the PRB



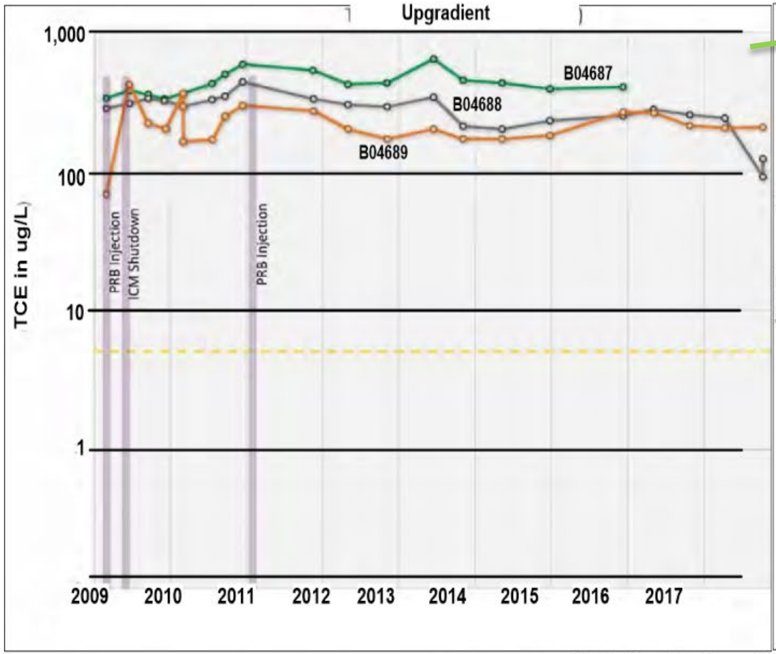
2009	2010	2011	2013	2018
• 98,321 gal with 2.4% 3DMe® (oil, lactates, & polylactates) • One PRB INJ well surfaced.	• 35,673 gal of 1.7% bicarbonate solution • Four PRB INJ wells surfaced • Fouling discovered in PWR INJ wells	• 77,858 gal with 5.2% 3DMe® and bicarbonate • Four PRB and one PWR INJ wells surfaced.	• 9,766 gal with 3.7% 3DMe® • Three planned PRB INJ wells surfaced and four others substituted	• ~94,526 gal with 2.4% 3DMe® with bioaugmentation • Four PRB wells surfaced

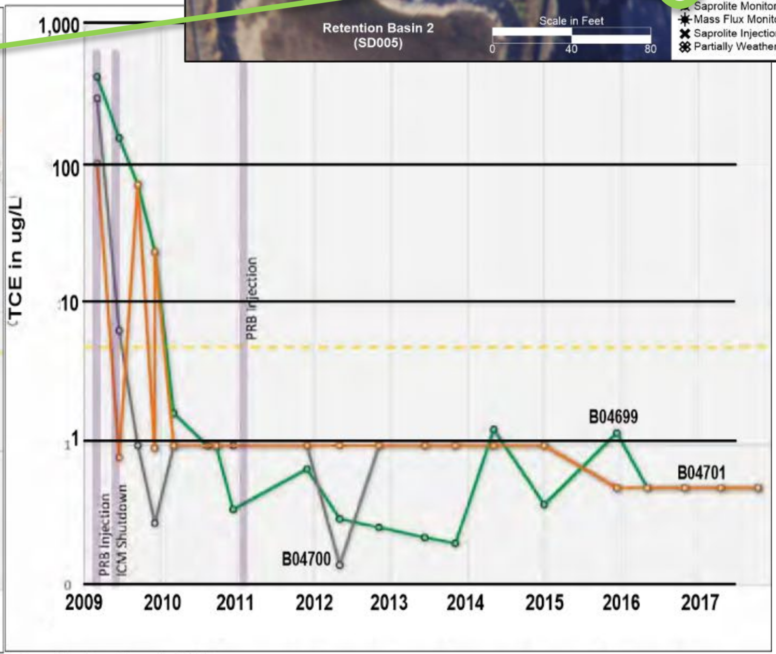
B04 PRB Performance – VOC Mass Flux

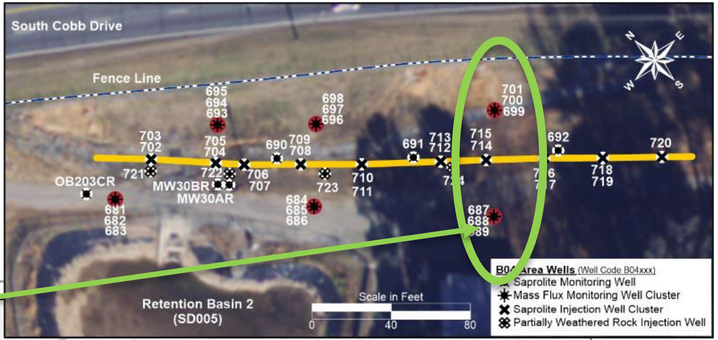
- 3 up- and 3 down-gradient clusters
- Upper, middle, and lower saprolite
- 2007 baseline derived from a regional hydraulic model
  - Each well has a fixed cross-sectional area and flow for all measurements
  - Concentration is the only variable
  - Only TCE is evaluated



