Naval Facilities Engineering Systems Command
EXWC Engineering and Expeditionary Warfare Center

NAVFAC Open Environmental Restoration Resources (OER2)

How High-resolution Site Characterization Tools Can Improve Conceptual Site Models and Support Remedy Optimization

Simon Kline and Trevre Andrews, Jacobs
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Anticipate • Innovate • Accelerate

Today's Speakers

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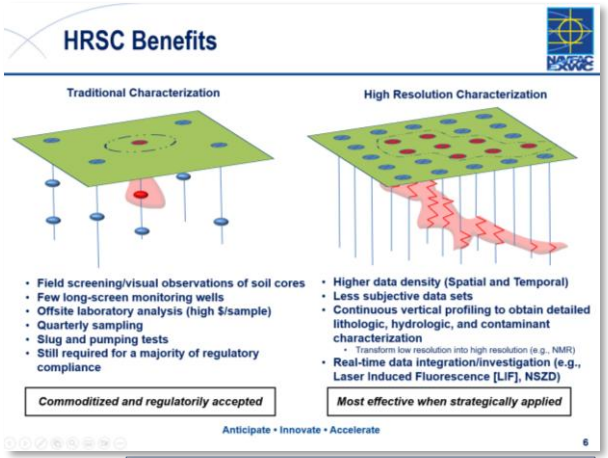
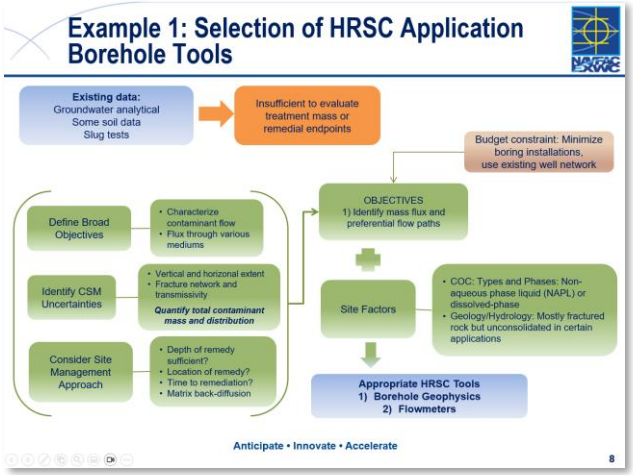
OER2 Webinar Series

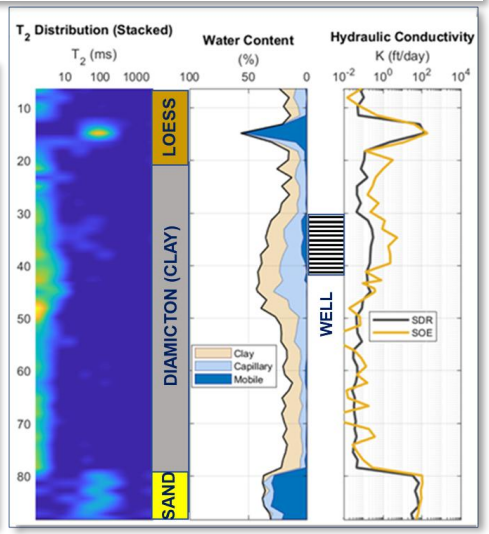
- **Why Attend?**
  - Obtain and hear about the latest Department of Defense (DoD) and Department of the Navy (Navy) policies/guidance, tools, technologies, and practices to improve the Environmental Restoration Program's (ERP's) efficiency
  - Promote innovation and share lessons learned
  - Feedback to the ERP Leadership
- **Who Should Attend?**
  - ERP Community Members: Remedial Project Managers (RPMs), Remedial Technical Managers (RTMs), Contractors, and other remediation practitioners who support and execute the ERP
  - Voluntary participation
- **Schedule and Registration:**
  - Offered quarterly
  - Registration link for each topic (announced through ER T2 email)
- **Topics and Presenters:**
  - ERP community members to submit topics (nonmarketing and Navy ERP-relevant) to points of contact (POCs) (EXWC.T2@us.navy.mil)
  - Selected topic will be assigned a Champion to work with presenter

Agenda

1. Review of High-resolution Site Characterization (HRSC)
2. Application of new HRSC tools
3. Borehole Tools
   1. Flowmeters
   2. Nuclear Magnetic Resonance (NMR)
4. Reapplication of HRSC to evaluate remedial performance
5. Applying Natural Source Zone Depletion (NSZD) as a delineation tool







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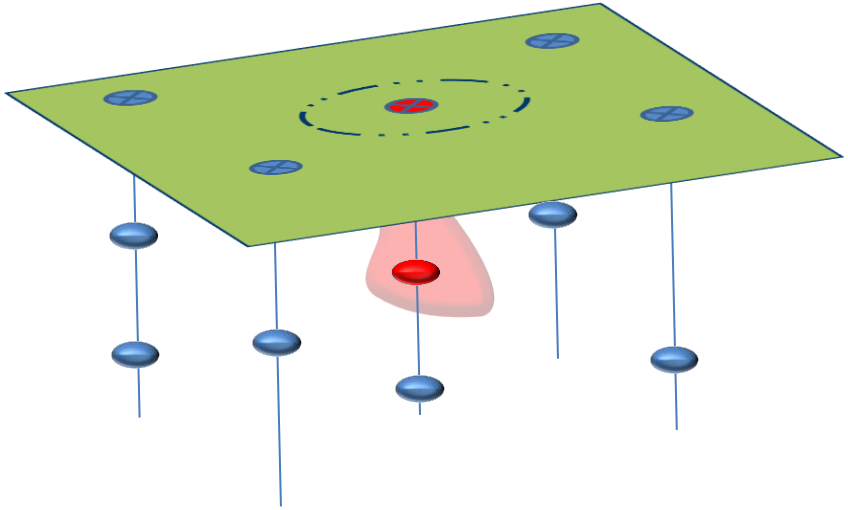
HRSC Benefits

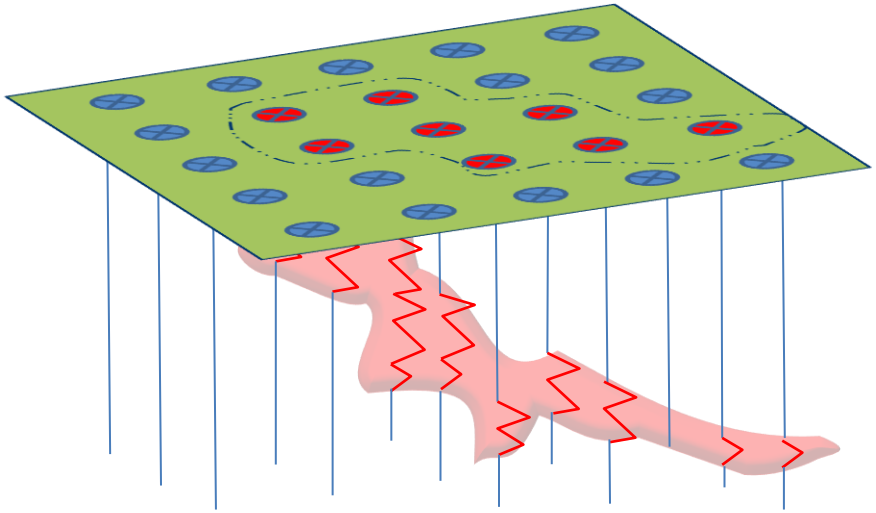
Traditional Characterization



- Field screening/visual observations of soil cores
- Few long-screen monitoring wells
- Offsite laboratory analysis (high $/sample)
- Quarterly sampling
- Slug and pumping tests
- Still required for a majority of regulatory compliance

