Starting Soon: Optimizing Injection Strategies and In Situ Remediation Performance

- Optimizing Injection Strategies and In Situ Remediation Performance (OIS-ISRP-1, 2020)
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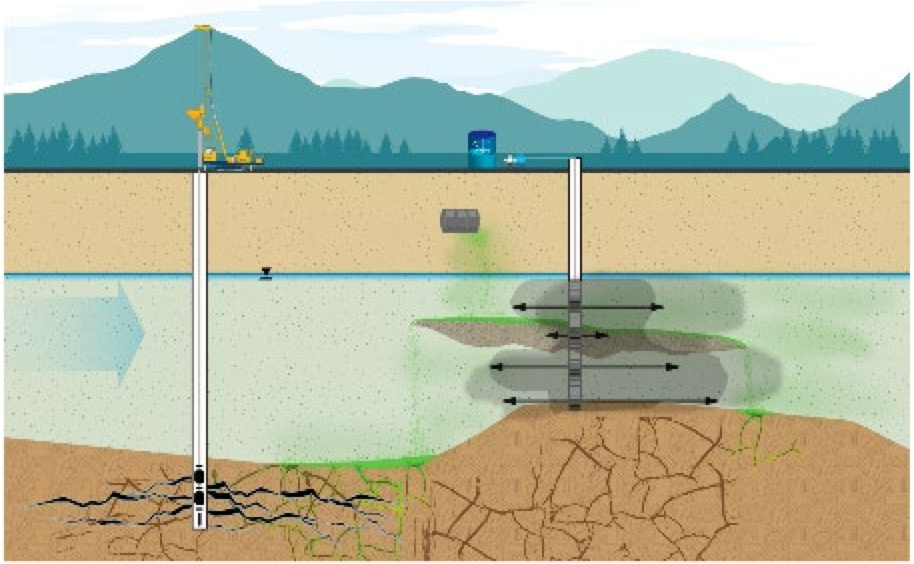
Optimizing Injection Strategies and In Situ Remediation Performance



Optimizing Injection Strategies and In Situ Remediation Performance (OIS-ISRP-1, 2020)

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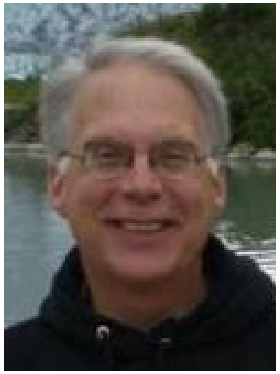

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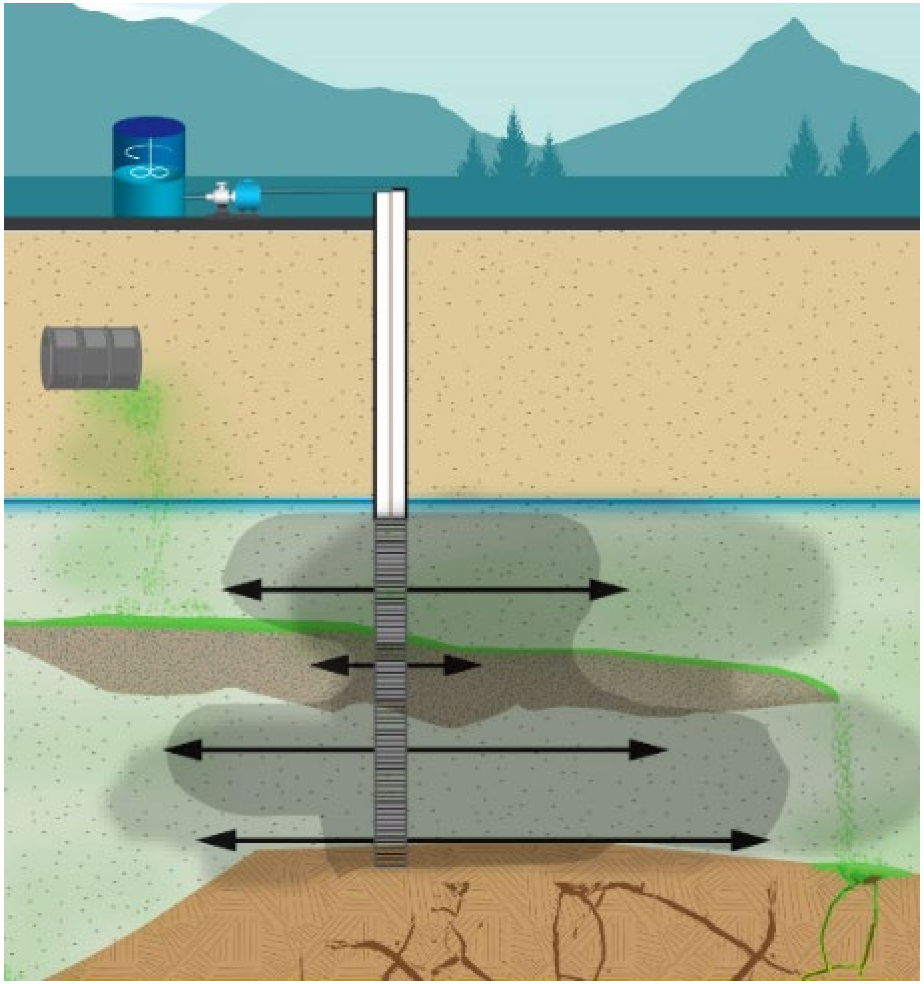
ITRC's Online Guidance for In Situ Remediation Optimization

Poll Question

Free Online Access at: https://ois-isrp-1.itrcweb.org

In Situ Remediation

- A typical in situ remedy includes **delivery** and **dosing** of **amendments** to enhance abiotic and/or biotic **processes** to treat contaminants in subsurface
- More than thirty years of experience with in situ remedies has greatly improved the state of the science and engineering; though challenges remain



State of Practice

The Problem

- Failing to achieve the objectives or performance requirements
- Unknown variables that influence effectiveness

The Need

- Conceptual Site Model (CSM) more complete
- More efficient and effective remedies
- Framework guidance to facilitate improvements

State regulator survey: ~40% of regulators deemed the first submittal for in situ remediation projects as incomplete

What is Optimization?

- Optimization is the effort (at any clean-up phase) to identify and implement actions that improve effectiveness and cost-efficiency of that phase. (From ITRC-GRO-1)
- Optimizing in situ remediation is:

  The management of risks and uncertainties through sound science and engineering during different stages of in situ remedy planning and implementation

- This training and accompanying guidance intended to help transfer "best practices" to benefit all

ITRC's In Situ Remediation Optimization Toolbox

Guidance Layout

Remedial Design Characterization

The Design Wheel

Performance Monitoring & Feedback Loop

Stakeholder Considerations

Optimization Process

Commonly Encountered Challenges

Amendment Factsheets

Delivery / Injection Screening Matrix & Factsheets

Bench / Pilot Testing Considerations for Design

Document Audience and Application

- Intended audience
  - Regulators
  - Responsible Parties
  - Consultants
- Two applications of this document:
  - Improving underperforming remedies
  - Planning, designing and implementing optimized in situ remedies

What are the Technical Challenges?

- Higher contaminant concentrations after injections
- Insufficient amendment distribution and contact
- Contaminants in low permeability zone
- Amendment is “daylighting”/short circuiting
- Using vendor’s dosing default values instead of CSM data

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Commonly Encountered Issues

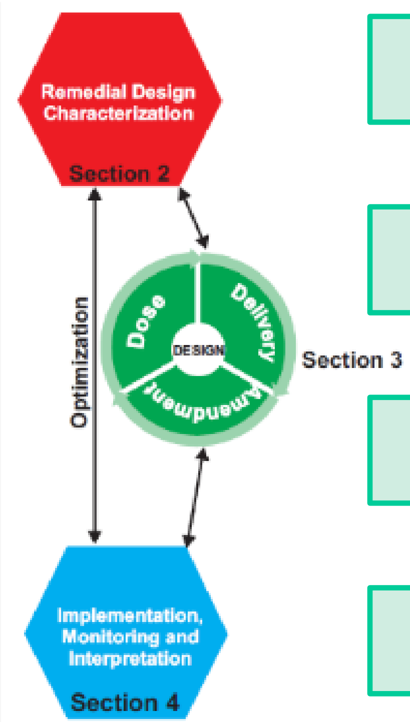
Commonly Encountered Issues Associated with Remedial Design Characterization – Section 2			
Lithology	**Contaminant**	**Challenges, Lessons Learned, and/or Best Practices**	**Discussion, Document Section, Links**
Bedrock		The amount of contaminant mass sorbed into bedrock secondary porosity.	(ITRC 2017a)
Soil		Lack of understanding of contaminant mass sorbed onto finer grained soils.	Application of MiHPT, MiHPT-CPT coupled with high density soil sampling to determine extent and distribution of contaminant mass (ITRC 2015).
		Limitations of solvent extraction in quantifying mass sorbed into soil.	See Discrete fracture network approach for studying contamination in fractured rock
Groundwater		Variability of K and calculated seepage velocity in contaminated intervals is needed to estimate ROI delivery approaches and residence time within ROI.	Higher resolution slug testing, tracer testing, or pilot testing with monitoring to determine amendment distribution in effective pore space.
		Mischaracterization of mass flux to be targeted in a mass flux reduction strategy.	Higher resolution sampling to identify transmissive zones for injection based on defined targeted K values, contaminant mass, and heterogeneity within the TTZ.
	NAPL or DNAPL	Mischaracterization resulting in not identifying the presence of LNAPL or DNAPL that overwhelms efficacy of in situ treatment.	Evaluate vertical extent of TTZ for presence of LNAPL or DNAPL (ITRC 2015) (ITRC 2018).