B04 PRB – East TCE Mass Flux

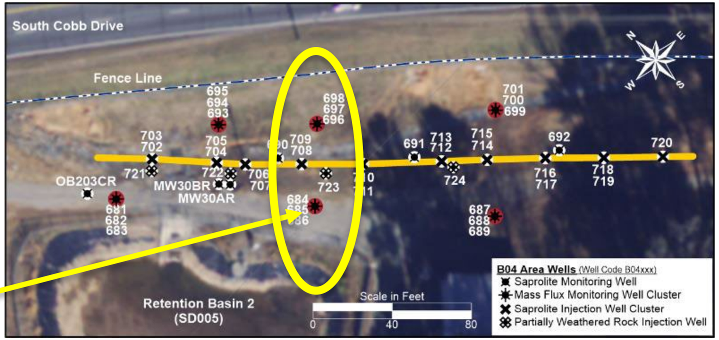


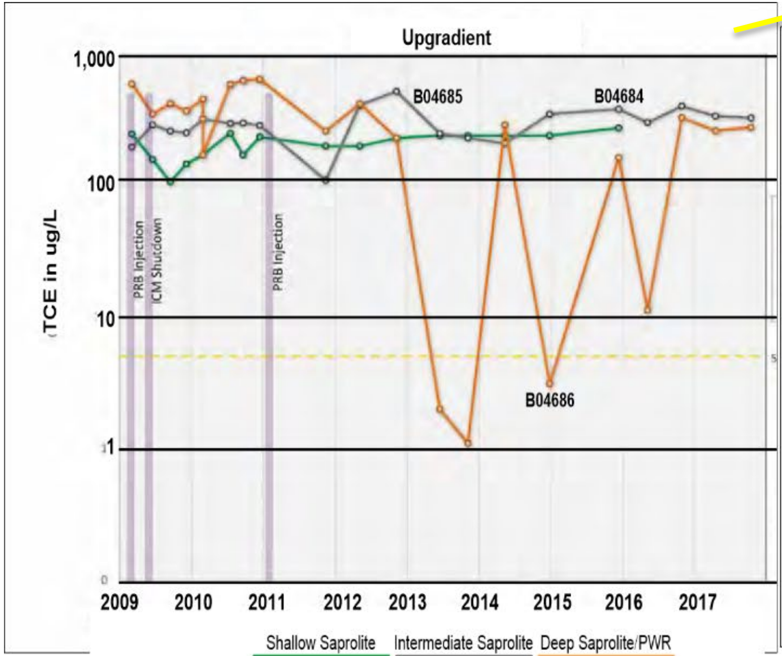


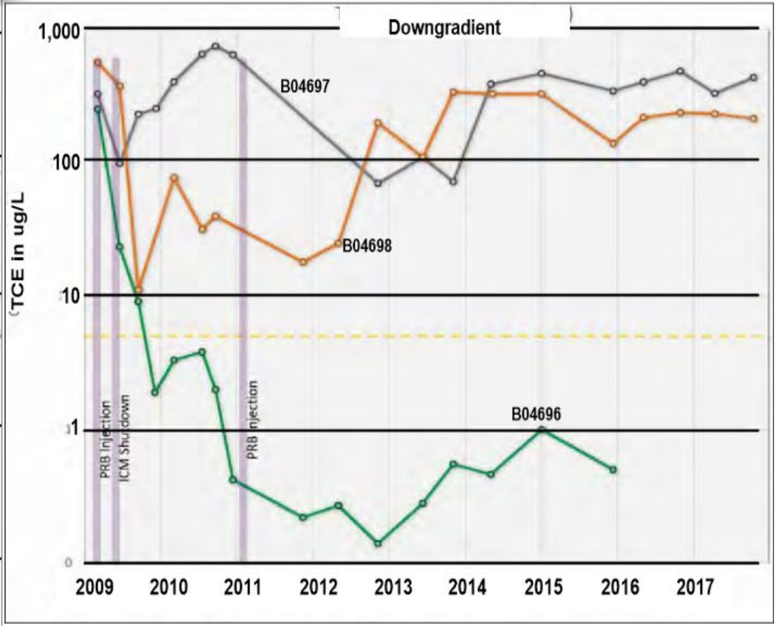


Shallow Saprolite Intermediate Saprolite Deep Saprolite/PWR

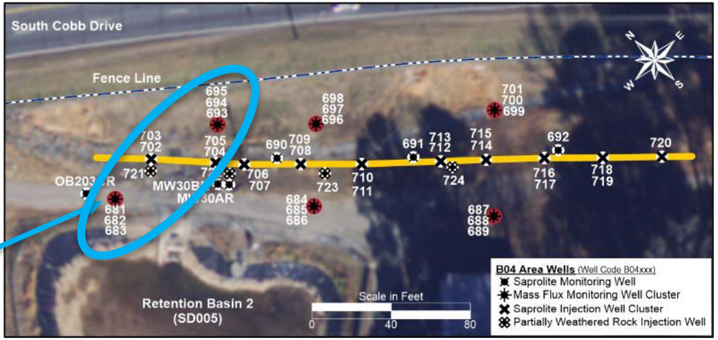
B04 PRB – Central TCE Mass Flux

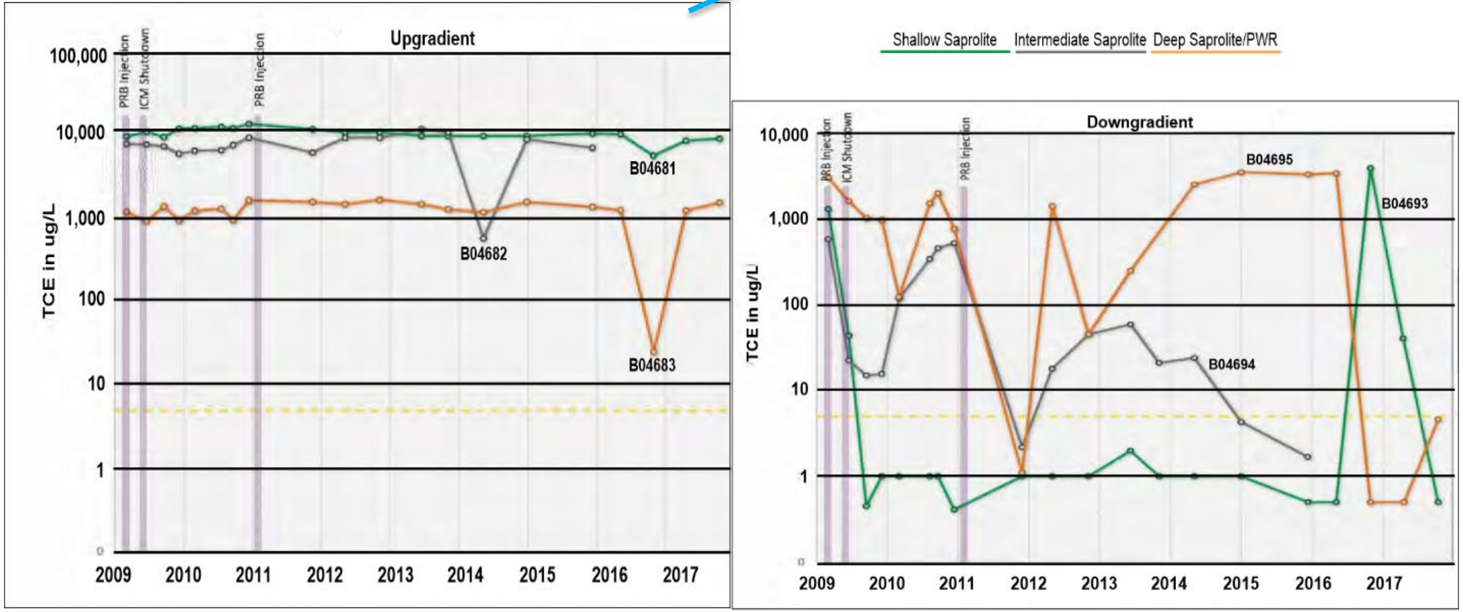






B04 PRB – West TCE Mass Flux





B04 Area PRB: Data Quality Objectives

- Develop more accurate and appropriate volatile organic compound (VOC) mass flux estimates.

Preliminary site recommendations included conducting a MIP/HPT evaluation.

- Characterize TCE degradation and conduct a mass balance with degradation by products.
- Assess the TCE hotspot upgradient of the PRB near monitoring well OB203CR and TCE bypassing northwest of the PRB that could be affecting offsite monitoring results.
- Assess the injected amendment distribution and causes of the observed surfacing and well fouling within the PRB.

B04 Demonstration: Use of HRSC Guidance Document and Tool

HRSC Guidance Tool Selections

Component of the CSM: Aquifer Properties

Step 1: Identify Site Characteristics (select one item per group)

Component of the CSM*	
Aquifer Properties	X
Chemical Distribution	
Chemical Attenuation	

Formation Type*	
Unconsolidated	X
Bedrock	

Step 2: Identify Type of Parameter/Data Required (multiple selections permitted)

Geology	
Lithology	
Lithologic Contacts	
Primary Porosity	X
Secondary Porosity: Fractures	
Structural Faults	
Competence	

Hydrogeology	
Depth to Water Table	
Water Content	
Hydraulic Conductivity	X
Preferential Flow Paths	X
Groundwater Discharge	X
Borehole Flow	
Borehole Condition	X
Fracture Connectivity	

- Develop more accurate and appropriate volatile organic compound (VOC) mass flux estimates.
  - Hydraulic conductivity
  - Groundwater flux
- Assess the TCE hotspot upgradient of the PRB and TCE bypassing northwest of the PRB.
  - Hydraulic conductivity
- Assess the injected amendment distribution and causes of the observed surfacing and well fouling within the PRB.
  - Primary porosity
  - Hydraulic conductivity
  - Borehole condition

HRSC Guidance Tool Selections

Component of the CSM: Chemical Distribution

Step 1: Identify Site Characteristics (select one item per group)

Component of the CSM*	
Aquifer Properties	
Chemical Distribution	X
Chemical Attenuation	

Formation Type*	
Unconsolidated	X
Bedrock	

Step 2: Identify Type of Parameter/Data Required (multiple selections permitted)

Chemicals	
LNAPL	
DNAPL	
Groundwater COC Concentration	X
Geochemical Tracking	X
Soil COC Concentration	
COC Flux	X

- Develop more accurate and appropriate volatile organic compound (VOC) mass flux estimates.
  - COC flux
- Assess the treatment zone extent.
  - Geochemical tracking
  - Groundwater COC concentration
- Characterize TCE degradation and conduct a mass balance with degradation by-products.
  - Groundwater COC concentration
- Assess the TCE hotspot upgradient of the PRB and TCE bypassing northwest of the PRB.
  - Groundwater COC concentration
- Assess the injected amendment distribution and causes of the observed surfacing and well fouling within the PRB.
  - Geochemical tracking

HRSC Guidance Tool Selections

Component of the CSM: Chemical Attenuation

Step 1: Identify Site Characteristics (select one item per group)

Component of the CSM*	
Aquifer Properties	
Chemical Distribution	
Chemical Attenuation	X

Formation Type*	
Unconsolidated	X
Bedrock	

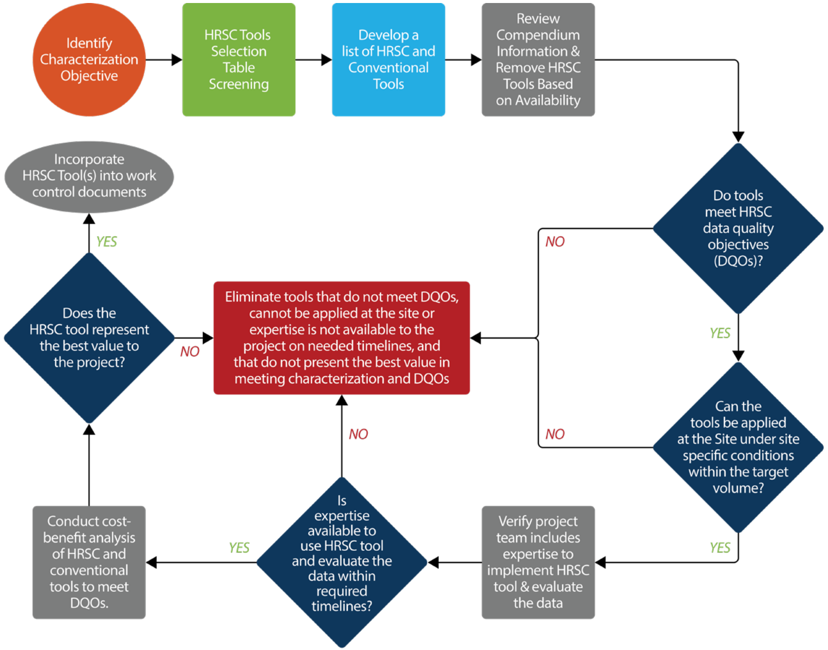
Step 2: Identify Type of Parameter/Data Required (multiple selections permitted)

Chemical Attenuation	
Biotic Degradation	X
Abiotic Degradation	
Sorption	
Diffusion	

- Develop more accurate and appropriate volatile organic compound (VOC) mass flux estimates.
  - Biotic degradation
- Assess the treatment zone extent.
  - Biotic degradation
- Characterize TCE degradation and conduct a mass balance with degradation by-products.
  - Biotic degradation

Output Evaluation

- Tools were eliminated based on availability or site-specific characteristics
- Remaining tools selected for technical and cost-benefit analysis
- Tools with multiple data quality objective capabilities were prioritized
- Add-on tools included if complementary to the primary tool (i.e., downhole geophysical suites)



HRSC Tool Elimination

HRSC Tool Category	HRSC Tool Selections	Data Quality Objective				
		Improve VOC mass flux estimates	Assess Treatment Zone	Characterize TCE degradation	Assess TCE bypassing the PRB	Assess PRB Condition
Surface Geophysics	Ground Penetrating Radar (GPR)				X	X
	Very Low Frequency				X	X
	Electrical Resistivity Tomography (ERT)				X	X
Downhole Geophysics: Hydrogeologic Properties	Magnetometric Resistivity (MMR)				X	X
	Optical Televiewer					X
	Resistivity					X
	Gamma-gamma (density)				X	X
	Neutron (porosity)				X	X
	Nuclear Magnetic Resonance (NMR)	X			X	X
	Acoustic Televiewer					X
	Cross-well Ground Penetrating Radar (GPR)				X	
In Situ Logging	Hydraulic Profiling Tool (HPT)	X			X	X
	High-Resolution Piezocone (HRP) with GeoVis	X			X	X
	Waterloo Advanced Profiling System	X	X	X	X	X
	Electrical Conductivity (EC)				X	X
	Cone Penetrometer Testing (CPT)	X			X	X
Downhole Geophysics: Hydraulic Properties	Colloidal Borescope	X				
	Heat-Pulse Flowmeter	X				
	Hydrophysical Logging	X				
Subsurface COC Profiling	Membrane Interface Probe (MIP)	X	X		X	
	Site Characterization and Analysis Penetrometer System	X	X	X	X	
	Passive Flux meters	X	X	X		
Attenuation	Quantitative Polymerase Chain Reaction (qPCR)			X		
	Meta-omics			X		
	Hybridization			X		
	Proteomics and Metabolomics			X		
	Enzyme Activity Probes			X		
	Compound Specific Isotope Analysis (CSIA)			X		
	Stable Isotope Probe (SIP)			X		
Conventional Tools	Groundwater Sampling	X	X	X	X	X
	Well Video Logging					X
	Slug Testing	X				