Commoditized and regulatorily accepted

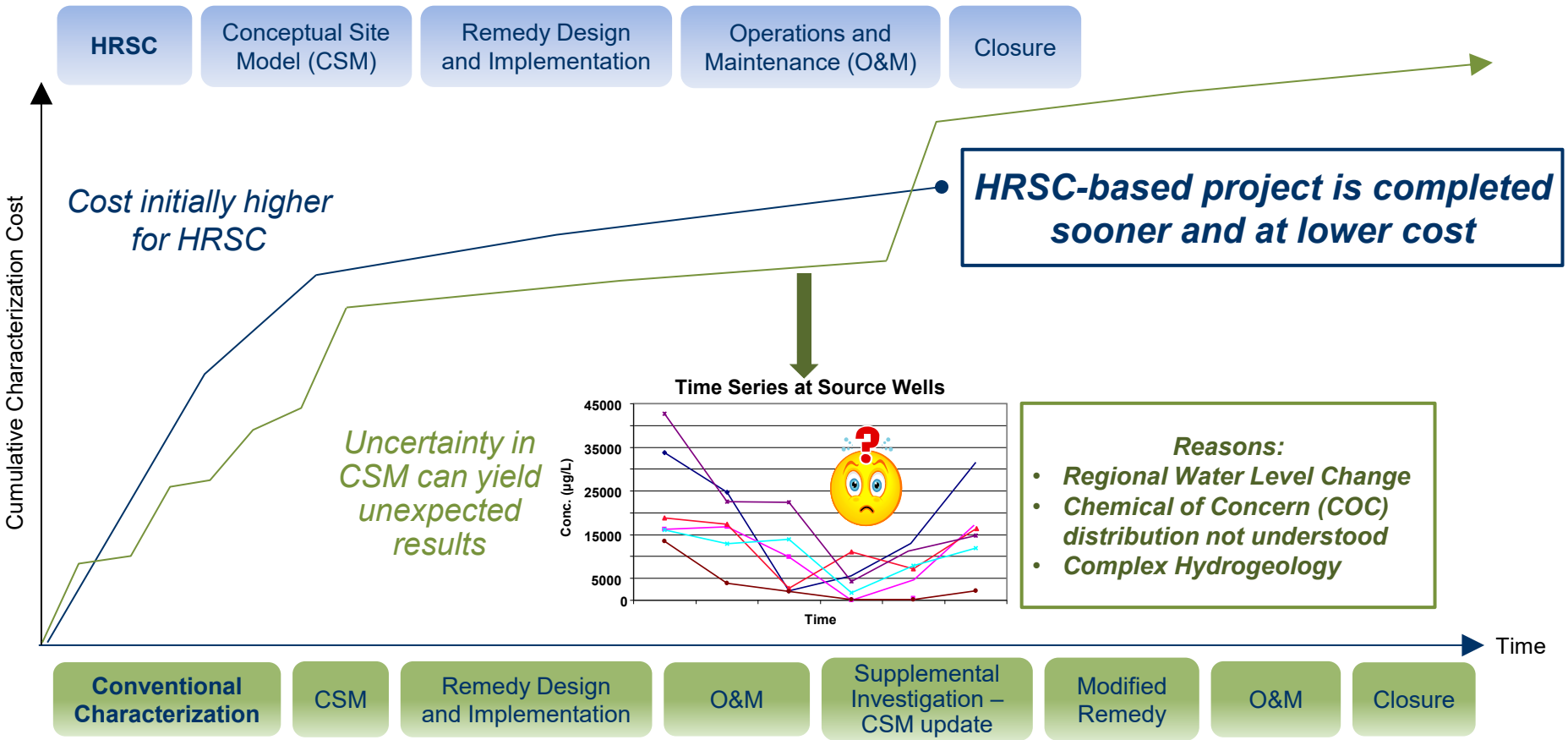
High Resolution Characterization



- Higher data density (Spatial and Temporal)
- Less subjective data sets
- Continuous vertical profiling to obtain detailed lithologic, hydrologic, and contaminant characterization
  - Transform low resolution into high resolution (e.g., NMR)
- Real-time data integration/investigation (e.g., Laser Induced Fluorescence [LIF], NSZD)

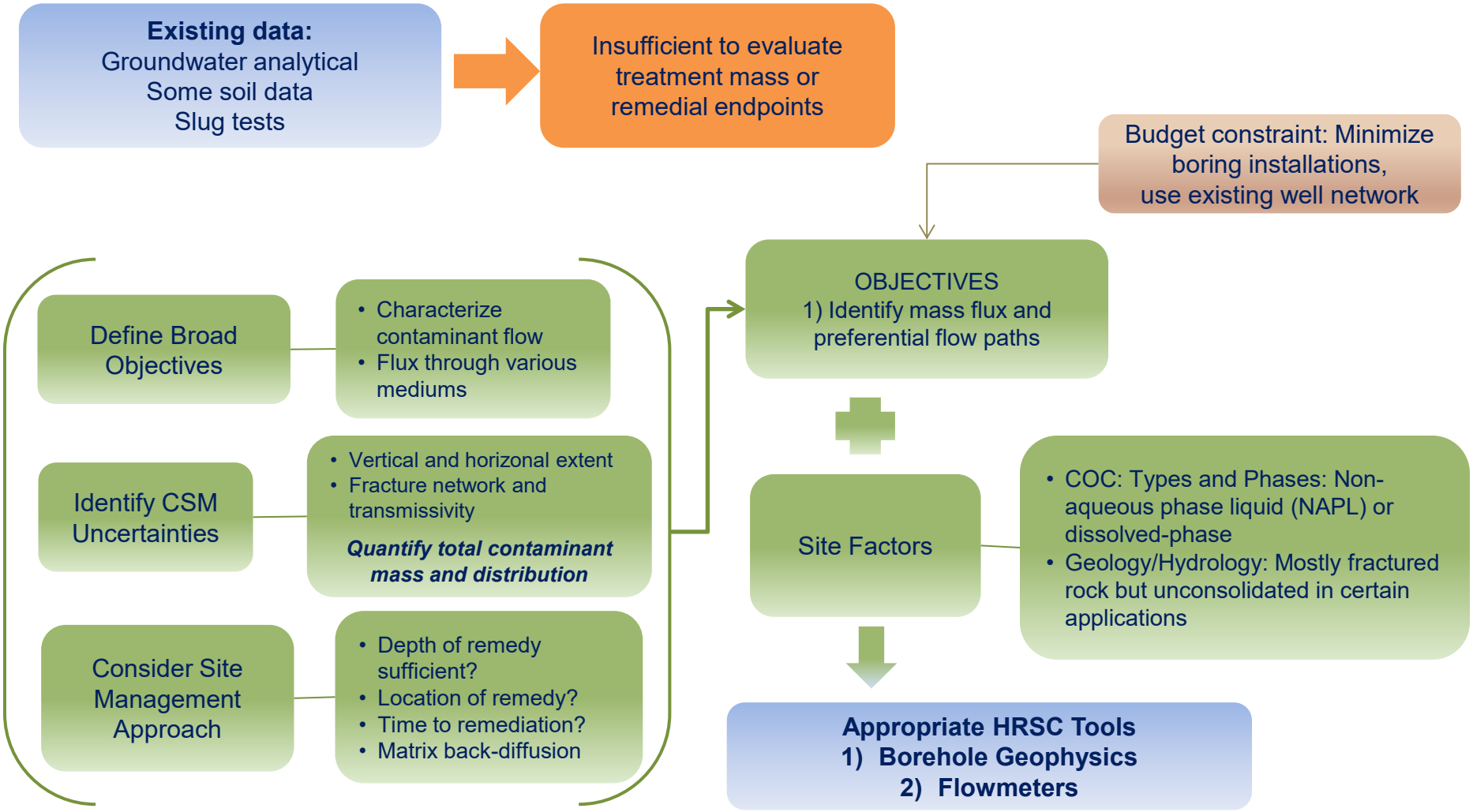
Most effective when strategically applied

Traditional versus HRSC Site Pathway



- **Consider HRSC investment within the spectrum of potential savings in remediation life-cycle costs**

Example 1: Selection of HRSC Application Borehole Tools



HRSC Tools Borehole Geophysics

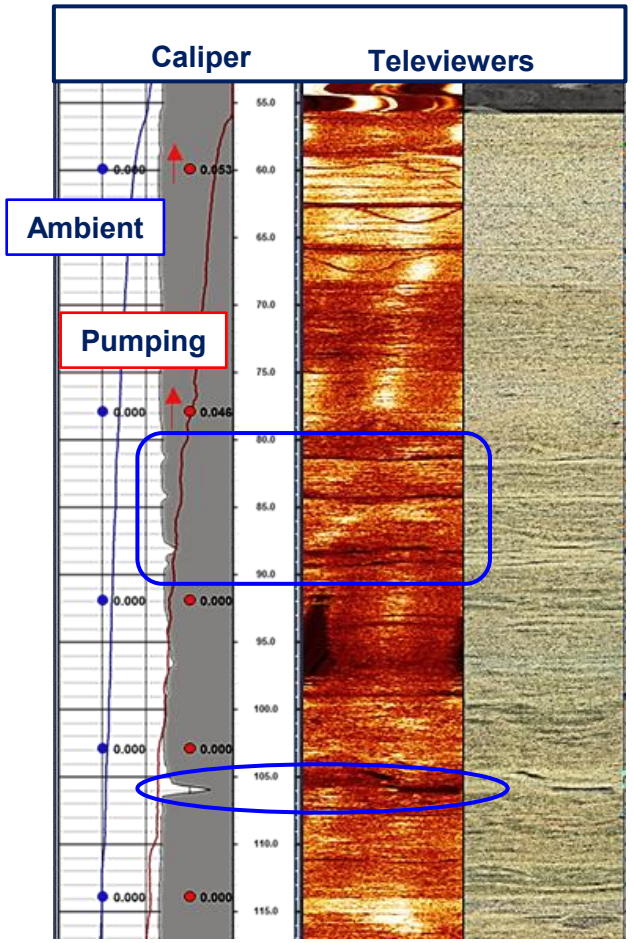
- **Basic Tool Selection for Investigation in Bedrock and Unconsolidated Deposits**

Bedrock	Tools	Uses
Best Practice	• Temperature and Conductivity • Caliper • Optical/Acoustic Televiewers • **Flowmeters**	• Broad changes in water column • Where are the fractures? • What is the fracture orientation? • What fractures are flowing?
Nice to Have	• Natural Gamma • Nuclear Magnetic Resonance	• Changes in lithology (shale, etc.) • Identify NAPL presence in fractures

Unconsolidated	Tools	Uses
Best Practice	• Natural Gamma • Electrical Logs (resistivity, guard, spontaneous potential) • Flowmeters (spinner, hydrophysical) • **Nuclear Magnetic Resonance**	• Differentiate high K^{40} clays • Fine-to-coarse-grained deposits • Flow of large intervals in borehole • Entire hydraulic K for borehole
Nice to Have	• Neutron • Sonic	• Unit porosity (active source) • Calibrate seismic geophysics