ITRC OIS-ISRP-1 Table 1-1 (See Additional Information, Appendix B)
Commonly Encountered Issues with In Situ Remediation

Training Program Learning Objectives

- Identify challenges
- Apply iterative optimization process at each stage of in situ remedy
- Determine amendment, dosing and delivery options
- Monitor performance to make optimization decisions
- Anticipate iterative refinement for remedy design and regulatory approvals

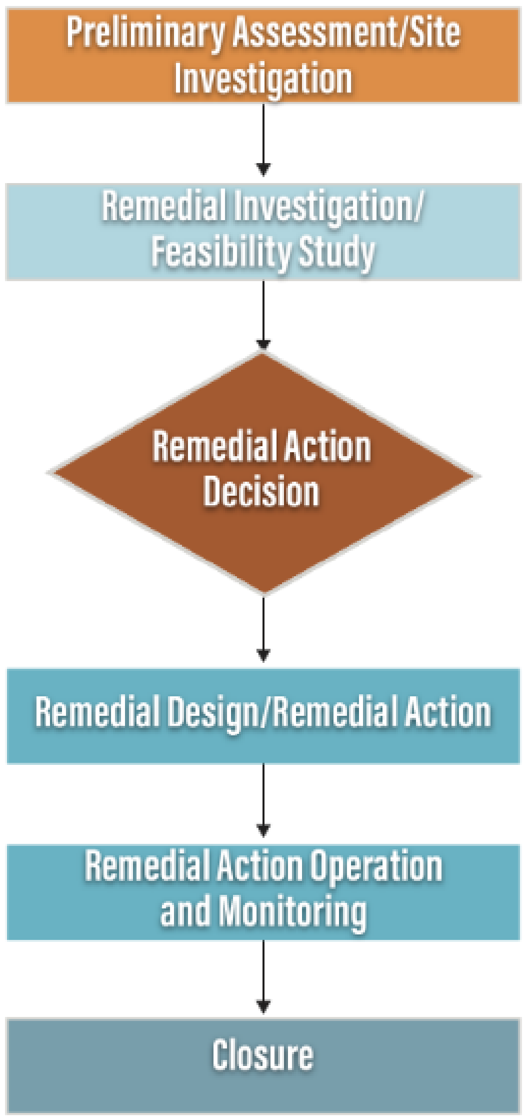
Presentation Road Map



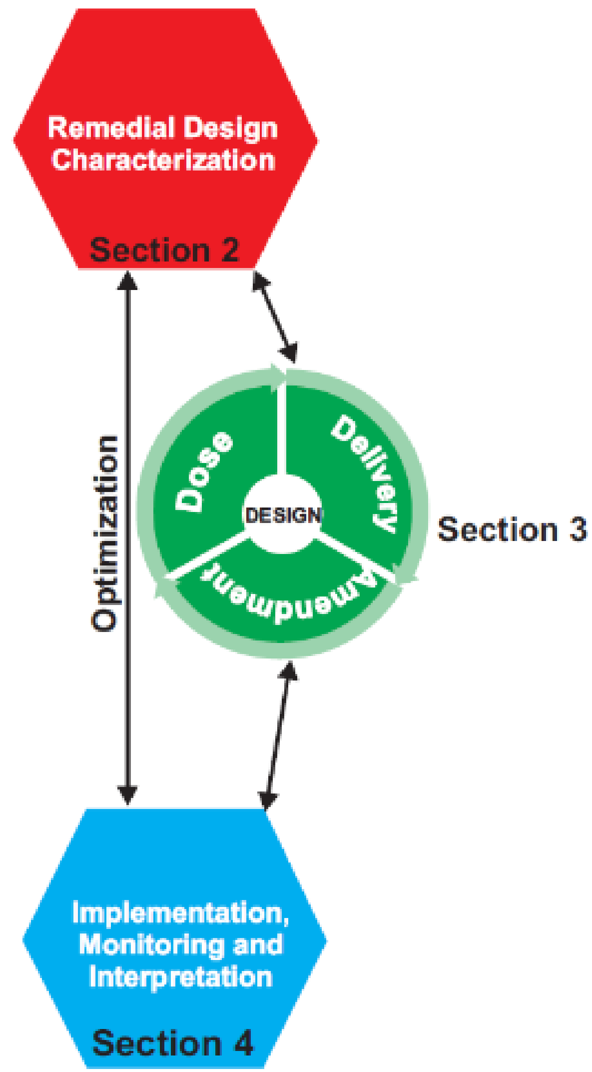
- **Optimization Process**
- Remedial Design Characterization
- Design: Amendment, Dose & Delivery
- Implementation, Monitoring & Interpretation
- Regulatory & Stakeholder Considerations