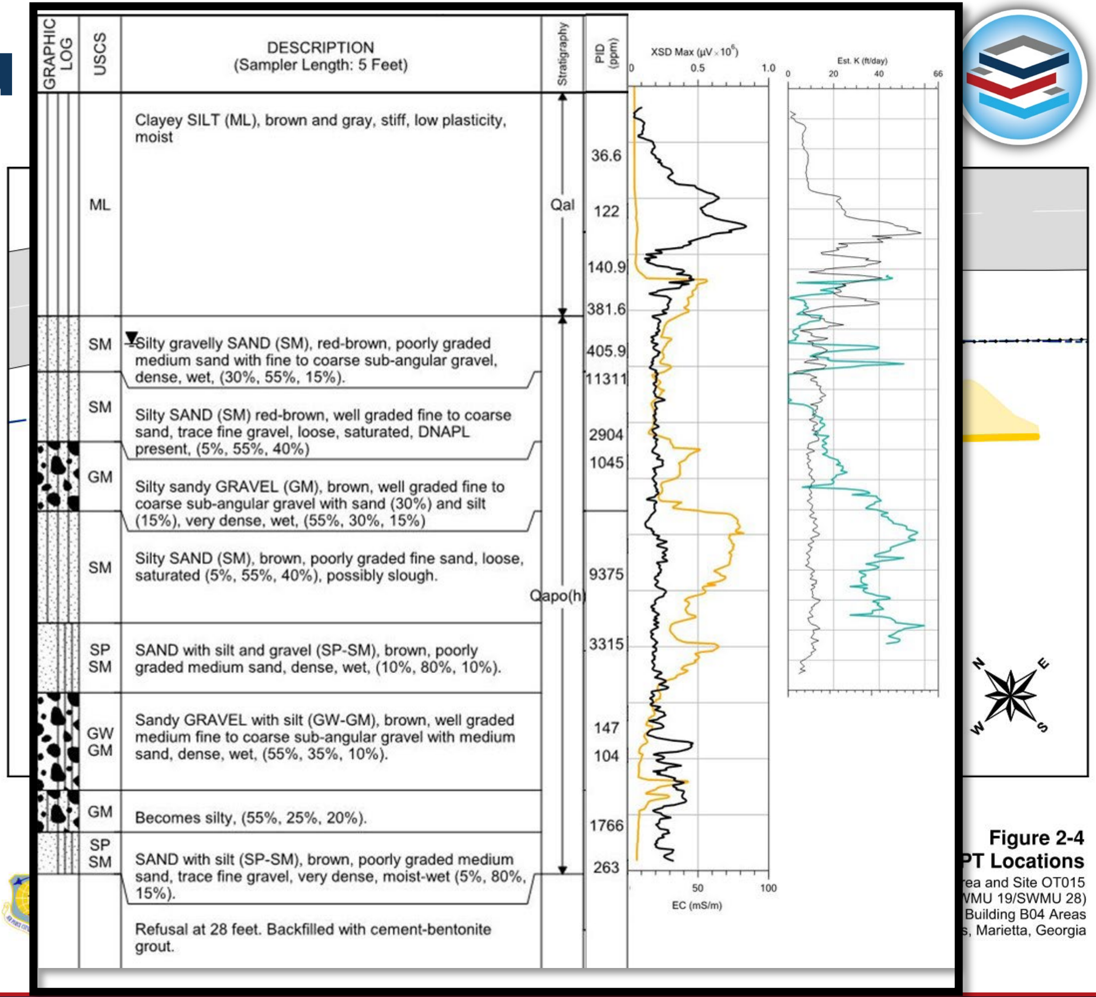
Output Evaluation and Cost Comparison

Technology	Cost
Electrical Resistivity Tomography (ERT)	~~$ 45,690~~
Magnetometric Resistivity (MMR)	~~$ 35,000~~
Geophysics: NMR, Neutron, Gamma, Density, Induction Well Logging	$ 50,549
MiHPT Borehole Logging (HPT, EC, MIP)	$ 47,171
Utility Locate for MiHPT	$ 1,500
Molecular-QuantArray-Chlor analysis (qPCR)	$ 8,250 [1]
Compound Specific Isotope Analysis- Carbon (PCE, TCE, cis-DCE, VC, ethene, ethane)	$ 6,750 [1]
Additional Groundwater Sample Analytes (VOCs, anions, nitrate/nitrite, dissolved gases, TOC, and ferrous iron)	$ 2,500 [1]
Passive Flux Meters	$ 34,524

Total $151,244

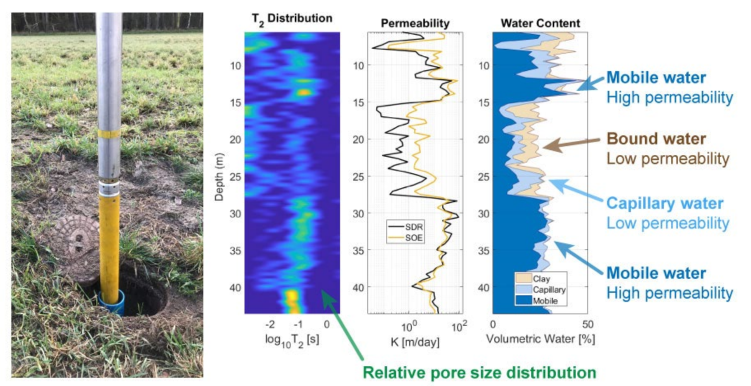
Direct Push In Situ

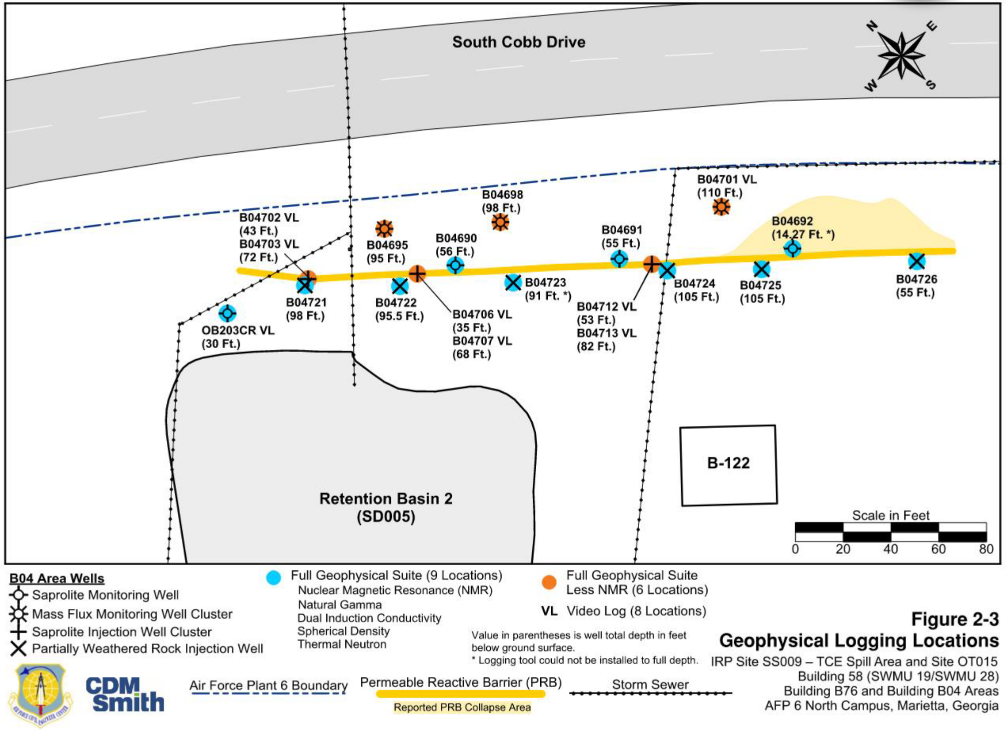
- Membrane Interface Probe (MIP) – COC Concentration
  - XSD – detector for TCE
  - PID – detector for volatiles
  - FID – detector for petroleum hydrocarbons
- Electrical Conductivity (EC) – lithology
- Hydraulic Profiling Tool (HPT) – hydraulic conductivity estimate



Downhole Geophysics

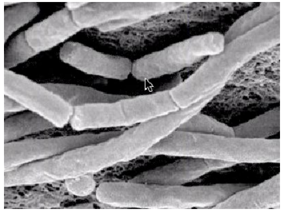
- Nuclear Magnetic Resonance (NMR)
  - Provides water content (in vadose zone) and porosity and hydraulic conductivity (in saturated zone)
  - Requires site-specific measurements for calibration
- Density, Neutron, Resistivity Logging
  - Provides lithology (approximate grain size and porosity)

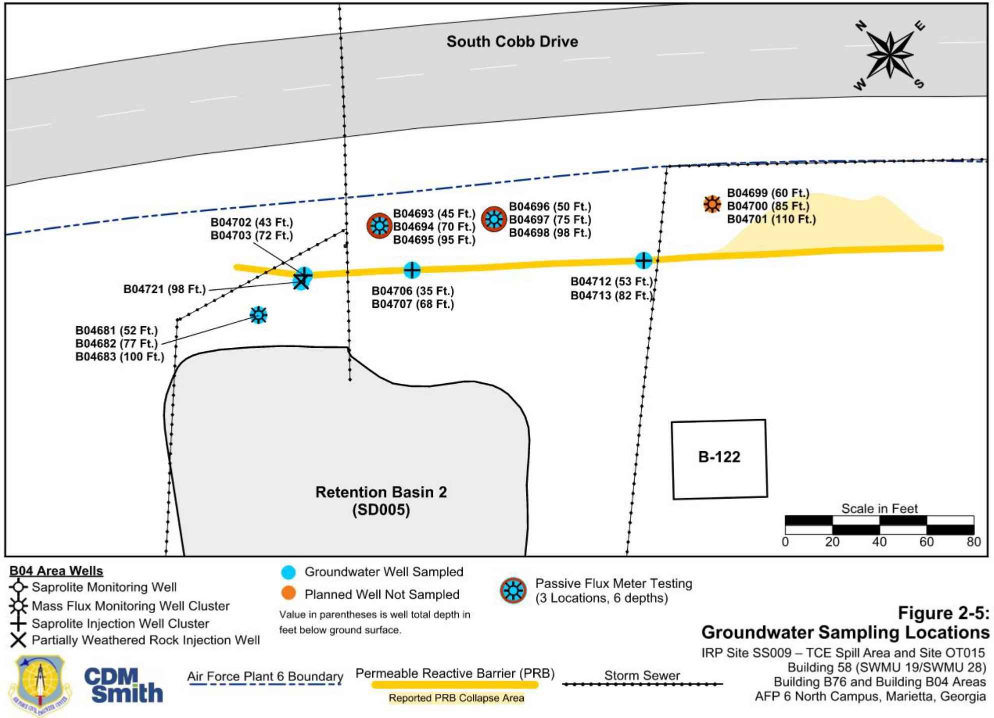




Sampling for Attenuation Parameters and Passive Fluxmeter

- Passive Fluxmeter
  - Provides hydraulic conductivity, COC groundwater concentration, groundwater flux, and COC flux
- Quantitative polymerase chain reaction (qPCR) by QuantArray®-Chlor
  - Quantifies specific microorganisms and functional genes to evaluate anaerobic dechlorination and aerobic cometabolism
  - Samples collected during conventional groundwater sampling
- Compound Specific Isotopic Analysis (CSIA)
  - TCE degradation