Common Flowmeter Types and Use

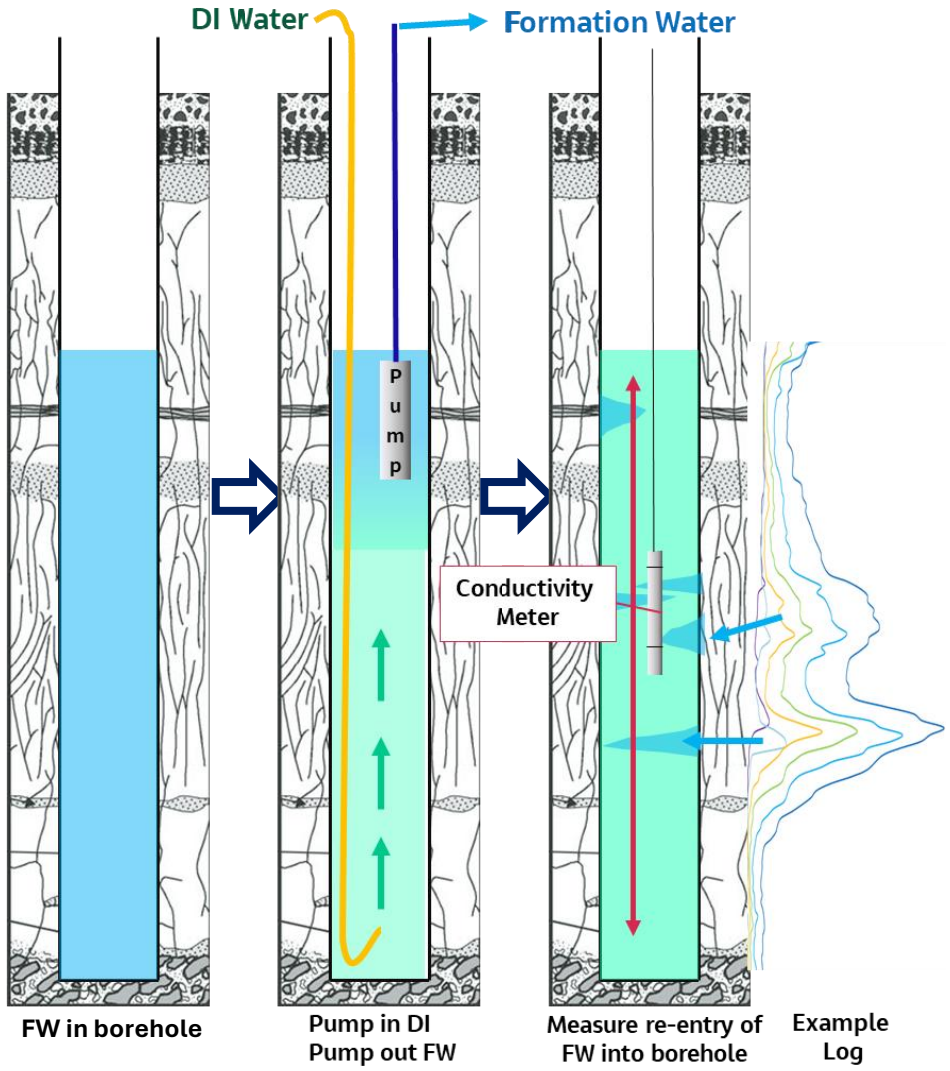
- **Spinner Logging**
  - Primarily for production wells for vertical movement of water
  - Detects leaks and cascading water in well casings
- **Heat-pulse Flowmeter (HPFM) and Electromagnetic Flowmeter (EMFM)**
  - HPFM – "Workhorse" of the environmental world
  - Data collected in pumping and non-pumping conditions
  - EMFM – More precision and can measure individual fracture sets
  - Identifies suitable candidates for interval packer testing or monitoring well screens
- **Less Used**
  - Colloidal Borescope – Measures horizontal flow intervals
  - Hydrophysics – Borehole formation water replacement



Example of Geophysical Log with HPFM
Note largest fracture from caliper log (105 feet) does not have fracture flow with smaller fractures from 80 to 90 feet being more transmissive

Hydrophysical Logging

- Developed for Department of Energy in the 1990s for nuclear waste isolation studies (e.g., Tsang 1990; Pedler 1992)
- Concept – Measuring the magnitude of flow based on induced changes in fluid conductivity
- Practice – Replacing borehole formation water with deionized (DI) (low-conductivity) water in the column and measuring re-entry of formation water (FW)
- Logs entire borehole – No interval selection needed
- If working with impacted water, can generate significant quantities of investigation-derived waste



Comparison Cheat Sheet for Flowmeters

- **Capabilities and specifications for your flowmeter types**

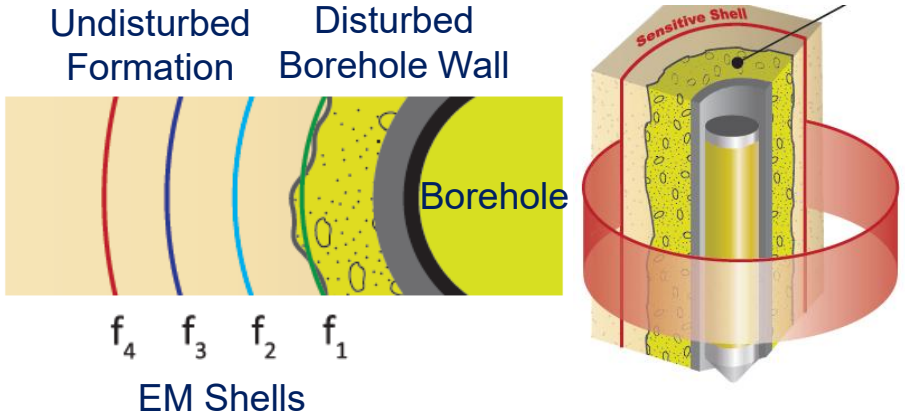
	Spinner Log	HPFM	EMFM	Colloidal	Hydro
Vertical Direction	Yes	Yes	Yes	No	Yes
Vertical Velocity	Yes	Yes	Yes	No	Yes (as volume)
Horizontal Direction	No	No	No	Yes	No
Horizontal Velocity	No	No	No	Yes	Yes
Instrument Diameter	2 inches	2 inches	2 inches	2 inches	2 inches
Continuous Borehole Profile	No	No	No	Yes	Yes
Time per Log (depth dependent)	1 to 3 hours	2 to 4 hours	2 to 4 hours	2 to 4 hours	6+ hours
Measurement Range (Theoretical)	0.1 to 100 gallons per minute (gpm)	0.03 to 1 gpm	0.01 to 10 gpm	Stagnant to approximately 35 gpm	0.0005 to 1,000 gpm
Maximum Depth	>10,000 feet	approximately 400 feet	6,000 feet	1,000 feet	5,000 feet
Vendor Software	No	No	No	Yes	Yes
Cost	$	$	$$	$$	$$$

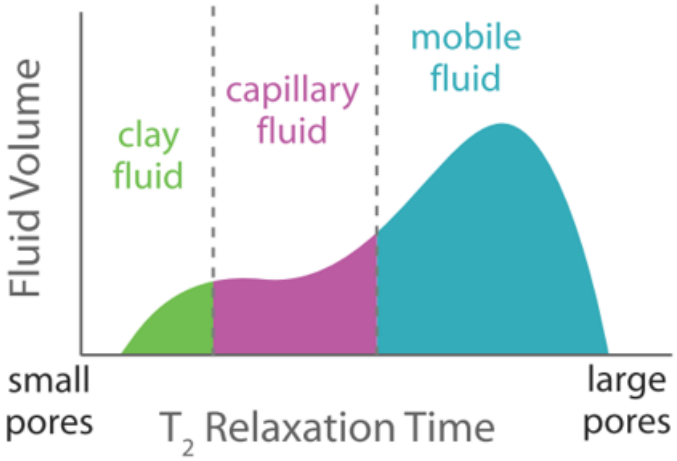
More specialized tools would include:

- ***Cross-borehole flowmeter logging – for more detailed data collection based on initial logging from aforementioned instruments***
- ***Acoustic doppler velocimeter – suitable for surface water and treatment plants – not commercially available?***

Introduction to Nuclear Magnetic Resonance (NMR)

- Quasi-combines Borehole Geophysics and Flowmeter Logging
- Directly measures fluid hydrogen in groundwater in electromagnetic (EM) "shells" (f_n) outside disturbed borehole wall
- Decay Time (T_2) of the EM signal determines if groundwater is "bound" in larger, more mobile pores (long relaxation time) or small pores (short relaxation time)
- Uses these data to estimate total and estimated porosity and hydraulic conductivity (K) from equations developed in the oil and gas industry