Learning Objective: Identify challenges

Linear Paradigm to Iterative Process

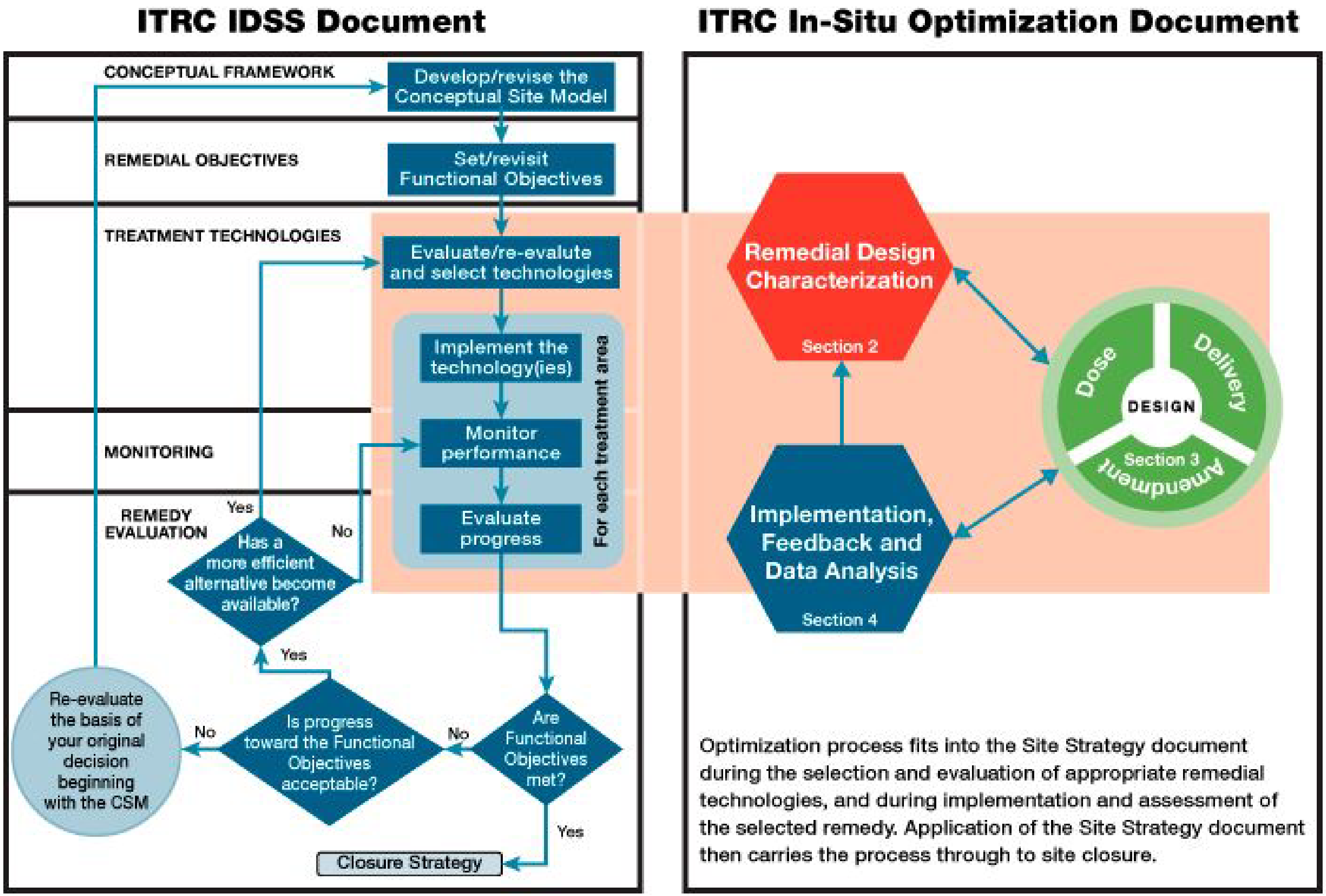


ITRC OIS-ISRP-1 Figure 5-1



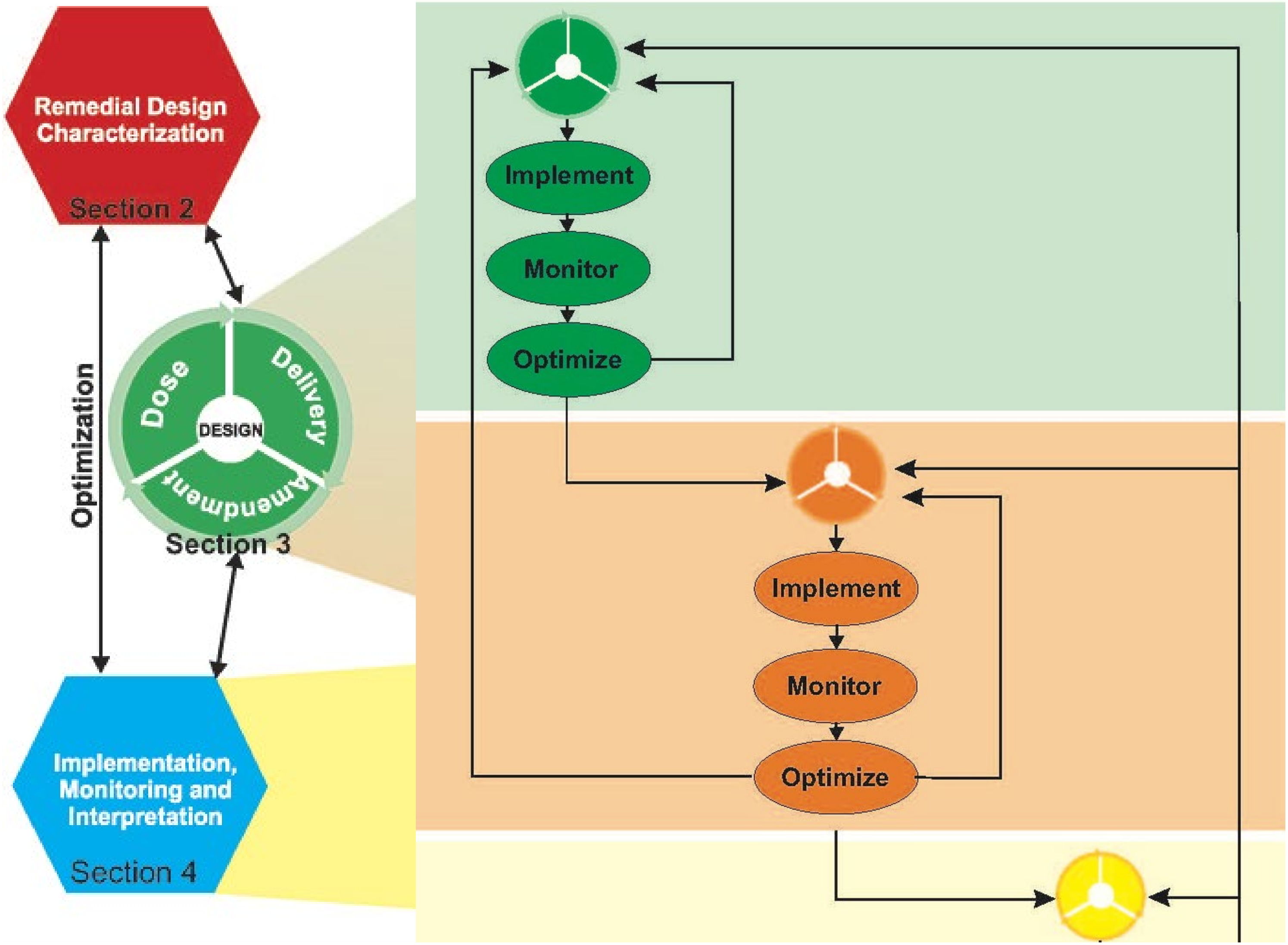
ITRC OIS-ISRP-1 Figure 3-1

ITRC Documents Support Interactive/Iterative Approach



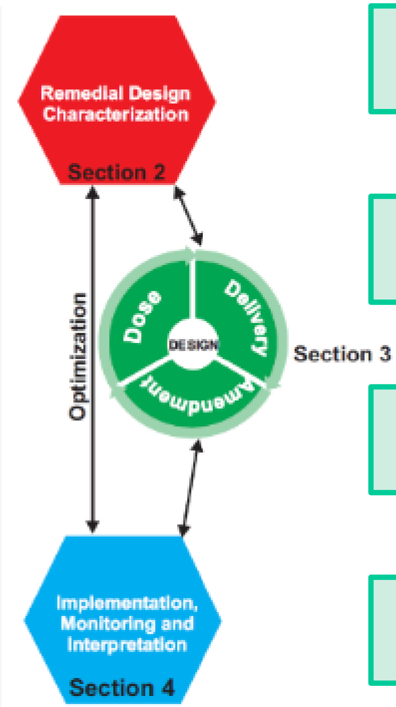
ITRC OIS-ISRP-1 Figure 1-1

Iterative Approach to Optimization



ITRC OIS-ISRP-1 Figure 3-1

Presentation Road Map



- Optimization Process
- **Remedial Design Characterization**
- Design: Amendment, Dose & Delivery
- Implementation, Monitoring & Interpretation
- Regulatory & Stakeholder Considerations

Learning Objective: Apply iterative optimization process at each stage of in situ remedy

RDC – WHAT IS IT?

RDC = REMEDIAL DESIGN CHARACTERIZATION

It is the collection of additional data, above and beyond general site characterization, necessary to develop a sufficiently detailed CSM