Conventional Tools

- Synoptic water elevations: detailed potentiometric surface mapping
- Groundwater sampling
  - VOC profiling
  - Geochemical conditions
- Slug testing: estimate hydraulic conductivity
- Video logging of wells





Building a HR-CSM from the Tool Selection Process

Potentiometric Surface

Significant upward vertical gradient (0.11-0.12) between deep saprolite/PWR and intermediate saprolite

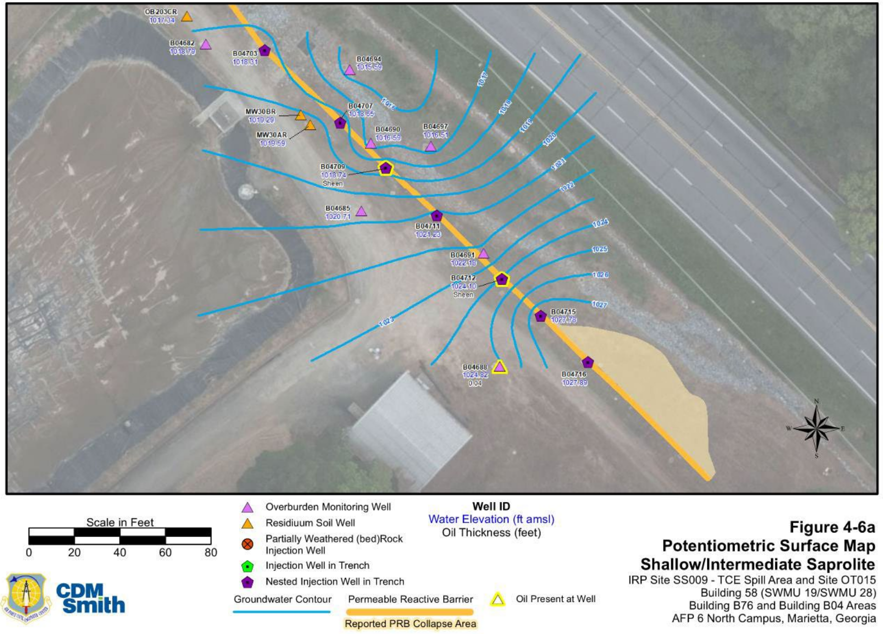


Figure 4-6a
Potentiometric Surface Map
Shallow/Intermediate Saprolite
IRP Site SS009 - TCE Spill Area and Site OT015
Building 58 (SWMU 19/SWMU 28)
Building B76 and Building B04 Areas
AFP 6 North Campus, Marietta, Georgia

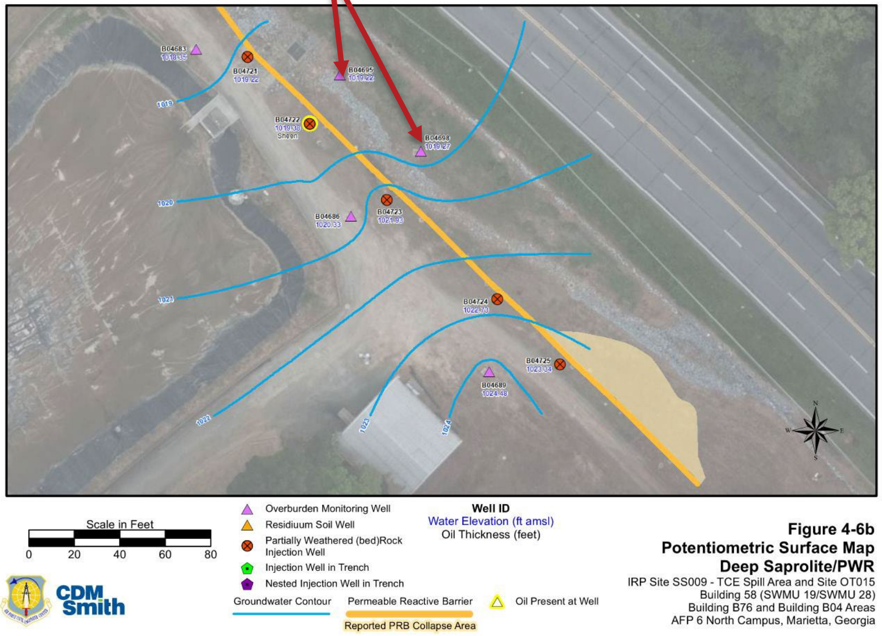


Figure 4-6b
Potentiometric Surface Map
Deep Saprolite/PWR
IRP Site SS009 - TCE Spill Area and Site OT015
Building 58 (SWMU 19/SWMU 28)
Building B76 and Building B04 Areas
AFP 6 North Campus, Marietta, Georgia

Attenuation Capacity

Dehalococcoides (DHC)
Dehalogenimonas (DHG)

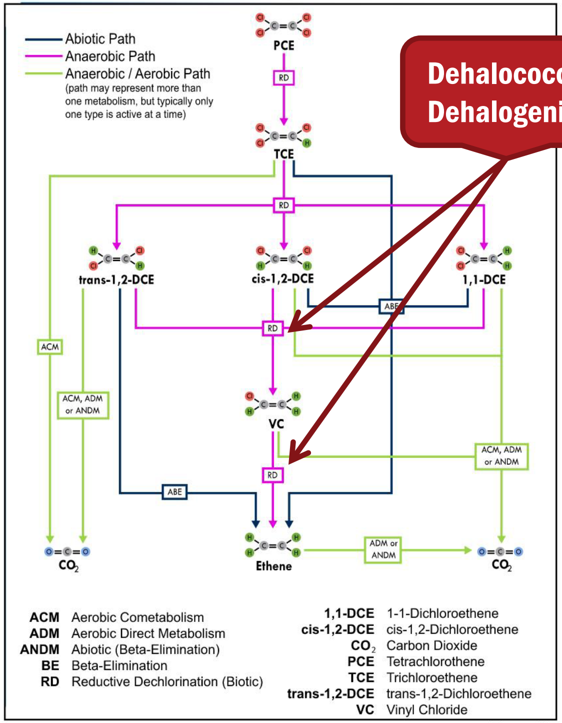
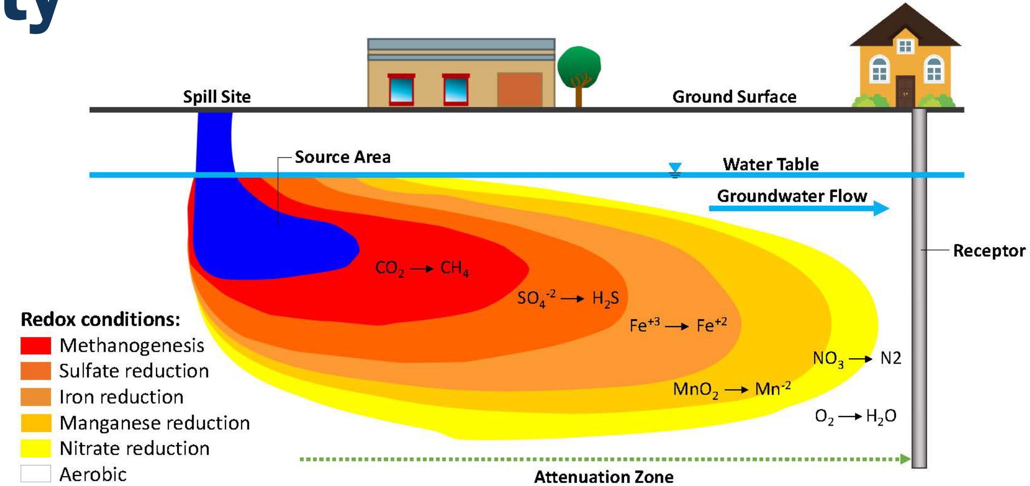


Figure 4-2
Conceptual Model for Aerobic and Anaerobic Degradation Pathways for Chlorinated Ethene Chemicals
IRP Site SS009 - TCE Spill Area and Site OT015
Building 58 (SWMU 19/SWMU 28)
Building B76 and Building B04 Areas
AFP 6 North Campus, Marietta, Georgia

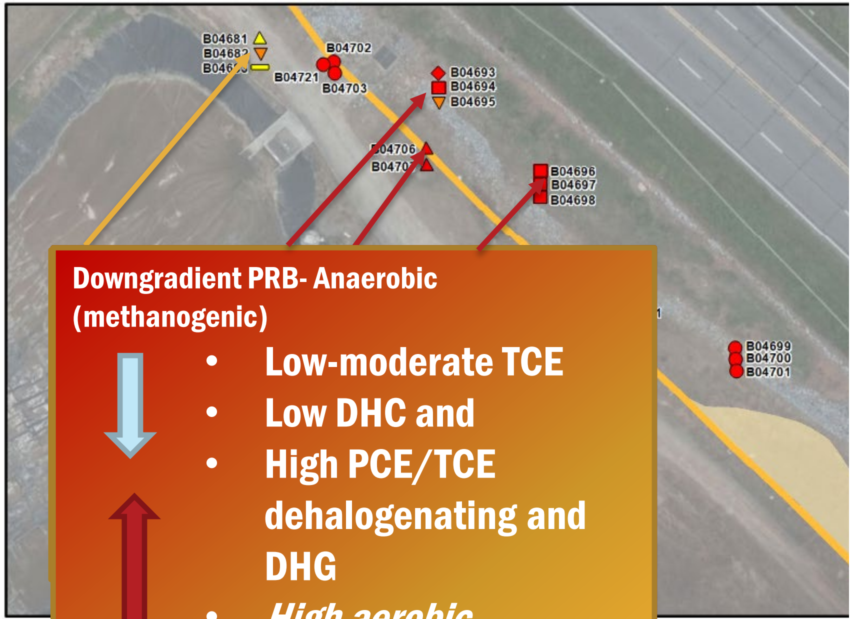
CDM Smith



Chemicals of Concern	Anaerobic Reductive Dechlorination	Anaerobic Cometabolism	Anaerobic Oxidation	Aerobic Cometabolism	Aerobic Oxidation
Chlorinated Ethenes	PCE, TCE, DCE, VC	PCE, TCE, DCE, VC	DCE, VC	TCE, DCE, VC	DCE, VC
Chlorinated Ethanes	HCA, PCA, TeCA, TCA, DCA, CA	HCA, PCA, TeCA, TCA, DCA, CA	DCA, CA	TCA, DCA, CA	DCA, CA