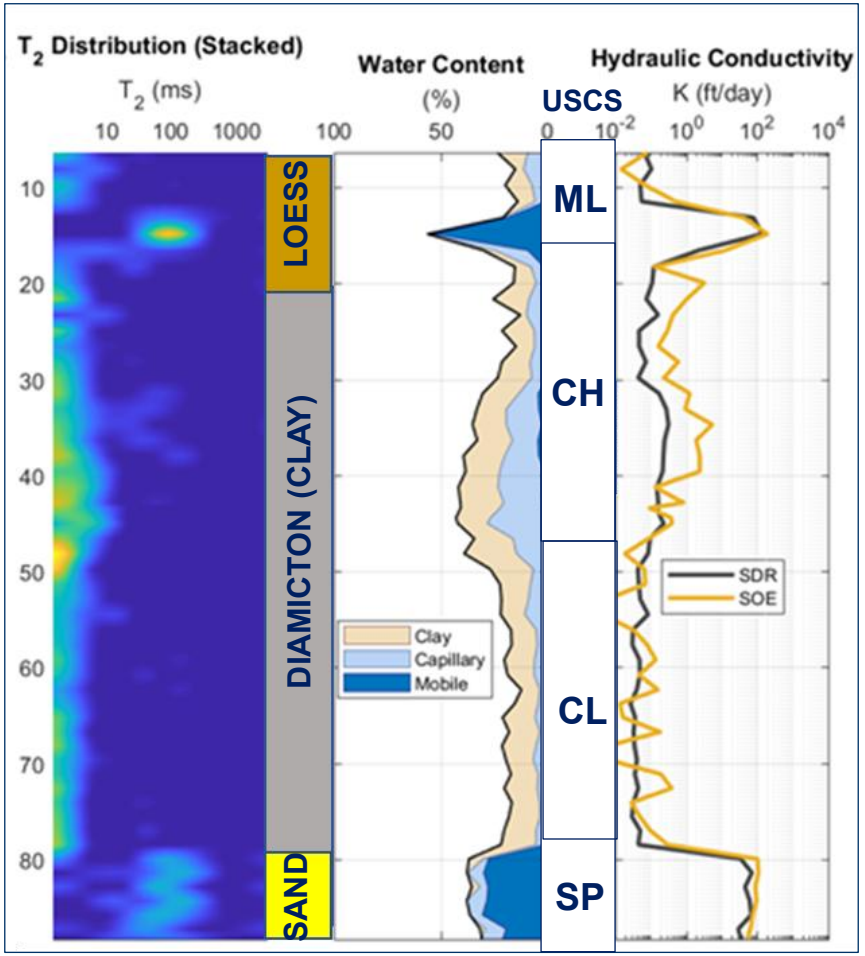




Images from Vista Clara

In Practice

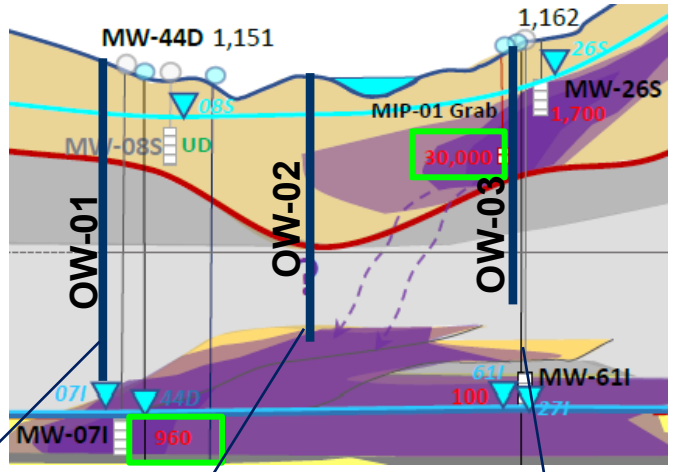
- **Results and Pros**
  - Total porosity/water content
  - Pore size distribution
  - Hydraulic conductivity values for entire borehole
  - Used in polyvinyl chloride (PVC) casing or existing wells
  - Direct-push aquifer remediation tool (DART) can be used in direct-push technology (DPT) applications
- **Cons**
  - "Slow" logging (approximately 30 to 50 feet/hour)
  - Highly susceptible to metal (centralizers and steel surface casings)
  - Diameter limitations – shells need to read undisturbed soil beyond annulus – discuss with driller and vendor before fieldwork!
    - 2-inch wells have maximum 8-inch diameter boring
    - 4-inch wells have maximum 11- to 12-inch diameter

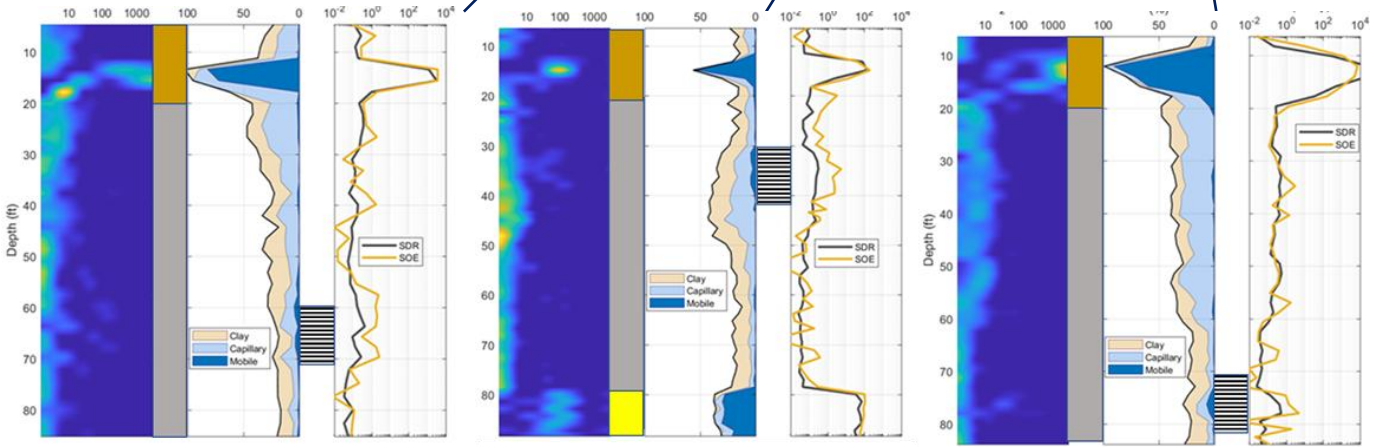


Example NMR Output with Lithology

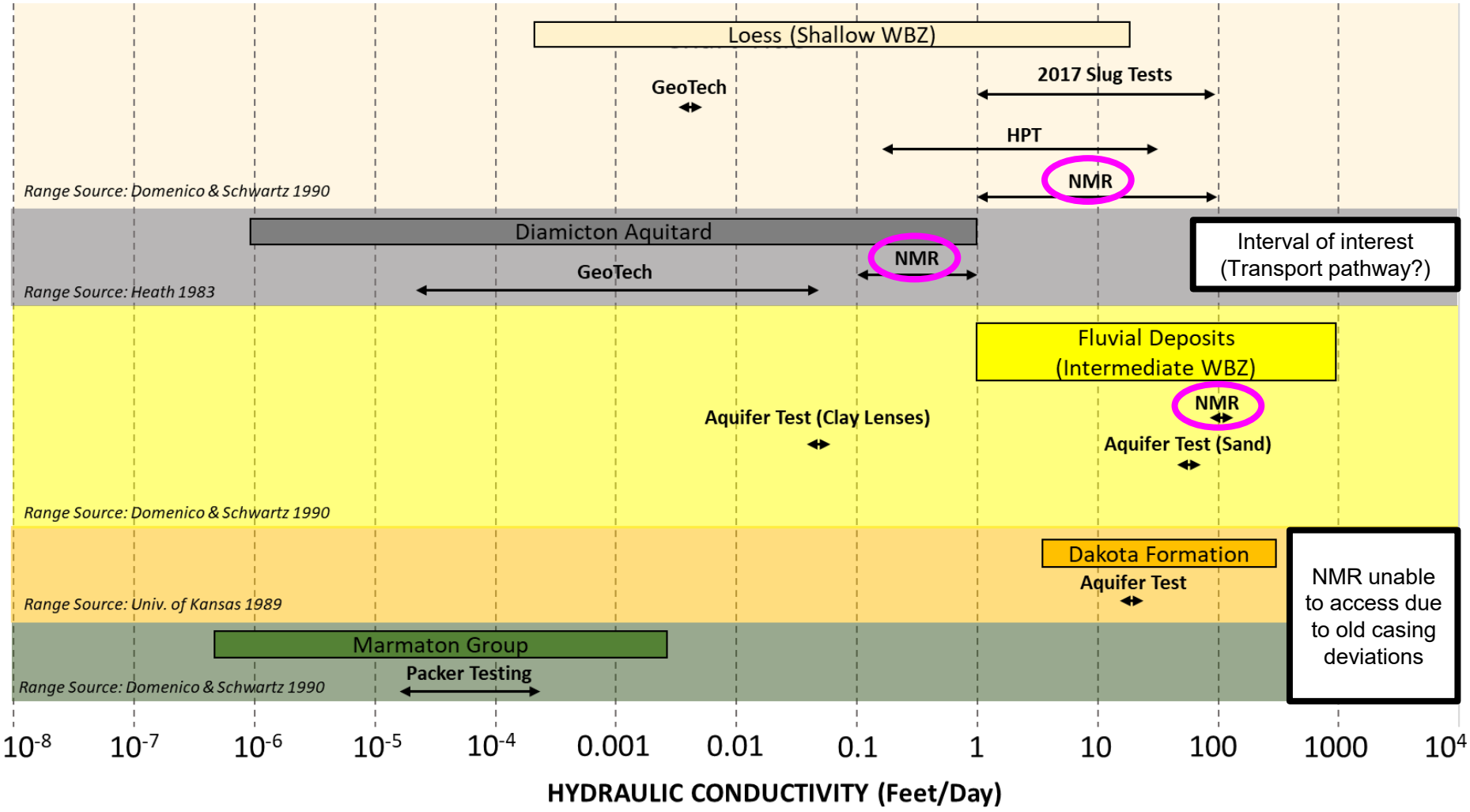
Application of NMR for Aquitard Characterization

- **How does the plume migrate from the loess through the diamicton into the fluvial deposits?**
  - **Fractures within diamicton?**
  - **Diffusion through diamicton?**
  - **Erosional 'window' through diamicton?**
- Drilling encountered very soft silt and clay in diamicton
- NMR logs show perched water on top of diamicton
- Capillary moisture and small amounts of mobile water present within diamicton
- Transducer trends in shallow and intermediate water-bearing zones (BZs) similar and show connection, just not on aquifer test time scales