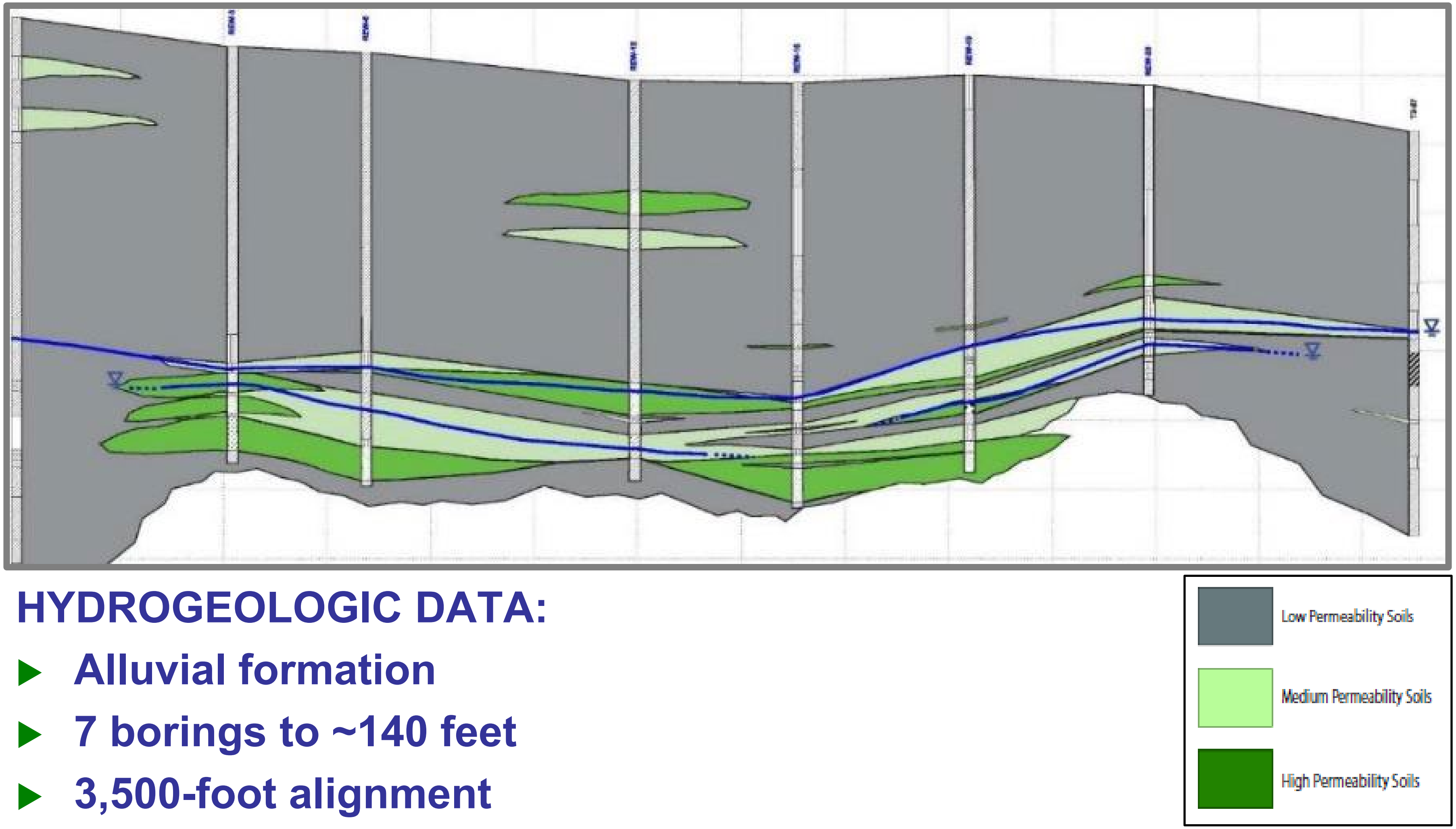
This enables the design basis for a successful in situ remedy

RDC – WHY DO IT?

When in situ remedies fail, or produce less than optimal outcomes, it is often due to a lack of detailed data or an insufficiently developed conceptual site model (CSM)

The success of in situ remedies is directly related to a thorough understanding of site and subsurface conditions

The Impact of Data



HYDROGEOLOGIC DATA:

- Alluvial formation
- 7 borings to ~140 feet
- 3,500-foot alignment
- Soil logged every 5 feet

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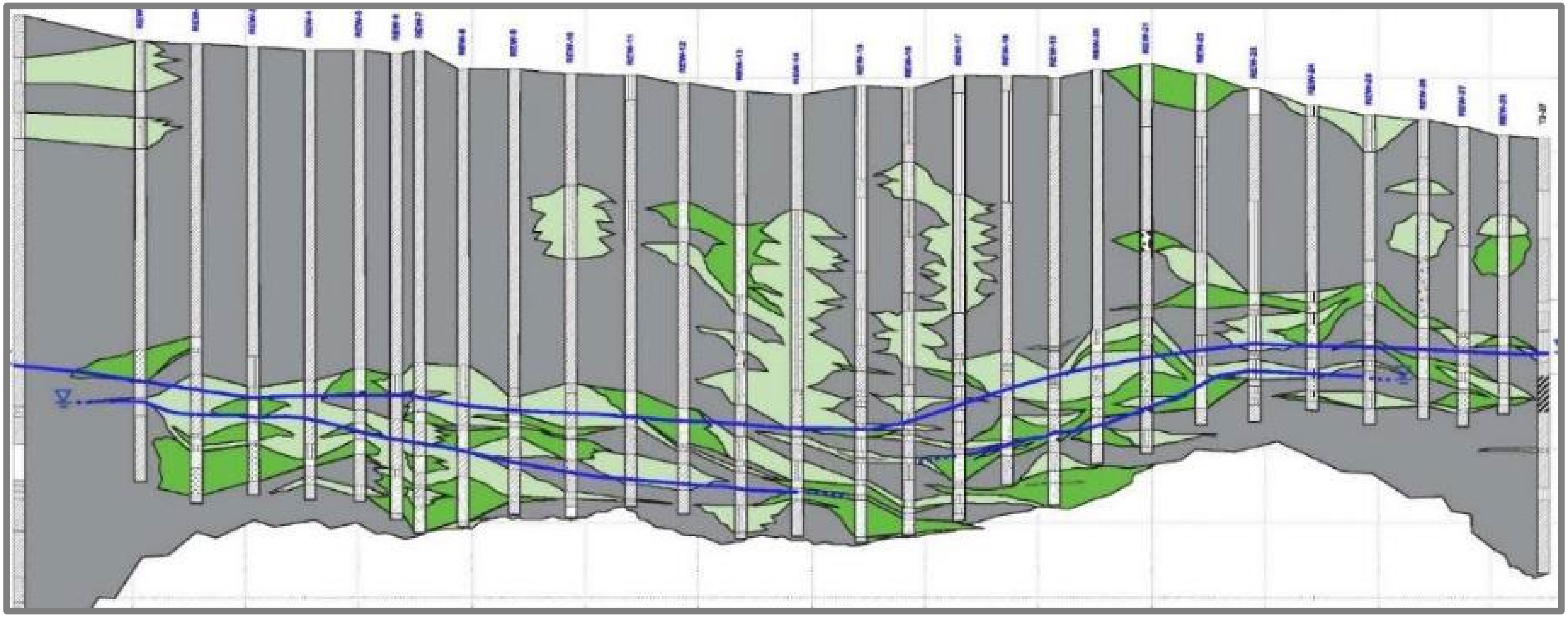
The Impact of More Data



MORE DATA

- ~40 borings over the 3,500-foot alignment
- Soil logged every 5 feet in vadose zone
- Soil logged continuously below first saturated zone
- Increasing complexity revealed

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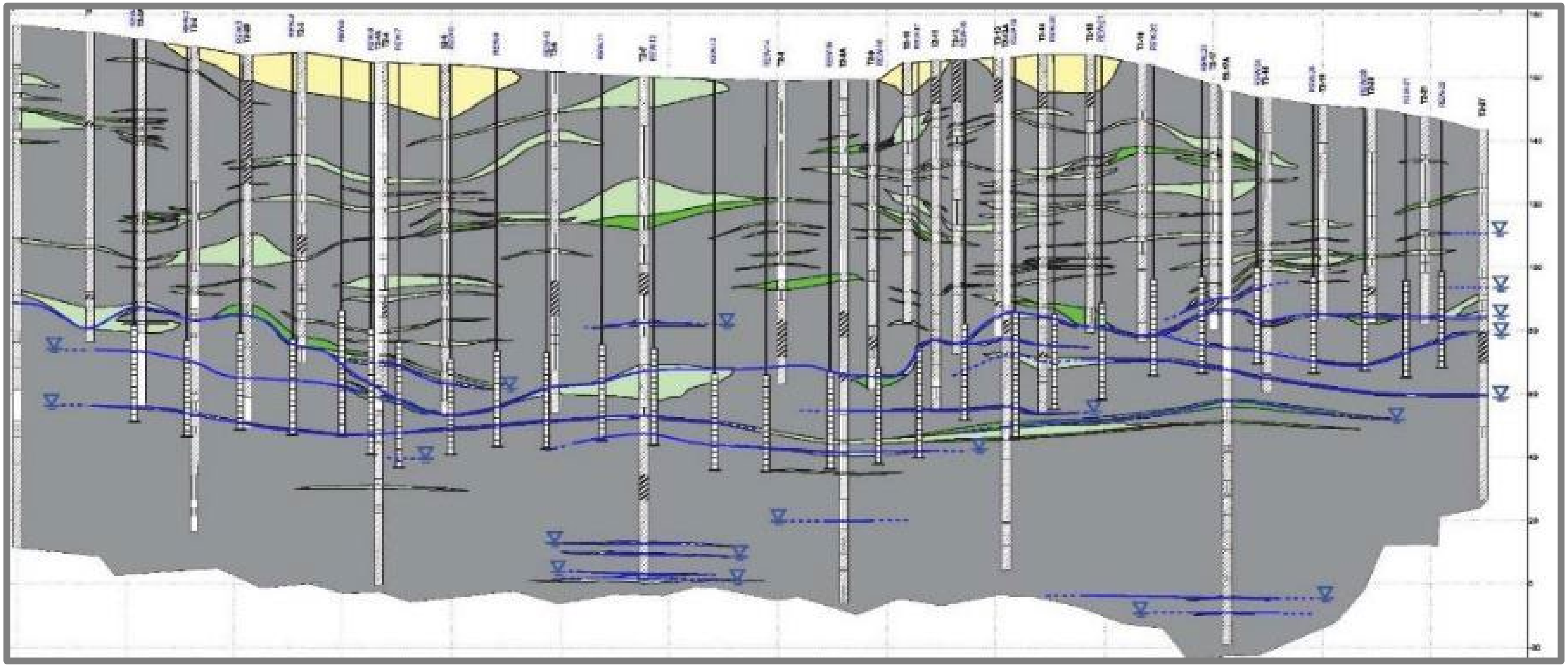
The Impact of More (and More) Data