PCE: tetrachloroethene, TCE: trichloroethene, VC: vinyl chloride, HCA: hexachloroethane, PCA: pentachloroethane, TeCA: tetrachloroethane, TCA: trichloroethane, DCA: dichloroethane, CA: chloroethane, CT: carbon tetrachloride, CF: chloroform, DCM: dichloromethane, CM: chloromethane

Geochemistry and Microbial Results



Downgradient PRB- Anaerobic (methanogenic)

- Low-moderate TCE
- Low DHC and
- High PCE/TCE dehalogenating and DHG
- *High aerobic cometabolic* in deep saprolite

Figure 4-3b
Redox Conditions and Microbiological Results
IRP Site SS009 - TCE Spill Area and Site OT015
Building 58 (SWMU 19/SWMU 28)
Building B76 and Building B04 Areas
AFP 6 North Campus, Marietta, Georgia

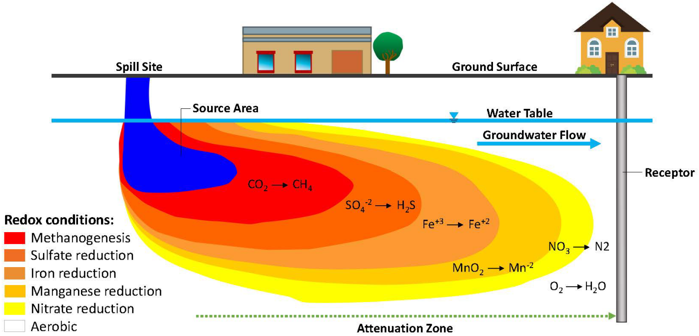
Table 4-5
Summary of Microbial Results

Location ID	B04681	B04682	B04693	B04694	B04695	B04696	B04697	B04698	B04706	B04707	B04691
Sample Date	7/29/2020	7/29/2020	7/30/2020	7/30/2020	7/30/2020	7/29/2020	7/29/2020	7/29/2020	7/30/2020	7/30/2020	5/20/2020
Microbial Population	cells/mL	cells/mL	cells/mL	cells/mL	cells/mL	cells/mL	cells/mL	cells/mL	cells/mL	cells/mL	cells/mL
PCE and TCE-Dehalogenating Bacteria*	3.73E+03	2.33E+01	2.60E+03	3.03E+02	8.98E+01	1.08E+03	5.65E+02	4.19E+03	1.00E+02	4.09E+03	NA
Dehalococcoides (DHC), DHC Functional Genes (tceA, bvcA, vcrA)	1.50E+00	4.17E+01	5.78E+01	4.73E+02	4.84E+01	1.11E+01	4.38E+02	6.22E+02	7.00E+00	3.55E+01	1.87E+02
Dehalogenimonas spp., Functional genes (TDR and cer Reductase)	1.38E+01	2.89E+02	1.43E+02	2.85E+04	2.07E+03	1.67E+02	8.54E+03	3.70E+04	5.01E+01	4.83E+01	NA
Aerobic (co)Metabolic Functional Genes^	9.22E+03	3.87E+03	7.41E+04	4.90E+01	2.35E+03	5.21E+02	1.57E+02	1.09E+03	1.55E+02	4.66E+02	NA
Possible Degradative Mechanism Based on Microbial Evidence‡	Anaerobic (incomplete) Aerobic	Anaerobic (complete) Aerobic	Anaerobic (complete) Anaerobic (incomplete) Aerobic	Anaerobic (complete) Anaerobic (incomplete)	Anaerobic (complete) Aerobic	Anaerobic (complete) Anaerobic (incomplete) Aerobic	Anaerobic (complete) Anaerobic (incomplete) Aerobic	Anaerobic (complete) Anaerobic (incomplete) Aerobic	Anaerobic (incomplete) Aerobic	Anaerobic (incomplete) Aerobic	Anaerobic (complete)

Notes:
* *Dehalobacter, Desulfitobacterium, Desulfuromonas,* PCE Reductase (PCE-1 and PCE-2)
^ SMMO, TOD, PHE, TCBO, RDEG, ROM, EtnC, EtnE, DCMA
‡ Complete degradation is PCE/TCE to ethene/ethane, incomplete degradation is PCE/TCE to DCE

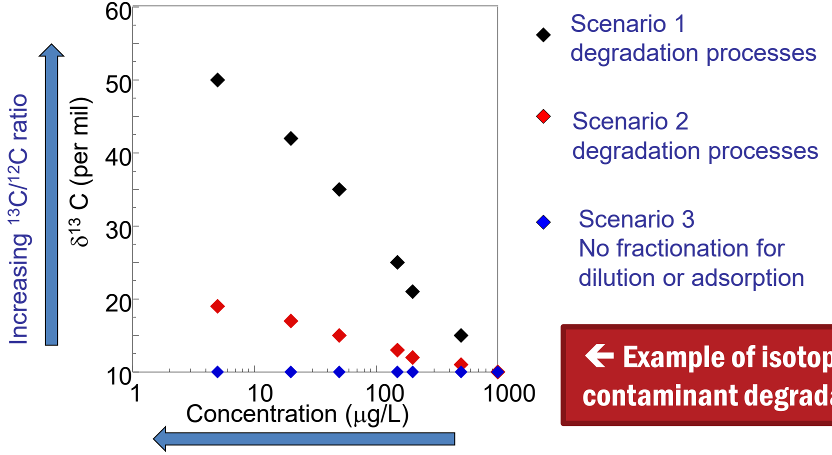
1.00E+03	signifcant (microbe likely metabolically active), greater than 10^3 cells/mL
1.00E+02 to 1.00E+03	moderate (microbe may be metabolically active), 10^2 to 10^3 cells/mL
1.00E+02	low (microbe likely not metabolically active), less than 10^2 cells/mL

< - results not detected
cell/mL - cells per milliliter
DCMA - Dichloromethane Dehalogenase
EtnC - Ethene Monooxygenase
EtnE - Epoxyalkane Transferase
NA - not analyzed
PHE - Phenol Hydroxylase
RDEG - Toluene Monooxygenase 2
RMO - Toluene Monooxygenase
SMMO - Soluble Methane Monooxygenase
TCBO - Trichlorobenzene Dioxygenase
TOD - Toluene Dioxygenase



CSIA Results

- Stable isotopes of carbon (C^{13}/C^{12}) analyzed
  Use Rayleigh model :
  $$\delta^{13}C = \ln(C/C_0)*\varepsilon + \delta^{13}C_0$$
- Biodegradation occurring at the Site



← Example of isotopic enrichment during contaminant degradation

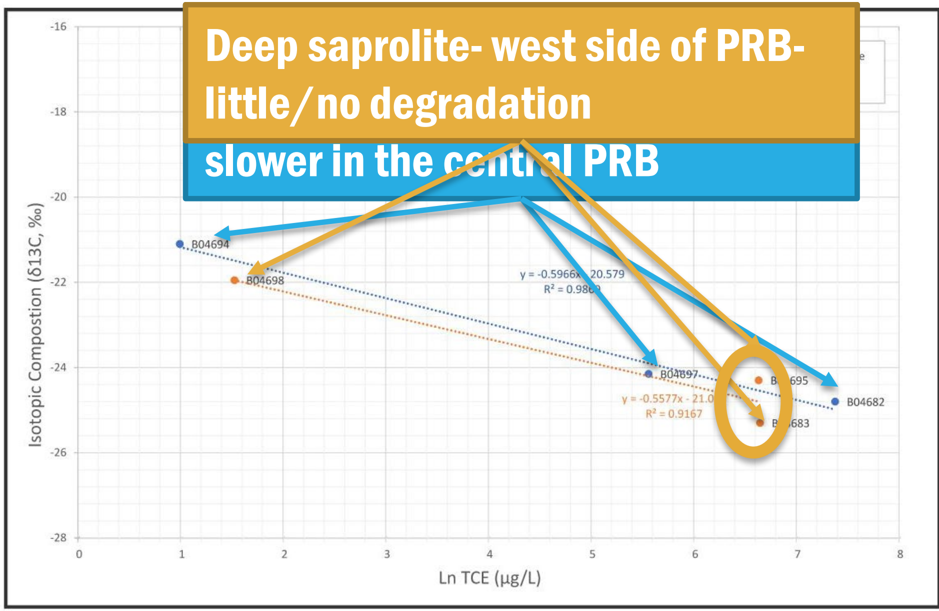


Figure 4-5
Trichloroethene Carbon Isotope Rayleigh Correlation Plot
IRP Site SS009 - TCE Spill Area and Site OT015
Building 58 (SWMU 19/SWMU 28)