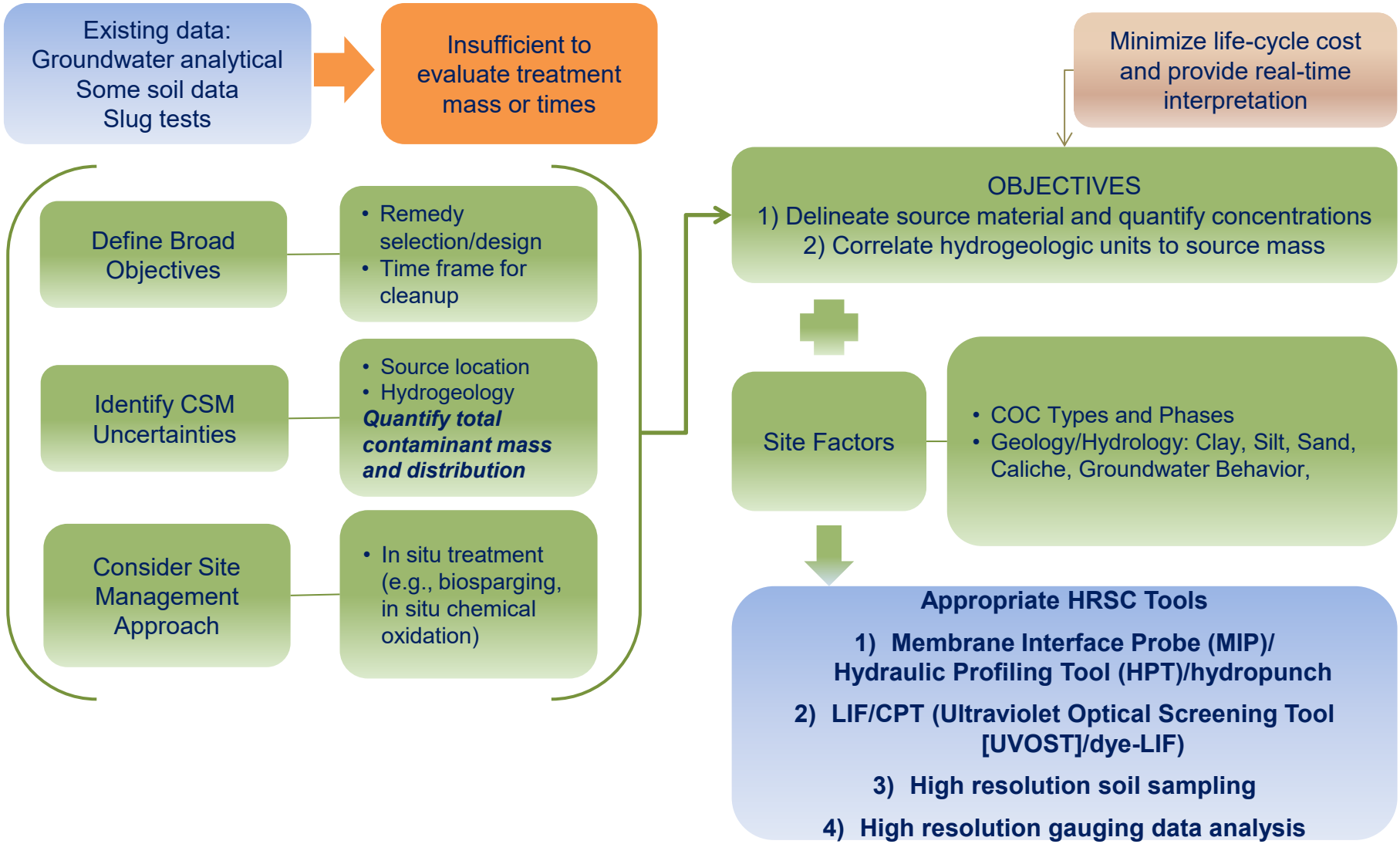




Hydraulic Conductivity (k) for Site Lithologies

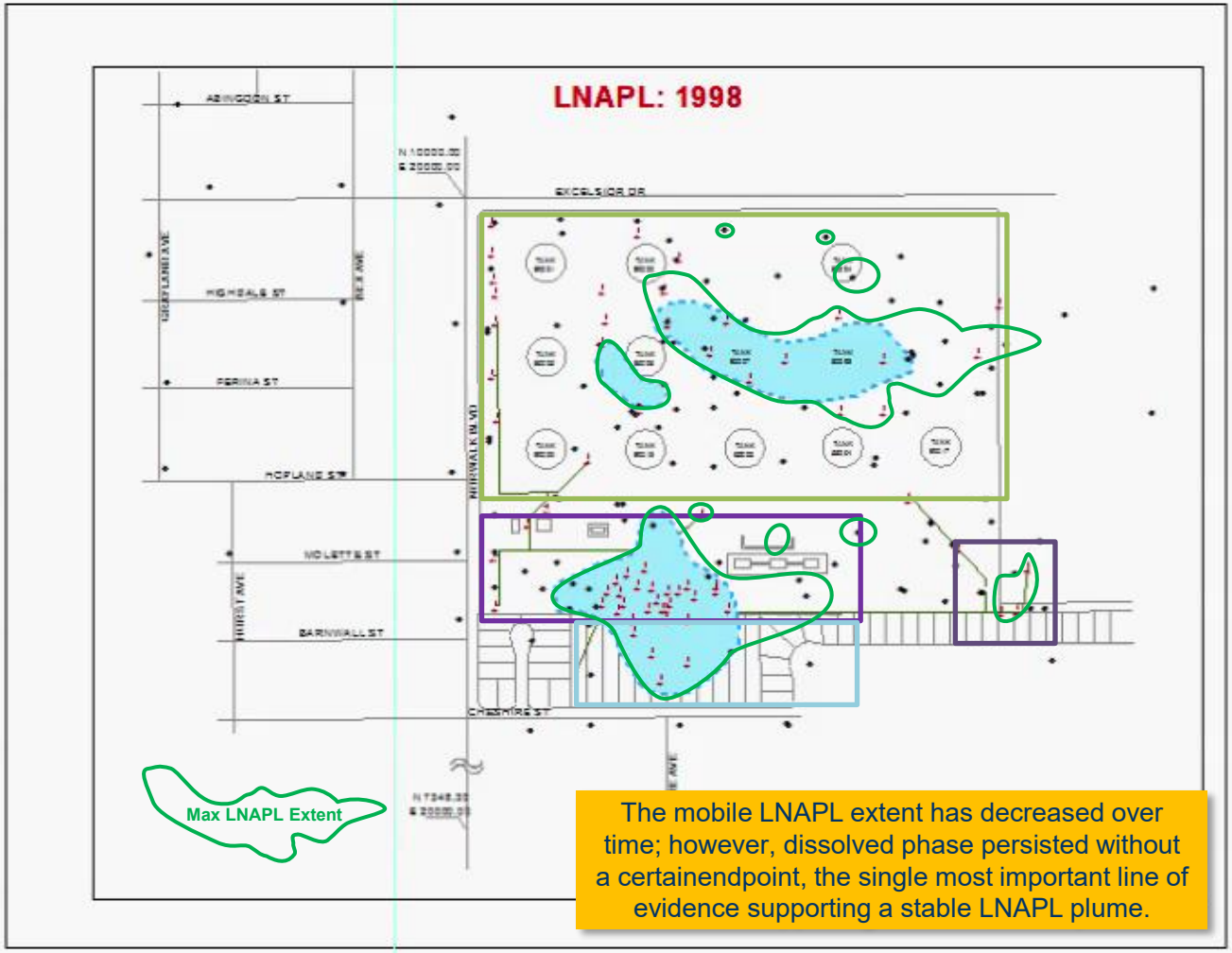


Example 2: Selection of HRSC Application Remedial Selection and Performance



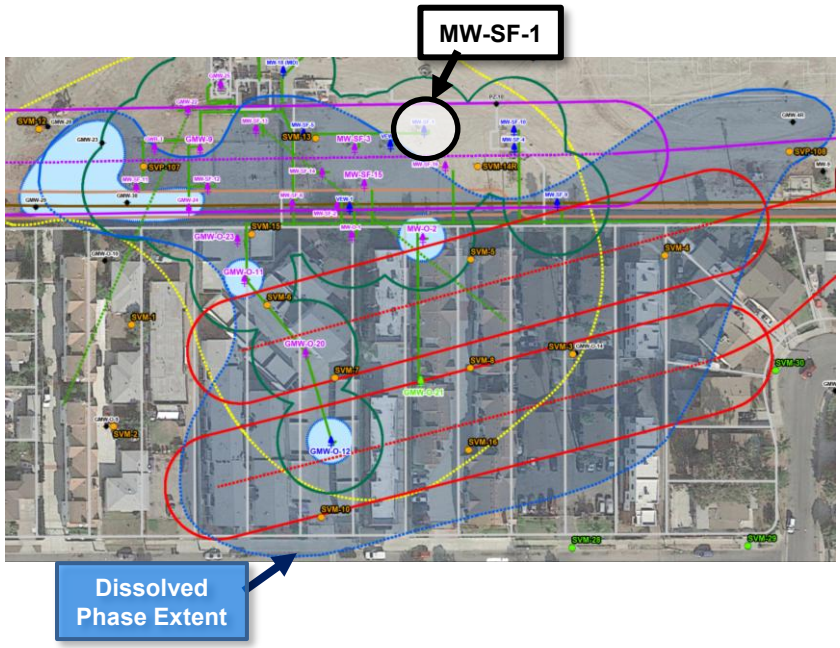
Temporal Application of LIF and Soil Data to Demonstrate Remedy Performance