EVEN MORE DATA

- ~60 borings over the 3,500-foot alignment
- Soil logged continuously
- Cross-section evolves – even more complex

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Remedial Design Characterization (RDC)

WHAT DO WE NEED TO KNOW?

Geology

properties that define flow regimes

Hydrogeology

properties that influence flow and transport

Geochemistry

electron acceptors, competitors, metal mobilization

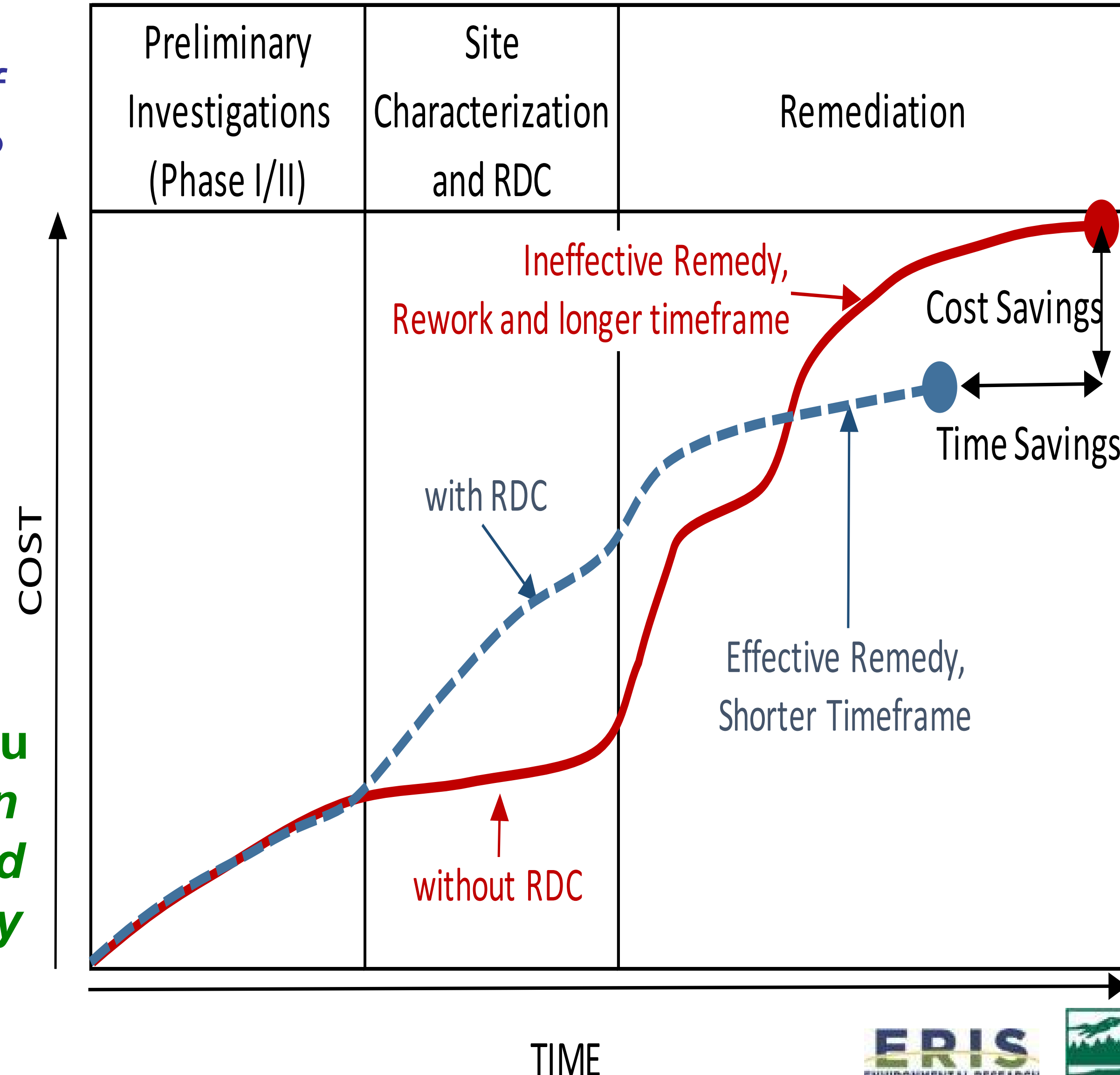
Microbiology

degradation potential

RDC - Why Do It? (Redux)

- What is the value of investigation (VOI)? Figure 2-1
- Why spend more money on characterization, when you could be spending it on cleanup?

<u>Remember</u>: when in situ remedies fail, it is often due to a lack of detailed data or an insufficiently developed CSM



ITRC OIS-ISRP-1 Figure 2-1

Value of Investigation (VOI) Case Study

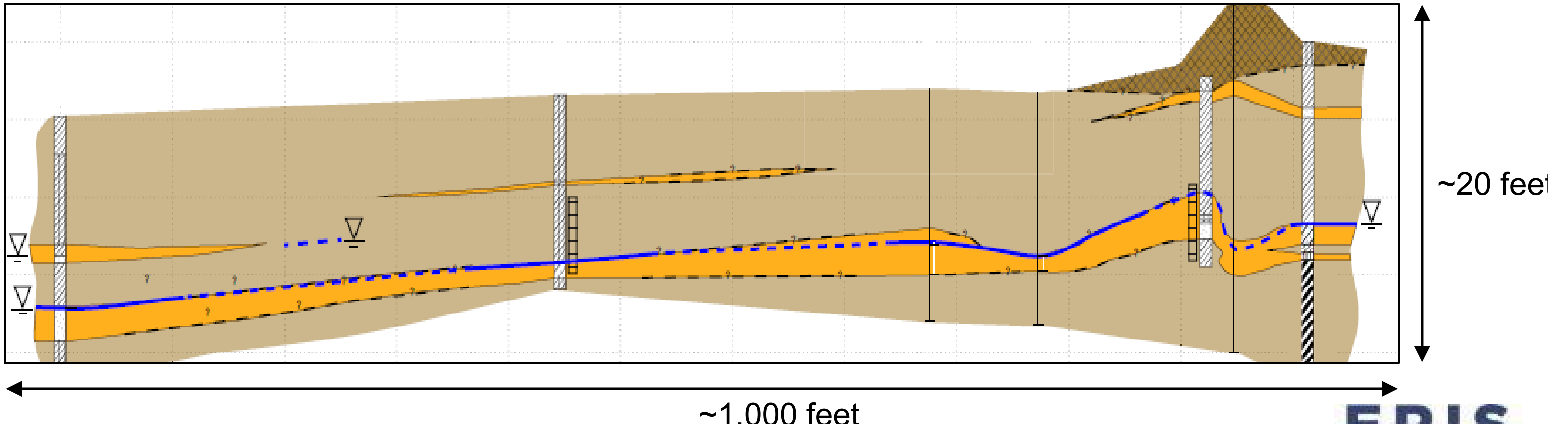
Case Study

The Setting:

- 20-acre site in California Central Valley
- VOC impacts to soils and groundwater
- Geology - floodplain deposits
- TTZ - sand lens, several feet thick approximately 15 feet below grade

Initial Remedy Attempt:

- Tight redevelopment timeframe
- Enhanced In Situ Bioremediation implemented using sodium lactate



Value of Investigation (VOI) Case Study

The Good

- Geology well characterized
- Injections properly performed within the sand interval