CSIA Results

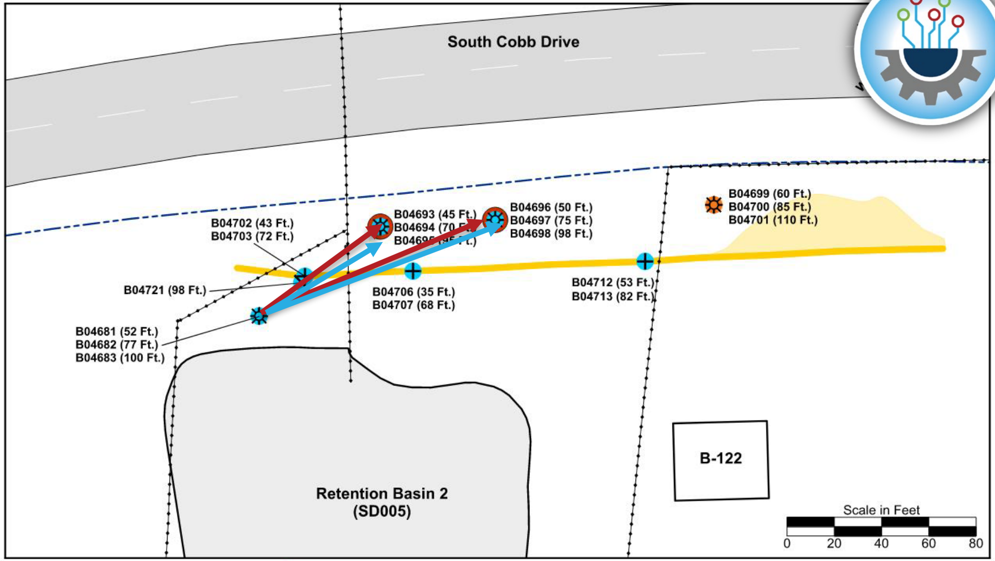


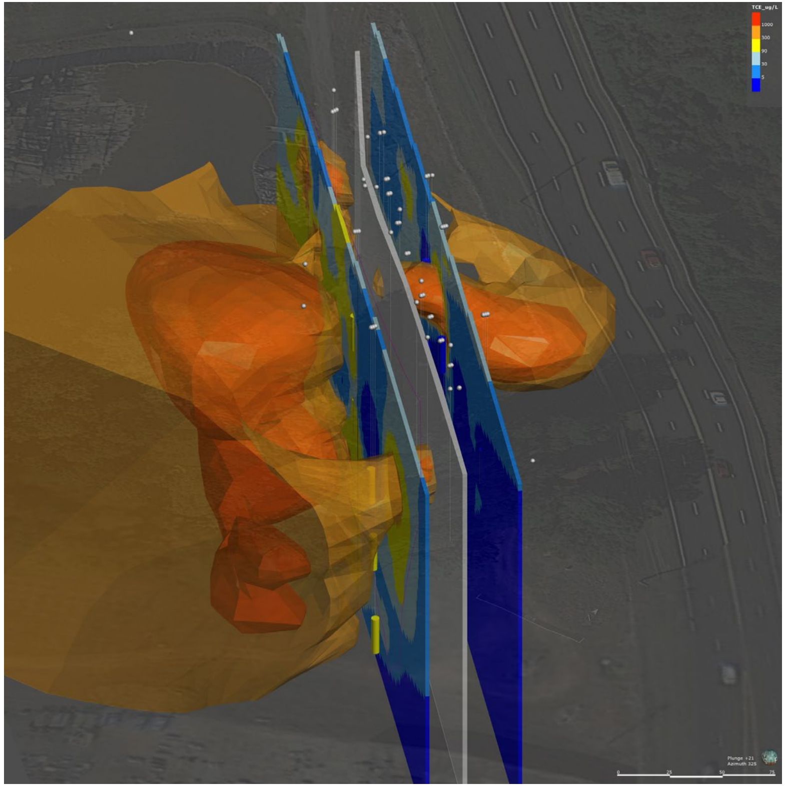
Figure 2-5:
Groundwater Sampling Locations
IRP Site SS009 – TCE Spill Area and Site OT015
Building 58 (SWMU 19/SWMU 28)
Building B76 and Building B04 Areas
AFP 6 North Campus, Marietta, Georgia

Table 4-7
Summary of Compound Specific Isotope Analysis Degradation Processes and Rates

Location 1 Along Flow Path	Location 2 Along Flow Path	Aquifer	Distance in Flow Path (feet)	Gradient (feet/feet)	Hydraulic Conductivity (feet/day)	Seepage Velocity (feet/day)	Travel Time (days)	Minimum Half Life (days)	Maximum Half Life (days)
B04682	B04694	Intermediate Saprolite	19	0.0935	1.6	0.748	25	12	85
B04683	B04695	Deep Saprolite/PWR	19	0.0258	2	0.258	74	124	906
B04682	B04697	Intermediate Saprolite	19	0.0935	1.6	0.748	25	66	481
B04683	B04698	Deep Saprolite/PWR	19	0.0258	2	0.258	74	37	271

Notes:
‰ = per mil

Integrating Data Sets: 3D Visualization

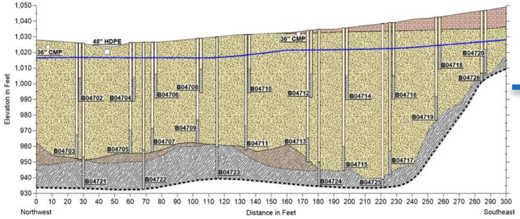


A variety of 3D visualization tools are available:

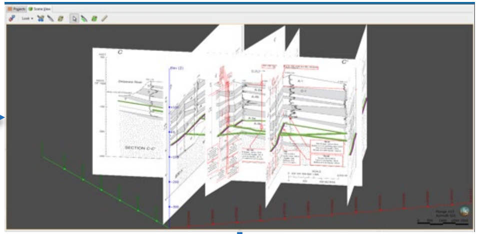
- Seequent's Leapfrog Works
- C Tech's EVS-Studio
- Rockworks
- ESRI ArcScene/3-D Analyst
- EarthVision
- GMS

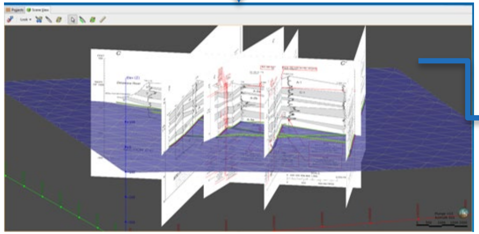
3D VA CSM: Geology

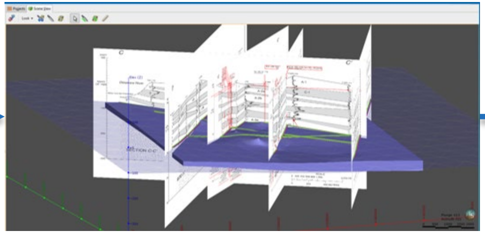
Original CSM

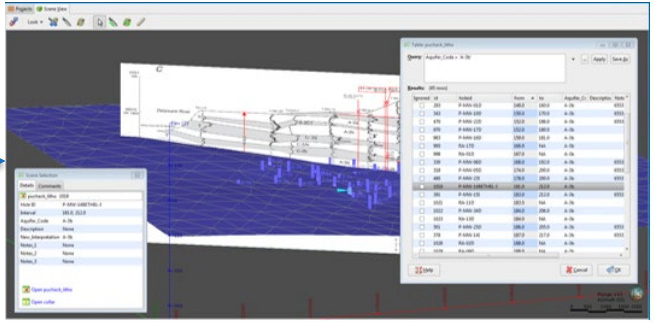


Quickly incorporate existing data into 3DVA CSM



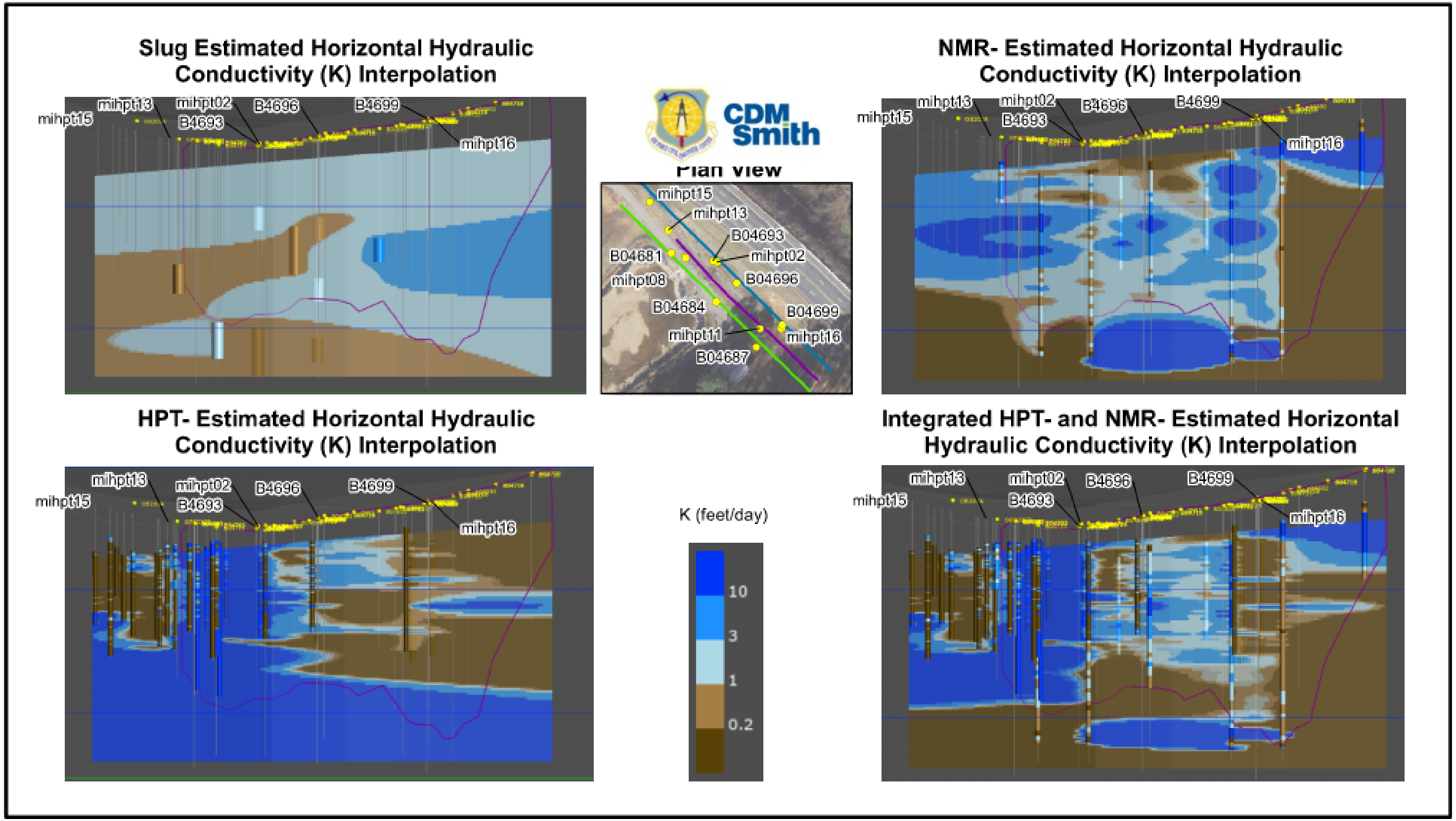






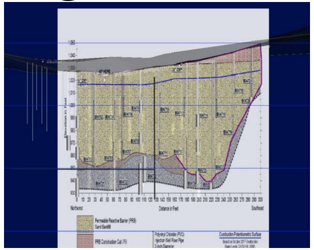
Incorporate borehole stratigraphic observations and revise contacts based on nearby observations