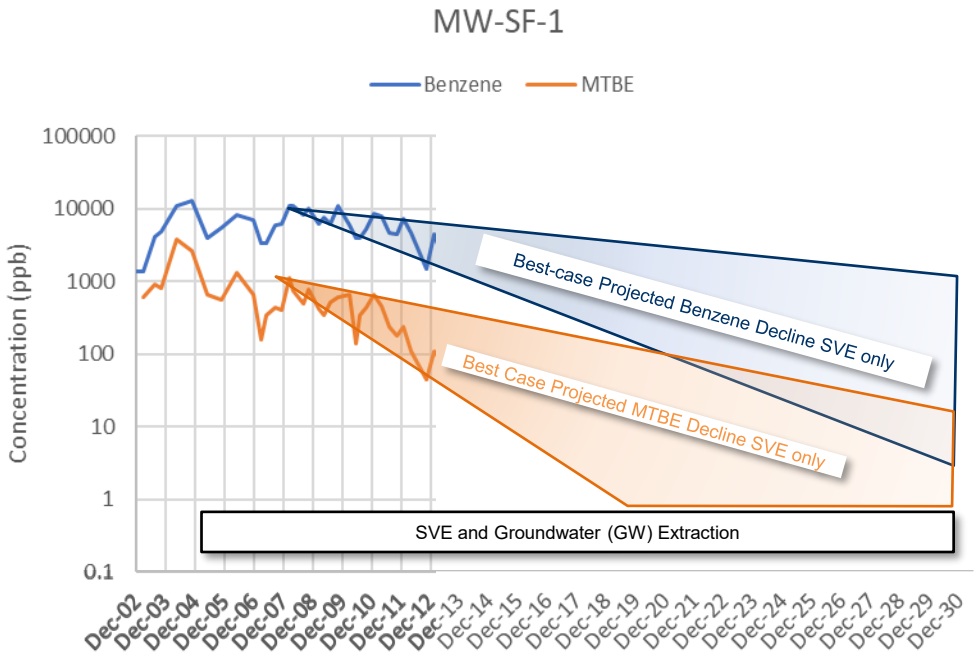
- NAPL site in Southern California
- 20+ years of various multi-phase extraction (MPE) remedies
- Light nonaqueous phase liquid (LNAPL) stable, but dissolved phase not declining



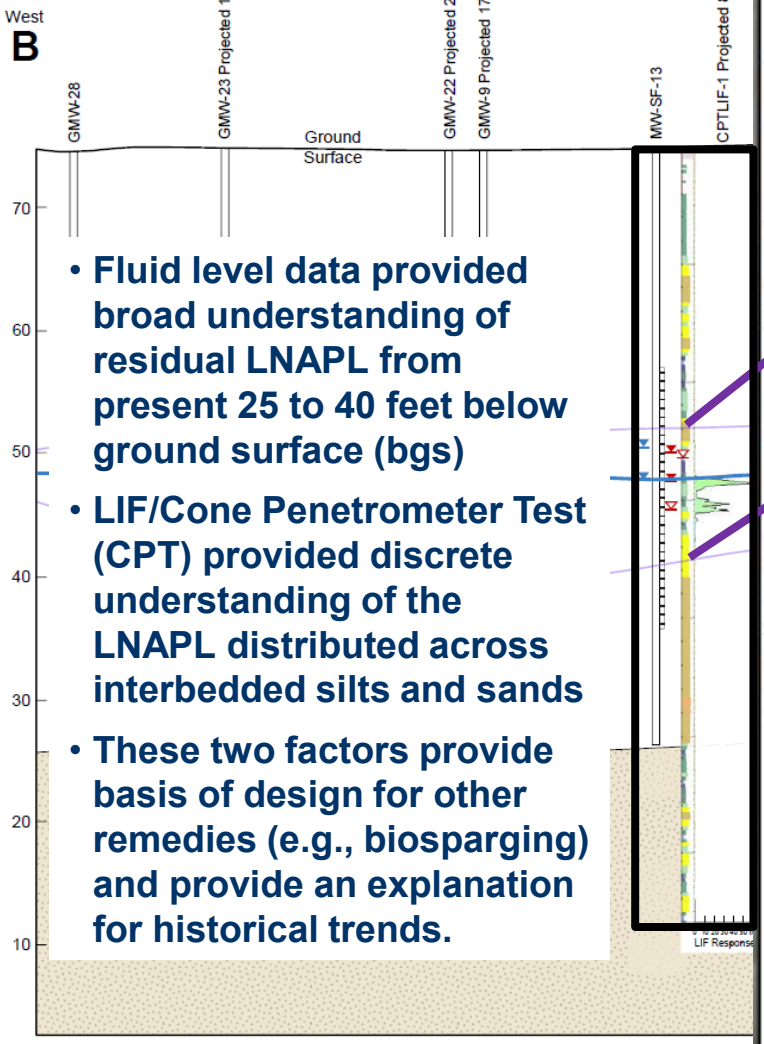
Driver for Remedy Optimization

- **Time to reach dissolved phase remedial endpoints approximately 8 to 15 years of soil vapor extraction (SVE) operation if trends persist**

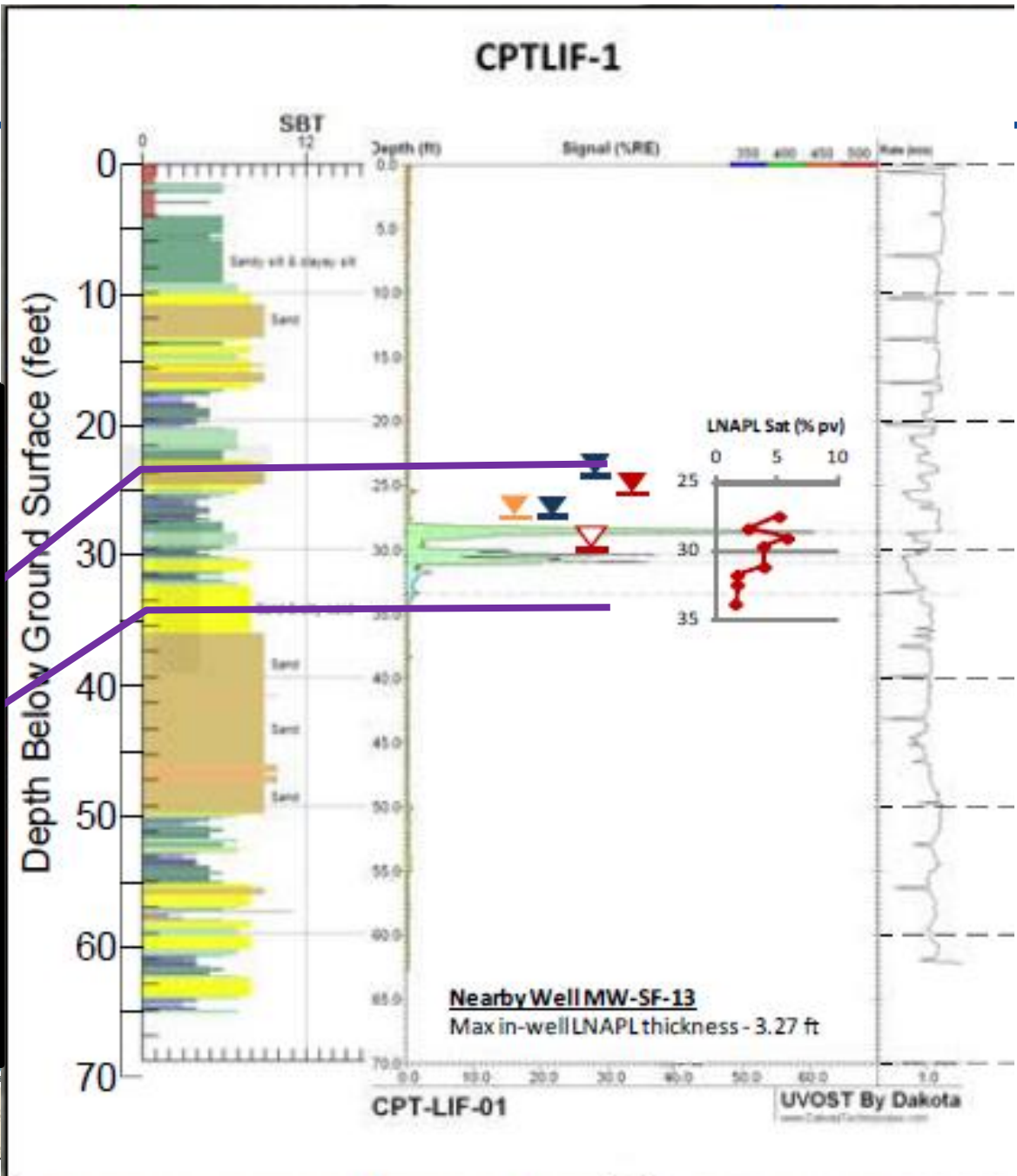




General LNAPL Distribution (2013 pre-biosparge)