The Bad

☹ Hydraulic conductivity not evaluated
☹ Injection test not performed
☹ Geochemical parameters not used to assess EISB viability
☹ No treatability testing
☹ Choice of substrate and dosing “based “similar sites”
☹ Microbial studies not performed
☹ Upgradient sources not assessed or removed

Value of Investigation (VOI) Case Study

The Ugly Outcome

- ☹ No reductions in groundwater contamination concentrations
- ☹ Site redevelopment was delayed

Site had to be re-characterized (RDC):

- ✓ Better definition of source areas
- ✓ Better plume definition
- ✓ Aquifer testing to estimate K and ROI
- ✓ Microbial testing
- ✓ Treatability studies to assess various substrates and specify dosing
- ✓ Upgradient sources removed

Poll Question

VOI Case Study
Cost Outcomes, Table 2-1

Case Study

	Item	Costs		Years	
		VOI Case Study	Hypothetical, Using RDC	VOI Case Study	Hypothetical, Using RDC
	Initial Site Characterization	$150,000	$150,000	2	2
	Upfront RDC (hypothetical)	$0	$160,000	0	1
Failed Remedy	EISB Implementation	$300,000	$0	1	0
	EISB Monitoring	$80,000	$0	2	0
VS *Re-work (RDC & Remedy)*	RDC (as part of Rework)	$160,000	$0	1	0
	Remedy Implementation	$200,000	$200,000	1	1
	Monitoring and Closure	$70,000	$70,000	1	1
	Totals	**$960,000**	**$580,000**	**8**	**5**
	Cost Savings and Time Saved with RDC	**$380,000**		**3**	

ITRC OIS-ISRP-1 Table 2-1

What Do We Need To Know? "THE TABLE" (2-2)

Parameters	In Situ Approach		Remediation Phase/Step		
	Abiotic	Biotic	Alternatives Screening	Remedial Design	Performance Monitoring
Physical Properties					
Provenance and Mineralogy	M	M	HIGH	MEDIUM	LOW
Stratigraphy	M	M	MEDIUM	HIGH	LOW
Degree of Weathering of Geologic Formation	M	M	MEDIUM	HIGH	LOW
Fracture Representative Aperture and Length	M	M	MEDIUM	HIGH	LOW
Fracture Connectivity / Rock Quality Designation	M	M	MEDIUM	HIGH	LOW
Fracture Orientation	M	M	MEDIUM	HIGH	LOW
Grain Size Distribution	M	M	LOW	HIGH	LOW
Bulk Density	M	M	LOW	HIGH	LOW
Fraction of Organic Carbon	M	M	MEDIUM	HIGH	LOW
Primary and Secondary Porosity	M	M	MEDIUM	HIGH	LOW
Flow Properties					
Flow Regime	M	M	HIGH	HIGH	HIGH
Groundwater Occurrence and Variability	M	M	HIGH	HIGH	HIGH
Hydraulic Conductivity	M	M	HIGH	HIGH	LOW
Degree of Heterogeneity	M	M	HIGH	HIGH	LOW
Anisotropic Orientation	M	M	HIGH	HIGH	LOW
Effective Porosity	M	M	HIGH	HIGH	LOW
Velocity/Flux	M	M	HIGH	HIGH	HIGH
Aqueous Geochemistry					
pH	M	M	HIGH	HIGH	HIGH
Temperature	M	M	HIGH	HIGH	HIGH
Alkalinity	M	M	HIGH	HIGH	HIGH
Conductivity, Salinity, and Total Dissolved Solids (TDS)	M	M	MEDIUM	MEDIUM	MEDIUM
Oxidation Reduction Potential (ORP)	M	M	HIGH	HIGH	HIGH
Dissolved Oxygen (DO)	M	M	HIGH	HIGH	HIGH
Nitrate (NO_3^-)	L	M	HIGH	HIGH	MEDIUM
Nitrite (NO_2^-)	L	M	LOW	LOW	MEDIUM
Manganese (Mn^{+4})	L	M	LOW	MEDIUM	MEDIUM
Manganese (Mn^{+2})	L	M	MEDIUM	MEDIUM	MEDIUM
Ferric Iron (Fe^{+3})	M	M	LOW	HIGH	HIGH
Ferrous Iron (Fe^{+2})	M	M	MEDIUM	HIGH	HIGH
Sulfate (SO_4^{2-})	M	M	HIGH	HIGH	HIGH
Sulfite (SO_3^{2-}), Sulfide (S^{2-})	M	M	LOW	MEDIUM	HIGH
Chloride (Cl^-)	L	M	MEDIUM	LOW	MEDIUM
COD (chemical oxygen demand)	L	L	LOW	LOW	LOW
SOD (soil oxidant demand)	M	L	MEDIUM	HIGH	LOW
TOD (total oxidant demand)	M	L	MEDIUM	HIGH	LOW
NOI (natural oxidant interaction)	M	L	MEDIUM	HIGH	LOW
TOC (total organic carbon)	M	M	MEDIUM	HIGH	MEDIUM
Anions, cations	*Individually listed*				
Arsenite (As^{+3})	M	L	LOW	MEDIUM	HIGH
Arsenate (As^{+5})	M	M	MEDIUM	HIGH	MEDIUM
Chromium (Cr^{+3})	M	M	MEDIUM	HIGH	MEDIUM
Chromium (Cr^{+6})	M	L	LOW	MEDIUM	HIGH
Other Heavy Metals (e.g., lead, copper, selenium)	L	L	LOW	MEDIUM	MEDIUM
Microbiology					
Stable Isotope Probing	L	M	LOW	MEDIUM	MEDIUM
PLFA (Phospholipid Fatty Acids)	L	M	LOW	MEDIUM	MEDIUM
Quantitative polymerase chain reaction (qPCR)	L	M	LOW	MEDIUM	MEDIUM
Degradation Potential					
CSIA (Compound Specific Isotope Analysis)	M	M	LOW	MEDIUM	MEDIUM
Dissolved Hydrocarbon Gases (Methane, Ethane, Ethene, Acetylene, Propane, Propene)	M	M	LOW	LOW	MEDIUM
Carbon Dioxide CO2	L	M	LOW	LOW	MEDIUM
Magnetic Susceptibility	M	L	MEDIUM	LOW	LOW

Legend	
More applicable	M
Less applicable / not applicable	L
Relative importance of data at the remediation phase indicated	LOW MEDIUM HIGH

Physical Properties

Flow Properties

Aqueous Geochemistry

Microbiology

Degradation Potential

ITRC OIS-ISRP-1 Table 2-2

and When? (Table 2-2)