HR-CSM: Hydraulic Conductivity

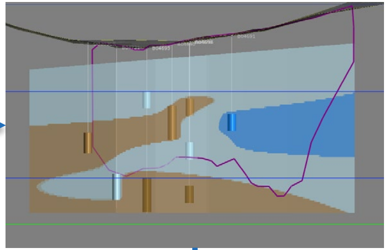


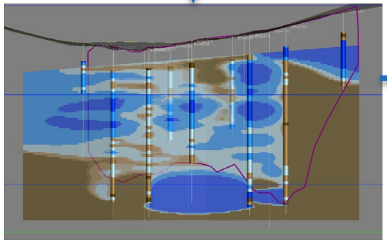
Integrating Data Sets: 3DVA – Hydrogeology

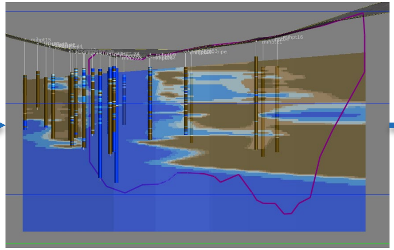
Original CSM

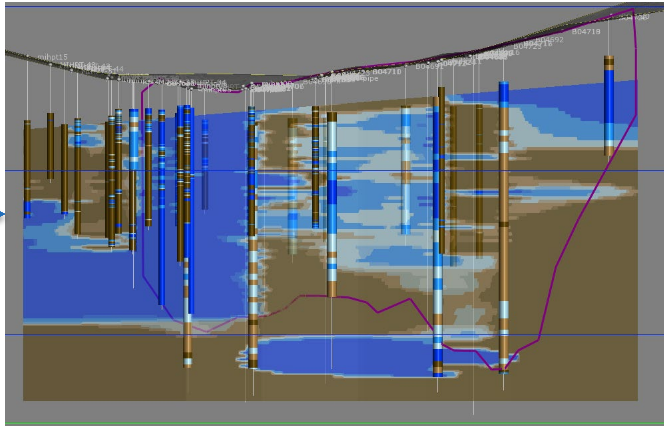


High Res CSM: Slug Test + NMR + HPT = Final HRCSM

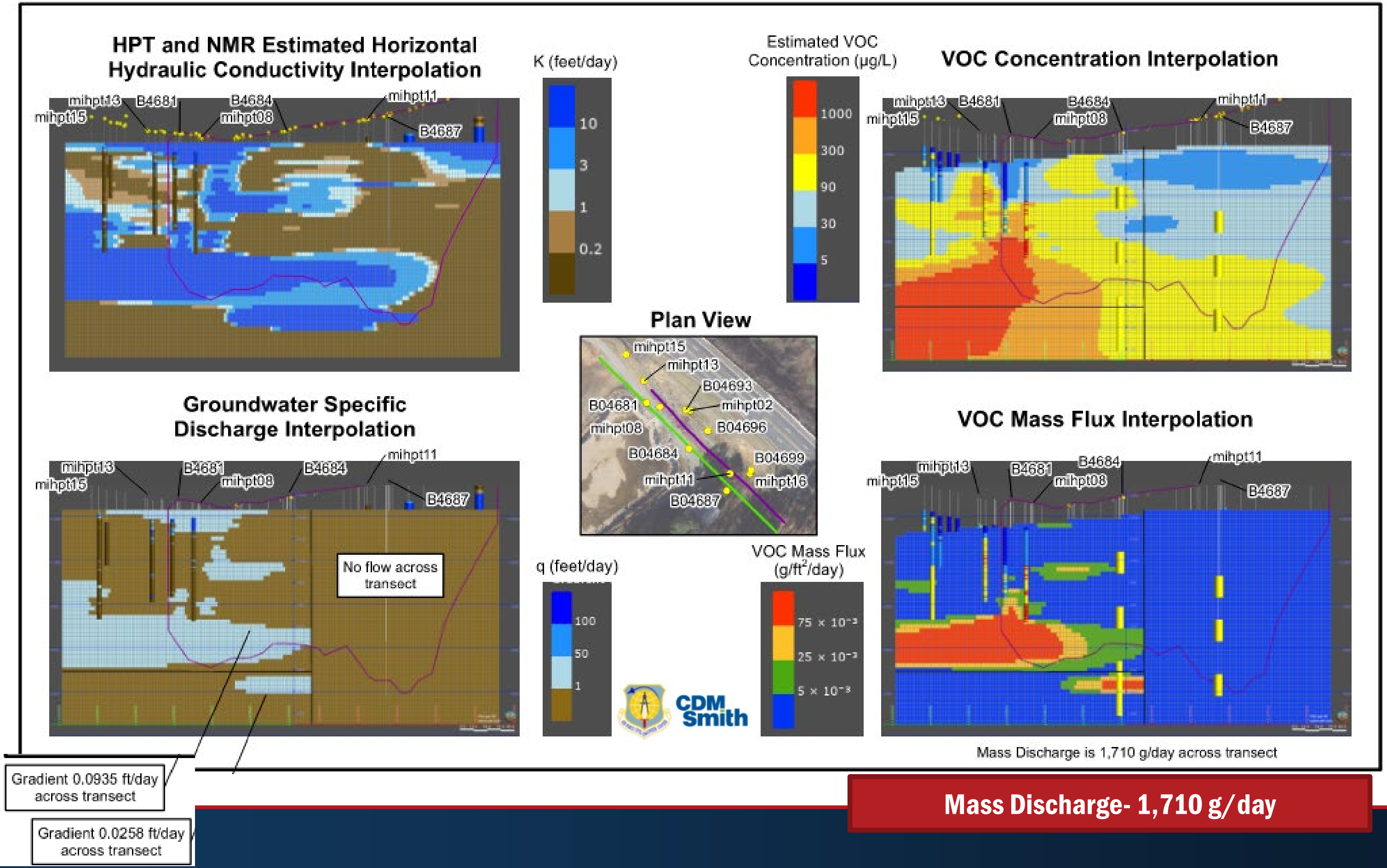








HR-CSM: Upgradient Mass Flux & Discharge

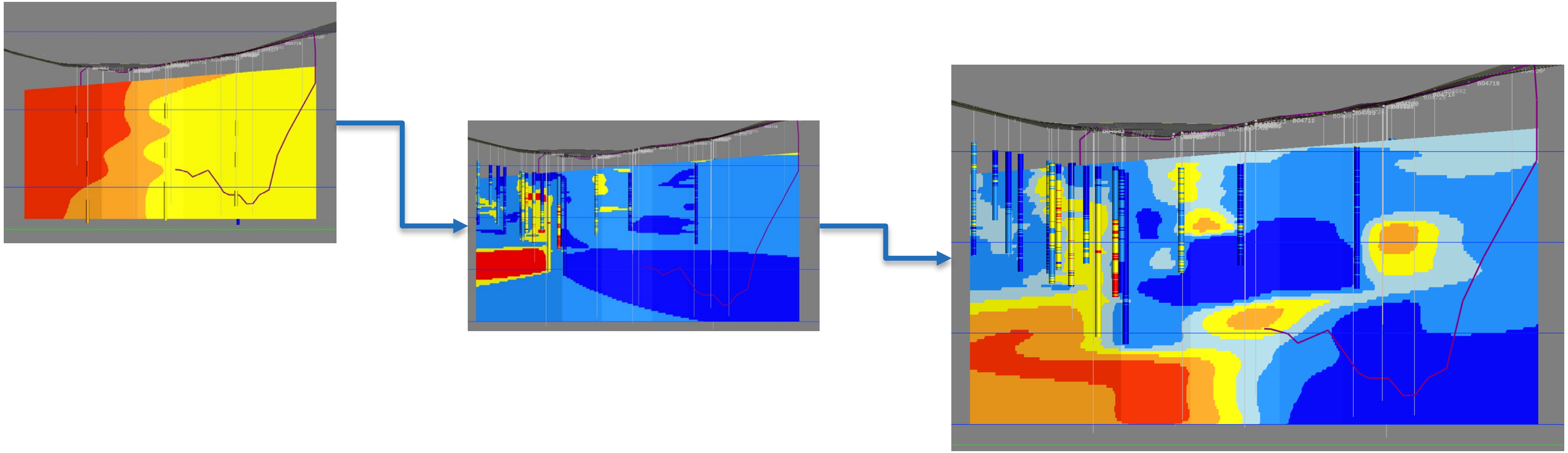


Mass Discharge- 1,710 g/day

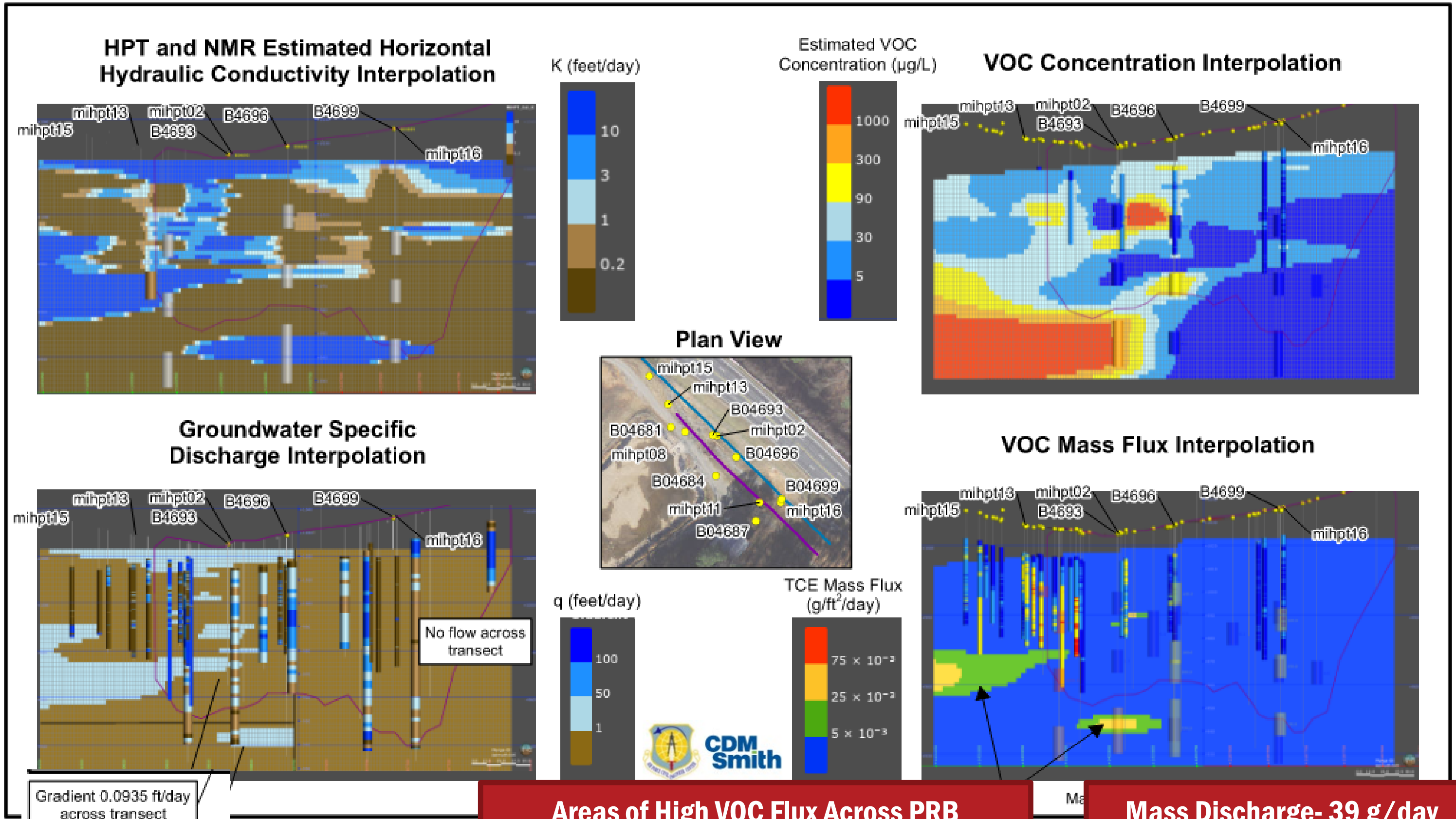
Integrating Data Sets: 3DVA – Contaminants