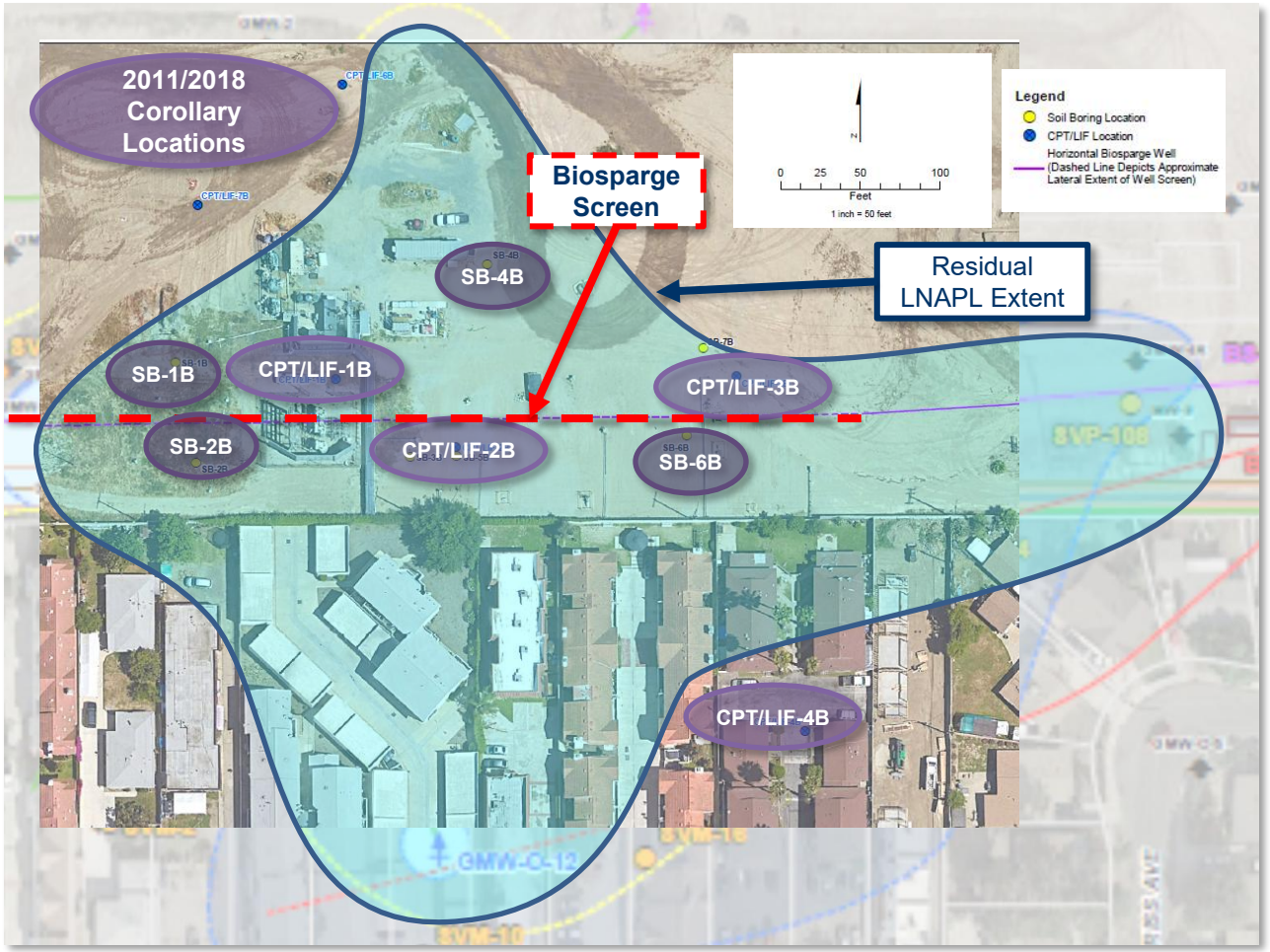
- Fluid level data provided broad understanding of residual LNAPL from present 25 to 40 feet below ground surface (bgs)
- LIF/Cone Penetrometer Test (CPT) provided discrete understanding of the LNAPL distributed across interbedded silts and sands
- These two factors provide basis of design for other remedies (e.g., biosparging) and provide an explanation for historical trends.



Temporal HRSC to Evaluate Remedy Performance

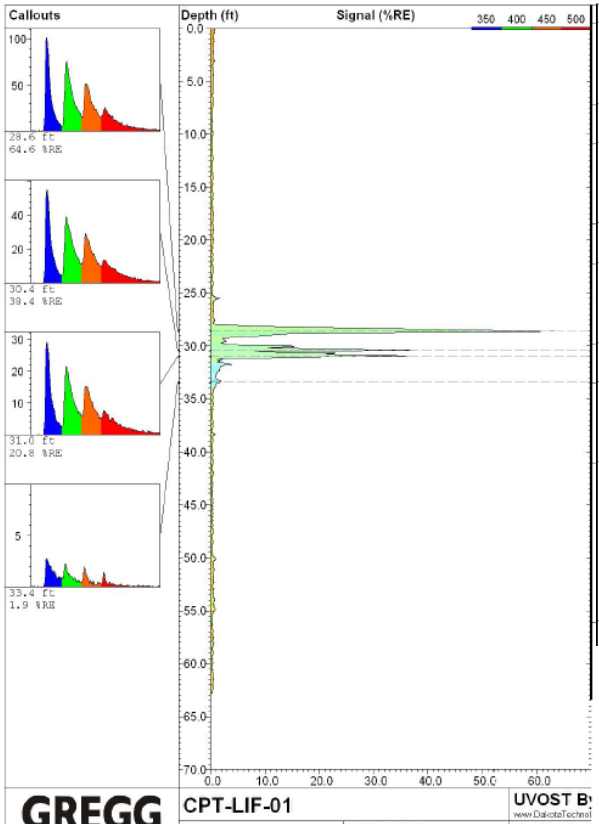
To evaluate biosparge pilot effectiveness, multiple lines of HRSC data were collected before and following biosparging

- **Replicate LIF borings**
- **Replicate undisturbed soil cores**
- **High-resolution soil analytical**

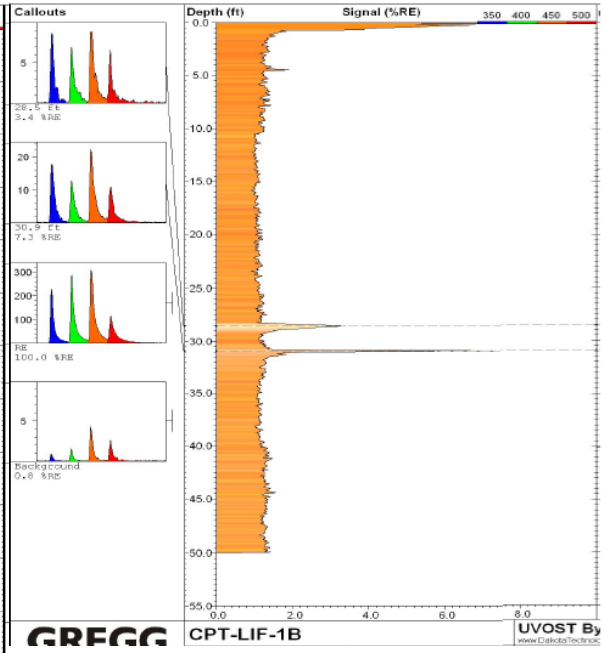


LIF and Undisturbed Soil Core Before and After

2011

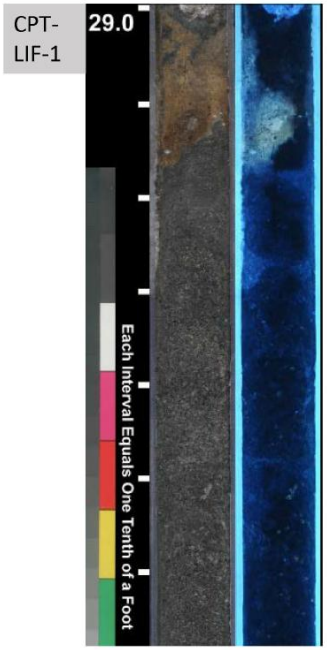


2018

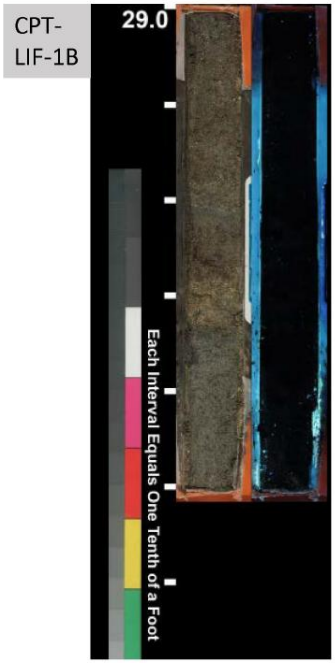


Replicate LIF borings provide semi-quantitative source depletion over time

2011



2018



Replicate undisturbed soil cores provide quantitative NAPL source depletion over time

Analytical Reductions Due to Biosparging

Traditional sampling can be used to evaluate remedy performance

- **Needs to be guided by HRSC data (e.g., LIF)**
- **Supports regulatory requirements**