Parameters	In Situ Approach		Remediation Phase/Step		
	Abiotic	Biotic	Alternatives Screening	Remedial Design	Performance Monitoring
Physical Properties					
Provenance and Mineralogy	M	M	HIGH	MEDIUM	LOW
Stratigraphy	M	M	MEDIUM	HIGH	LOW
Degree of Weathering of Geologic Formation	M	M	MEDIUM	HIGH	LOW
Fracture Representative Aperture and Length	M	M	MEDIUM	HIGH	LOW
Fracture Connectivity / Rock Quality Designation	M	M	MEDIUM	HIGH	LOW
Fracture Orientation	M	M	MEDIUM	HIGH	LOW
Grain Size Distribution	M	M	LOW	HIGH	LOW
Bulk Density	M	M	LOW	HIGH	LOW
Fraction of Organic Carbon	M	M	MEDIUM	HIGH	LOW
Primary and Secondary Porosity	M	M	MEDIUM	HIGH	LOW
Flow Properties					
Flow Regime	M	M	HIGH	HIGH	HIGH
Groundwater Occurrence and Variability	M	M	HIGH	HIGH	HIGH
Hydraulic Conductivity	M	M	HIGH	HIGH	LOW
Degree of Heterogeneity	M	M	HIGH	HIGH	LOW
Anisotropic Orientation	M	M	HIGH	HIGH	LOW
Effective Porosity	M	M	HIGH	HIGH	LOW
Velocity/Flux	M	M	HIGH	HIGH	HIGH
Aqueous Geochemistry					
pH	M	M	HIGH	HIGH	HIGH
Temperature	M	M	HIGH	HIGH	HIGH
Alkalinity	M	M	HIGH	HIGH	HIGH
Conductivity, Salinity, and Total Dissolved Solids (TDS)	M	M	MEDIUM	MEDIUM	MEDIUM
Oxidation Reduction Potential (ORP)	M	M	HIGH	HIGH	HIGH
Dissolved Oxygen (DO)	M	M	HIGH	HIGH	HIGH
Nitrate (NO_3^-)	L	M	HIGH	HIGH	MEDIUM
Nitrite (NO_2^-)	L	M	LOW	LOW	MEDIUM
Manganese (Mn^{+4})	L	M	LOW	MEDIUM	MEDIUM
Manganese (Mn^{+2})	L	M	MEDIUM	MEDIUM	MEDIUM
Ferric Iron (Fe^{+3})	M	M	LOW	HIGH	HIGH
Ferrous Iron (Fe^{+2})	M	M	MEDIUM	HIGH	HIGH
Sulfate (SO_4^{2-})	M	M	HIGH	HIGH	HIGH
Sulfite (SO_3^{2-}), Sulfide (S^{2-})	M	M	LOW	MEDIUM	HIGH
Chloride (Cl^-)	L	M	MEDIUM	LOW	MEDIUM
COD (chemical oxygen demand)	L	L	LOW	LOW	LOW
SOD (soil oxidant demand)	M	L	MEDIUM	HIGH	LOW
TOD (total oxidant demand)	M	L	MEDIUM	HIGH	LOW
NOI (natural oxidant interaction)	M	L	MEDIUM	HIGH	LOW
TOC (total organic carbon)	M	M	MEDIUM	HIGH	MEDIUM
Anions, cations	*Individually listed*				
Arsenite (As^{+3})	M	L	LOW	MEDIUM	HIGH
Arsenate (As^{+5})	M	M	MEDIUM	HIGH	MEDIUM
Chromium (Cr^{+3})	M	M	MEDIUM	HIGH	MEDIUM
Chromium (Cr^{+6})	M	L	LOW	MEDIUM	HIGH
Other Heavy Metals (e.g., lead, copper, selenium)	L	L	LOW	MEDIUM	MEDIUM
Microbiology					
Stable Isotope Probing	L	M	LOW	MEDIUM	MEDIUM
PLFA (Phospholipid Fatty Acids)	L	M	LOW	MEDIUM	MEDIUM
Quantitative polymerase chain reaction (qPCR)	L	M	LOW	MEDIUM	MEDIUM
Degradation Potential					
CSIA (Compound Specific Isotope Analysis)	M	M	LOW	MEDIUM	MEDIUM
Dissolved Hydrocarbon Gases (Methane, Ethane, Ethene, Acetylene, Propane, Propene)	M	M	LOW	LOW	MEDIUM
Carbon Dioxide CO2	L	M	LOW	LOW	MEDIUM
Magnetic Susceptibility	M	L	MEDIUM	LOW	LOW

Legend	
More applicable	M
Less applicable / not applicable	L
	LOW
Relative importance of data at the remediation phase indicated	MEDIUM
	HIGH

Remediation Phase/Step

Alternatives Screening | Remedial Design | Performance Monitoring

In Situ Approach

Abiotic | Biotic

Legend	
More applicable	M
Less applicable / not applicable	L
	LOW
Relative importance of data at the remediation phase indicated	MEDIUM
	HIGH

ITRC OIS-ISRP-1 Table 2-2

Physical Properties (Table 2-2)

Parameters	In Situ Approach		Remediation Phase/Step		
	Abiotic	Biotic	Alternatives Screening	Remedial Design	Performance Monitoring
Physical Properties					
Provenance and Mineralogy	M	M	HIGH	MEDIUM	LOW
Stratigraphy	M	M	MEDIUM	HIGH	LOW
Degree of Weathering of Geologic Formation	M	M	MEDIUM	HIGH	LOW
Fracture Representative Aperture and Length	M	M	MEDIUM	HIGH	LOW
Fracture Connectivity / Rock Quality Designation	M	M	MEDIUM	HIGH	LOW
Fracture Orientation	M	M	MEDIUM	HIGH	LOW
Grain Size Distribution	M	M	LOW	HIGH	LOW
Bulk Density	M	M	LOW	HIGH	LOW
Fraction of Organic Carbon	M	M	MEDIUM	HIGH	LOW
Primary and Secondary Porosity	M	M	MEDIUM	HIGH	LOW

THE “HOVER” TABLE (2-3)

Provenance and mineralogy of a rock or soil matrix are the properties of its physicochemical formation - geologic structure, chemical composition, distribution, and occurrence. They are the governing factors for the physical, flow, and geochemical properties, discussed in Table 2-2, that are necessary to understand and quantify in order to design an optimal in-situ approach.

				Phase/Step	
				dial gn	Performance Monitoring
Physical Properties					
Provenance and Mineralogy	M	M	HIGH	MEDIUM	LOW
Stratigraphy	M	M	MEDIUM	HIGH	LOW
Degree of Weathering of Geologic Formation	M	M	MEDIUM	HIGH	LOW
Fracture Representative Aperture and Length	M	M	MEDIUM	HIGH	LOW
Fracture Connectivity / Rock Quality Designation	M	M	MEDIUM	HIGH	LOW
Fracture Orientation	M	M	MEDIUM	HIGH	LOW
Grain Size Distribution	M	M	LOW	HIGH	LOW
Bulk Density	M	M	LOW	HIGH	LOW
Fraction of Organic Carbon	M	M	MEDIUM	HIGH	LOW
Primary and Secondary Porosity	M	M	MEDIUM	HIGH	LOW

ITRC OIS-ISRP-1 Table 2-2

Physical Properties

Stratigraphy describes the geologic layering in a formation. Formations with more layers (e.g., gravels, sands, silts) and complex "fingering" of high permeability units within low permeability media will require detailed characterization so that amendments can be emplaced properly.

Stratigraphy

Parameters	In Situ Approach		Remediation Phase/Step		
	[illegible]	[illegible]	Alternatives [illegible]	Remedial [illegible]sign	Performance Monitoring
Pr[illegible]logy	M	M	HIGH	MEDIUM	LOW
[illegible]	M	M	MEDIUM	HIGH	LOW
Degree of Weathering of Geologic Formation	M	M	MEDIUM	HIGH	LOW
Fracture Representative Aperture and Length	M	M	MEDIUM	HIGH	LOW
Fracture Connectivity / Rock Quality Designation	M	M	MEDIUM	HIGH	LOW
Fracture Orientation	M	M	MEDIUM	HIGH	LOW
Grain Size Distribution	M	M	LOW	HIGH	LOW
Bulk Density	M	M	LOW	HIGH	LOW
Fraction of Organic Carbon	M	M	MEDIUM	HIGH	LOW
Primary and Secondary Porosity	M	M	MEDIUM	HIGH	LOW

ITRC OIS-ISRP-1 Table 2-2

Flow Properties

Parameters	In Situ Approach		Remediation Phase/Step		
			...ves ...ng	Remedial Design	Performance Monitoring
				HIGH	HIGH
				HIGH	HIGH
			HIGH	HIGH	LOW
Deg...	M	M	HIGH	HIGH	LOW
Anisotrop...	M	M	HIGH	HIGH	LOW
Effective Porosity	M	M	HIGH	HIGH	LOW
Velocity/Flux	M	M	HIGH	HIGH	HIGH

Heterogeneity refers to the variability in soil types within an aquifer (gravels, sands, silts, clays, bedrock/fractures). Heterogeneity is related to a unit's provenance and conditions of formation, for example, alluvial units are more heterogeneous than fluvial units. Understanding and mapping the more permeable zones is a critical step in characterization, because these zones are more likely to be saturated with groundwater and contain contaminants. The less permeable units are more likely to have sorbed contaminants that will be slowly released over time via back-diffusion.

Heterogeneity

ITRC OIS-ISRP-1 Table 2-2

Flow Properties

Parameters	In Situ Approach		Remediation Phase/Step		
	Abiotic	Biotic	Alternatives Screening	Remedial Design	Performance Monitoring
Flow Properties					
[illegible]	[illegible]	[illegible]	[illegible]	HIGH	HIGH
[illegible]	[illegible]	[illegible]	[illegible]	HIGH	HIGH
[illegible]	[illegible]	[illegible]	[illegible]	HIGH	LOW
Deg[illegible]	M	M	HIGH	HIGH	LOW
[illegible]	M	M	HIGH	HIGH	LOW
Effective [illegible]	M	M	HIGH	HIGH	LOW
Velocity/Flux	M	M	HIGH	HIGH	HIGH

Anisotropy refers to the directionality of physical aquifer properties. Layered units are generally anisotropic, with continuity of properties and flow in the lateral direction, limited in the vertical direction by low permeability layers.