Original CSM - Wells

High Res CSM: Wells + MIP = Final HRCSM



HR-CSM: Downgradient Mass Flux & Discharge



Gradient 0.0935 ft/day across transect

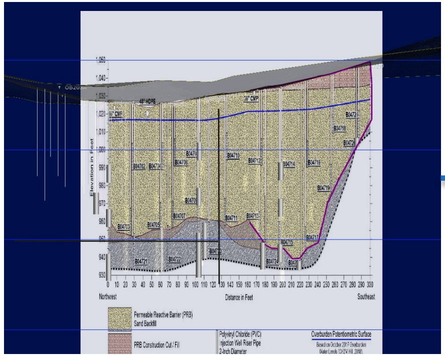
Gradient 0.0258 ft/day across transect

Areas of High VOC Flux Across PRB

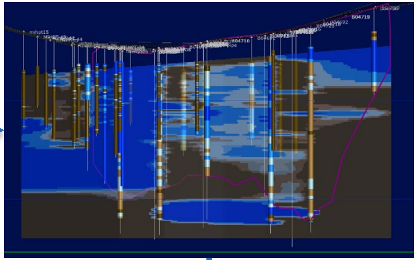
Mass Discharge- 39 g/day

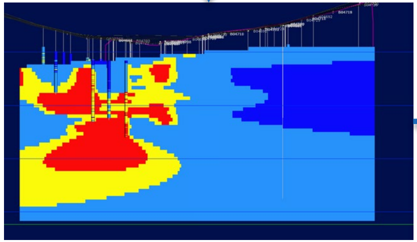
Integrating Data Sets: 3DVA – Mass Flux/Discharge

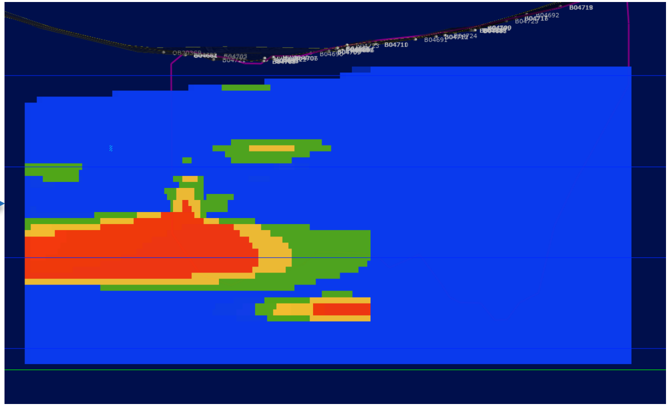
Original CSM



High Res CSM: Estimated permeability + Contaminant Distribution = Mass Flux/Discharge



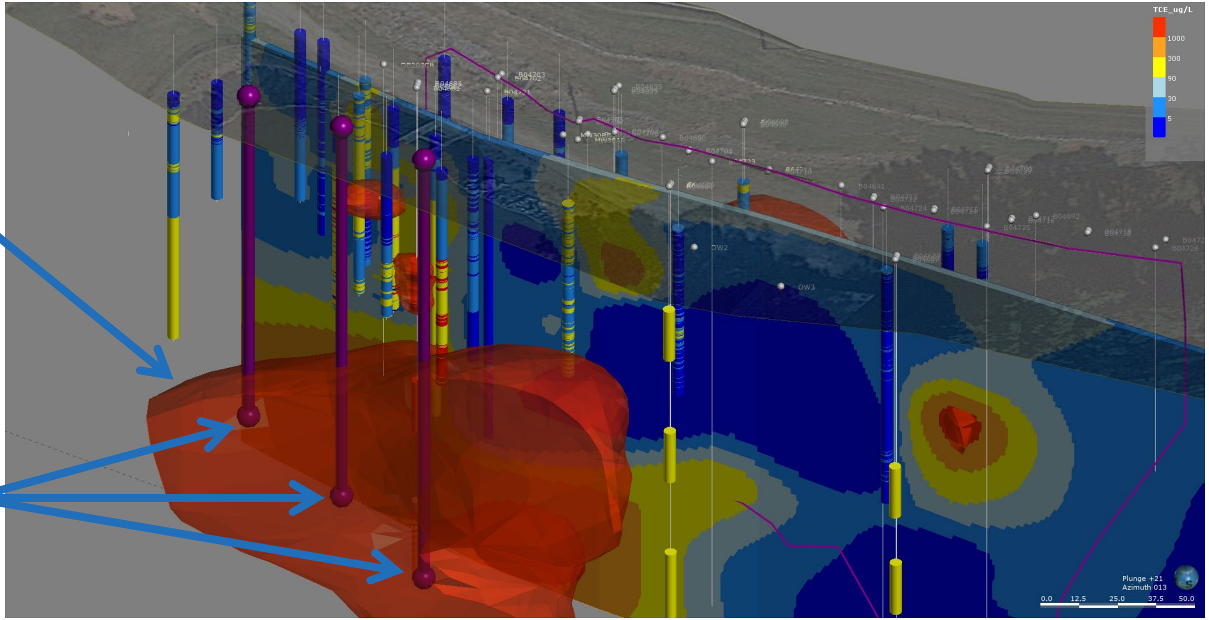




Using HR-CSM and 3D Model – Remedial Alternatives

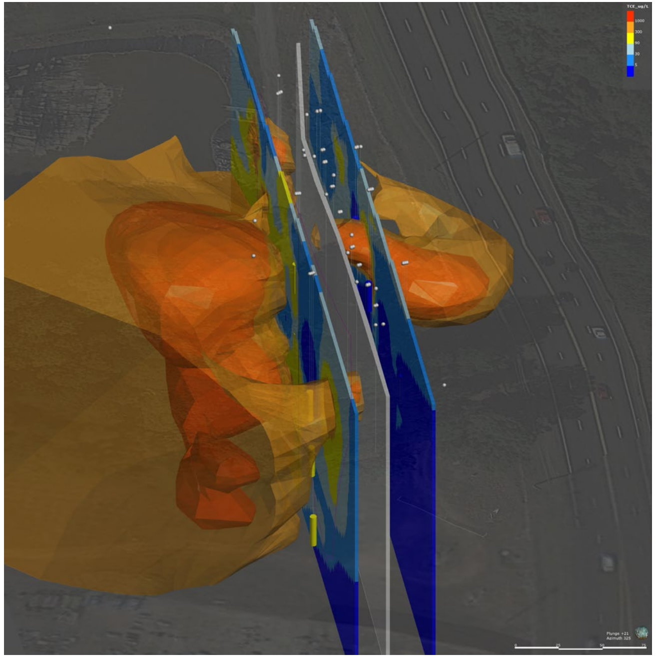
TCE > 1000 ug/L

Possible injection well locations – 65, 75, 85 ft bgs



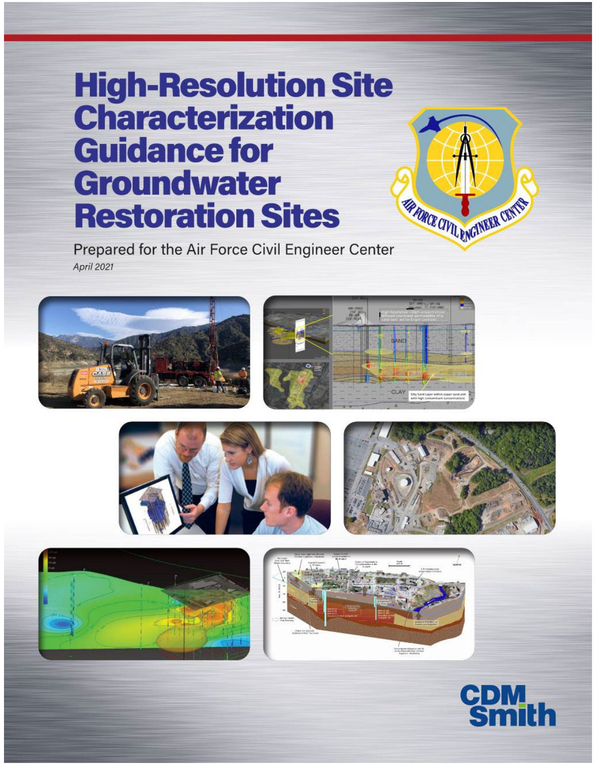
HRSC diagnosed causes of surfacing and well fouling within the PRB.

- Excessive oil observed at the downgradient wells -PRB collapse and preferential pathways.
- Well-fouling was significant
- HPT and downhole density, natural gamma, and neutron logs for wells within the PRB were reviewed to evaluate lower hydraulic conductivity and/or porosity areas.
- There were no evident areas of reduced hydraulic conductivity or porosity within the PRB, suggesting that fouling limited the well sand pack.



Conclusions

- HRSC Guidance Process identified a broader suite of tools to consider, and a more comprehensive characterization program was developed.
- HRSC
  - Improved VOC extent and mass flux estimates
  - Diagnosed TCE bypassing northwest and beneath the PRB
  - Verified biotic TCE degradation was slower along flow paths not impacted by the PRB
- Diagnosed inefficiencies in the PRB injection system.



Guidance Document and Tools Selection Table Release: May 2023

Questions?

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