2012 Pre-Sparging Soil Result

2018 Post-Sparging Soil Result

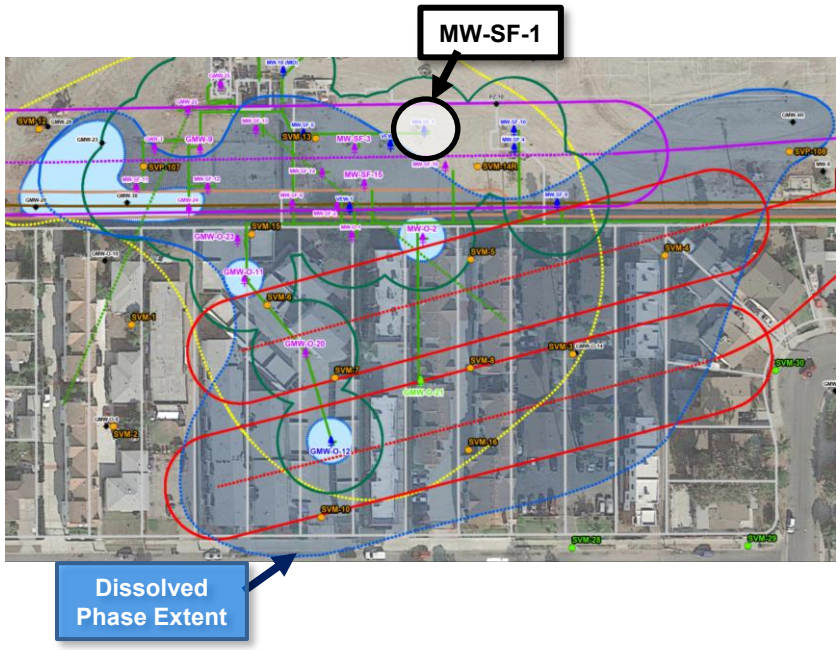
General Area	Sample Location	Sample Date	Sample ID	Sample Depth Interval (feet bgs)	TPH-g (mg/kg)	TPH-d (mg/kg)	Benzene (µg/kg)
SC	**SB-1**	9/19/2012	SB-1-28.5	28-28.5	**23,000**	**4,000**	**240,000**
	SB-1B	7/27/2018	SB-1B-30	30	**310**	**1,800**	<0.10
	SB-2	9/19/2012	SB-2-28.5	28-28.5	**25,000**	**2,500**	**310,000**
	SB-2B	7/26/2018	SB-2B-30	30	**7.3 J**	**2.6 J**	**3.5**
	SB-3B	7/26/2018	SB-3B-30	30	<0.47	**58**	<0.0019
	SB-4	9/20/2012	SB-4-27	26.5-27	**11,000**	**15,000**	**110,000**
	SB-4B	7/27/2018	SB-4B-35	35	**310**	**850**	<0.083
	SB-5B	7/26/2018	SB-5B-30	30	**330**	**940**	<0.13
	SB-6	9/20/2012	SB-6-29	28.5-29	**6,100**	**13**	**51,000**
	SB-6B	7/26/2018	SB-6B-30	30	<0.43	**2,700**	<0.0028
	SB-7B	7/25/2018	SB-7B-30	30	**20 J**	**160**	<0.0016

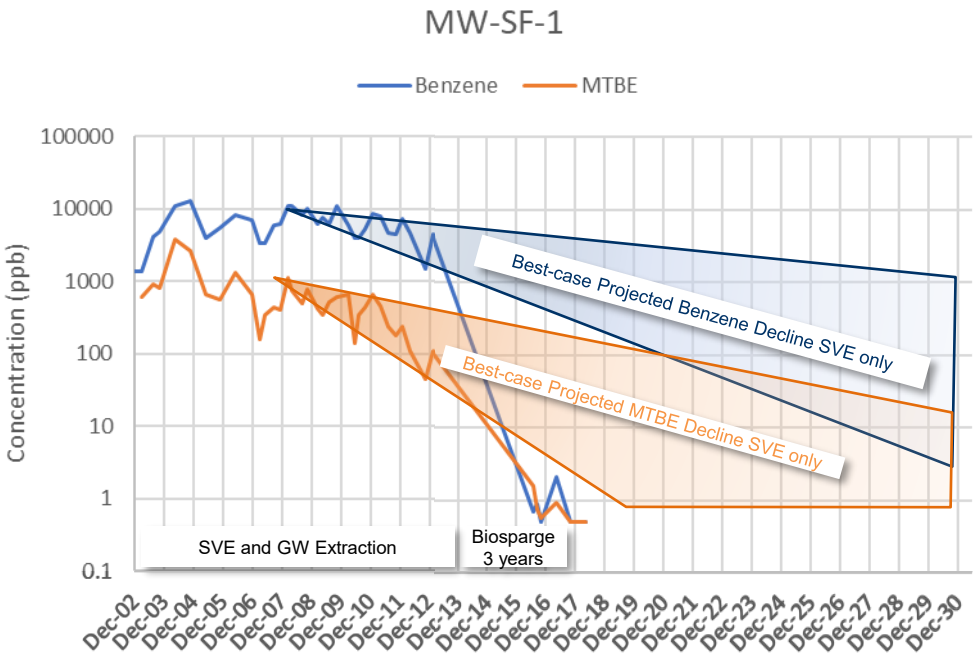
µg/kg = microgram(s) per kilogram
ID = identification
mg/kg = milligram(s) per kilogram
TPH-g = total petroleum hydrocarbons-gasoline
TPH-d = total petroleum hydrocarbons-diesel

Representative maximums observed at each location

Performance of Remedy Optimization

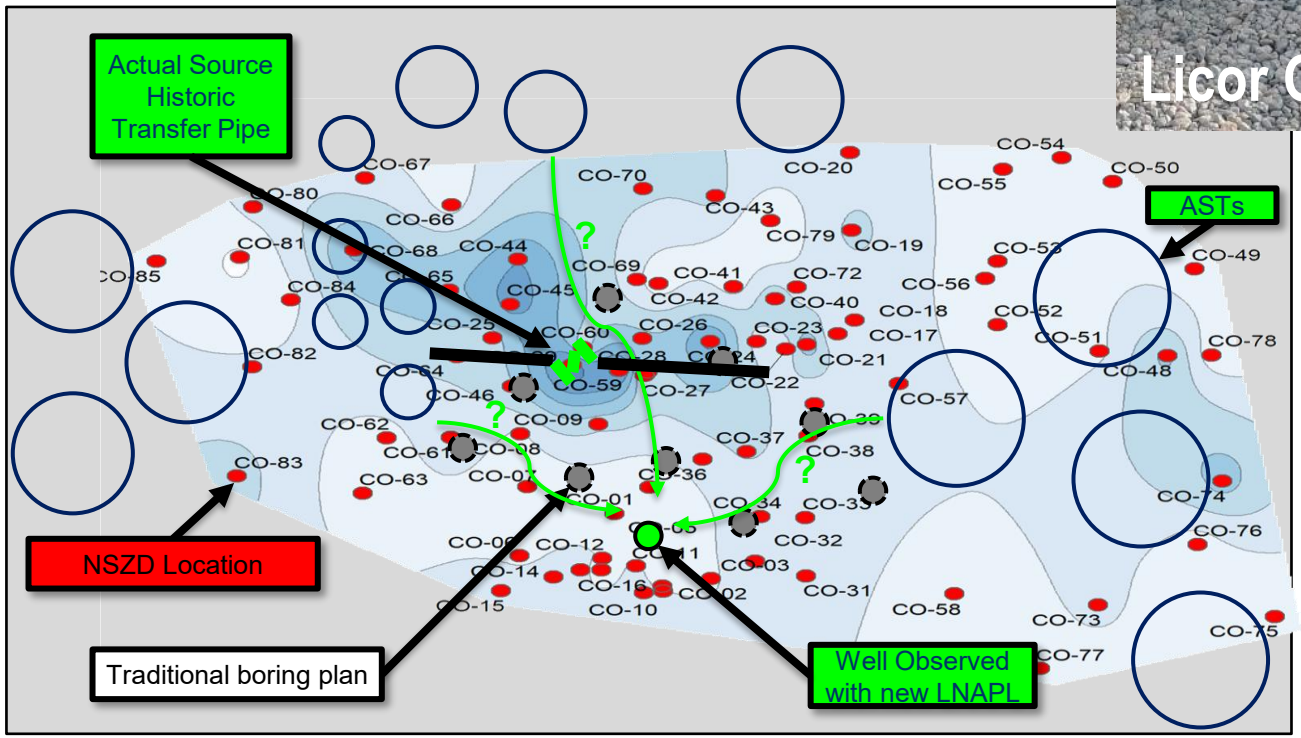
- Time to reach dissolved-phase remedial endpoints approximately 8 to 15+ years of SVE operation if trends persist
- Compared to approximately 3 years with biosparging





Bonus NSZD for High-resolution Source Delineation/Confirmation

- LNAPL (or high dissolved phase petroleum hydrocarbons) is observed at monitoring locations
- Typically delineated by borings/wells
  - LIF potentially; however, this is still costly and time consuming



Is there a better way to delineate?

NSZD, typically a remedial tool, provides real-time, non-intrusive, petroleum hydrocarbon degradation footprint, which often aligns with source extent.

Take Home Messages

- Flowmeters
  - Inexpensive: Insightful CSM tool can be applied to existing wells
  - Many options: Use the matrix provided to select the appropriate application
- NMR
  - Excellent option for correlating existing K data continuously in existing closed boreholes
  - Note borehole and well construction limits
- HRSC is not always an initial characterization, sometimes useful as CSM questions arise or site conditions change
  - Regional long-term water level trends (development, climate)
  - Site objectives change
- Think outside the box with characterization tools
- Consider LIF/MIP/high-resolution soil interim sampling to track or optimize remedial progress
- HRSC tools point you toward the regulatory answers, but often require traditional sampling to support results (which can be optimized)

Points of Contact

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Questions? Email to EXWC.T2@us.navy.mil

Wrap Up

- A short survey will be sent to webinar registrants and participants
- Stay tuned for upcoming OER2's by email: EXWC.T2@us.navy.mil
- You can find previous presentations on the ERB Website> OER2 Presentations and our OER2 YouTube channel, all found on https://exwc.navfac.navy.mil/go/erb
- Thank you for participating!