Anisotropy

ITRC OIS-ISRP-1 Table 2-2

Aqueous Geochemistry

ITRC OIS-ISRP-1 Table 2-2

Parameters	In Situ Approach		Remediation Phase/Step		
	Abiotic	Biotic	Alternatives Screening	Remedial Design	Performance Monitoring
Aqueous Geochemistry					
					HIGH
					HIGH
					HIGH
					MEDIUM
					HIGH
					HIGH
					MEDIUM
					MEDIUM
					MEDIUM
					MEDIUM
					HIGH
	M	M	MEDIUM	HIGH	HIGH
Sulfate (SO_4^{2-})	M	M	HIGH	HIGH	HIGH
	M	M	LOW	MEDIUM	HIGH
Chloride (Cl^-)	L	M	MEDIUM	LOW	MEDIUM
COD (chemical oxygen demand)	L	L	LOW	LOW	LOW
SOD (soil oxidant demand)	M	L	MEDIUM	HIGH	LOW
TOD (total oxidant demand)	M	L	MEDIUM	HIGH	LOW
NOI (natural oxidant interaction)	M	L	MEDIUM	HIGH	LOW
TOC (total organic carbon)	M	M	MEDIUM	HIGH	MEDIUM
Anions, cations	***Individually listed***				
Arsenite (As^{+3})	M	L	LOW	MEDIUM	HIGH
Arsenate (As^{+5})	M	M	MEDIUM	HIGH	MEDIUM
Chromium (Cr^{+3})	M	M	MEDIUM	HIGH	MEDIUM
Chromium (Cr^{+6})	M	L	LOW	MEDIUM	HIGH
Other Heavy Metals (e.g., lead, copper, selenium)	L	L	LOW	MEDIUM	MEDIUM

Sulfate is naturally present in many ground waters as a product of geologic formations and their naturally occurring minerals and is often elevated in saline waters. It can also be a manufacturing or agricultural contaminant and a byproduct of persulfate used in some ISCO treatments. Sulfate needs to be carefully considered when selecting a remedial approach, as it can be beneficial and impeding, depending on the technology selected. Natural or pre-remediation sulfate at elevated concentrations can inhibit reductive processes such as reductive dechlorination, because sulfate, at elevated concentrations, is a powerful competitor for electrons. Typically, approximately 400 mg/L or greater sulfate at pre-remediation conditions can be a potential cause for concern (for reductive dechlorination) and special consideration for dosing. On the other hand, sulfate can react in situ with iron to form iron sulfides, which can provide long-term anaerobic chemical reduction. Sulfate reduction is yet another process, where sulfate is used as the primary electron acceptor, that can degrade specific contaminants (i.e., petroleum hydrocarbons).

The Redox Ladder

Poll Question

Terminal Electron Acceptors	→	Associated Metabolic Byproducts
Oxygen (O_2)	Oxidizing	Water (H_2O)
Nitrate (NO_3^-)		Nitrite (NO_2^{-1}), Nitrogen (N_2)
Tetrachloroethene (PCE)		Trichloroethene (TCE), Chloride (Cl^-)
Manganic Manganese (Mn^{4+})		Manganous Manganese (Mn^{2+})
Ferric Iron (Fe^{3+})	Reducing	Ferrous Iron (Fe^{2+})
Trichloroethene (TCE)		cis- and trans- Dichloroethene (cis-, trans- DCE)
Vinyl Chloride (VC)		Ethene (C_2H_4), Chloride (Cl^-)
cis- and trans- Dichloroethene (cis-, trans- DCE)		VC, Chloride (Cl^-)
Sulfate (SO_4^{2-})		Sulfite (SO_3^{2-}) and Sulfide (S^{2-})
Carbon Dioxide (CO_2)		Methane (CH_4)

ITRC OIS-ISRP-1 Figure 2-2. Electron acceptors and products in order of reaction preference in progressively reducing groundwater conditions. Select contaminants are included for reference.

Aqueous Geochemistry

Poll Question

Parameters	In Situ Approach		Remediation Phase/Step		
	Abiotic	Biotic	Alternatives Screening	Remedial Design	Performance Monitoring
Aqueous Geochemistry					
pH	M	M	HIGH	HIGH	HIGH
Temperature	M	M	HIGH	HIGH	HIGH
Alkalinity	M	M	HIGH	HIGH	HIGH
Conductivity, Salinity, and Total Dissolved Solids (TDS)	M	M	MEDIUM	MEDIUM	MEDIUM
Oxidation Reduction Potential (ORP)	M	M	HIGH	HIGH	HIGH
Dissolved Oxygen (DO)	M	M	HIGH	HIGH	HIGH
Sulfit	M	M	LOW	MEDIUM	HIGH
Chloride Cl^-	L	M	MEDIUM	LOW	MEDIUM
CO	L	L	LOW	LOW	LOW
SOD (soil oxidant demand)	M	L	MEDIUM	HIGH	LOW
TOD (total oxidant demand)	M	L	MEDIUM	HIGH	LOW
NOI (natural oxidant interaction)	M	L	MEDIUM	HIGH	LOW
TOC (total organic carbon)	M	M	MEDIUM	HIGH	MEDIUM
Anions, cations	*Individually listed*				
Arsenite (As^{+3})	M	L	LOW	MEDIUM	HIGH
Arsenate (As^{+5})	M	M	MEDIUM	HIGH	MEDIUM
Chromium (Cr^{+3})	M	M	MEDIUM	HIGH	MEDIUM
Chromium (Cr^{+6})	M	L	LOW	MEDIUM	HIGH
Other Heavy Metals (e.g., lead, copper, selenium)	L	L	LOW	MEDIUM	MEDIUM

As reductive dechlorination occurs chloride ions are released and the concentration of chloride may increase. However, naturally and anthropogenic chloride may be present in groundwater at concentrations high enough that this change could be difficult to detect or attribute solely to remediation of the chlorinated solvents. In high chloride environments, such as landfills and areas subject to seawater intrusion, chloride can cause toxicity to microbes, typically at concentrations in the thousands of mg/L.

ITRC OIS-ISRP-1 Table 2-2

Microbiology and Degradation Potential

Dissolved hydrocarbon gases are typical degradation products of reductive dechlorination of chlorinated ethenes (e.g., PCE), methanes (e.g., carbon tetrachloride), and propanes (e.g., 1,2-dichloropropane). Acetylene is thought to be primarily a byproduct of the abiotic reduction of chlorinated ethenes by reaction with ZVI or ferrous sulfide. The presence of these dissolved gases generally indicates that some complete reductive dechlorination is occurring. Methane can be produced from the contaminant(s), electron donor, other organics, or carbon dioxide. Methane is also the product of methanogenesis, that is, the reduction of carbon dioxide, and in that case is indicative of a significantly reducing environment. Natural gas contains many of these dissolved gases.

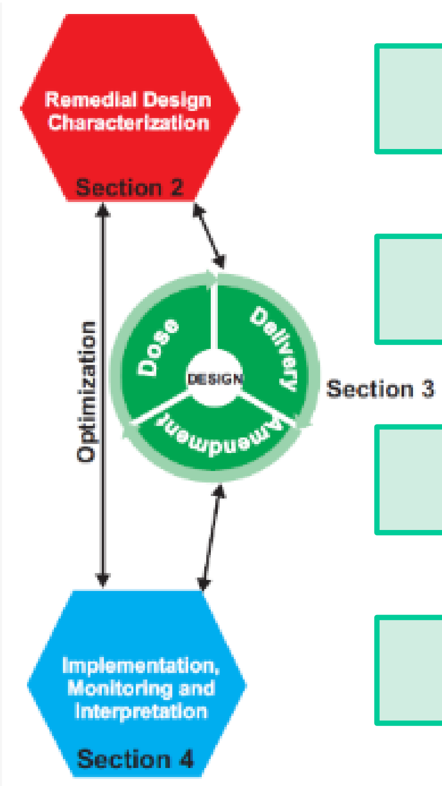
	In Situ Approach		Remediation Phase/Step		
					Performance Monitoring
					MEDIUM
					MEDIUM
					MEDIUM
CSIA (Compound Specific...	M	M	LOW	MEDIUM	MEDIUM
Dissolved hydrocarbon gases		M	LOW	LOW	MEDIUM
Carbon Dioxide CO2	L	M	LOW	LOW	MEDIUM
Magnetic Susceptibility	M	L	MEDIUM	LOW	LOW

ITRC OIS-ISRP-1 Table 2-2

Q&A Break

Follow ITRC:

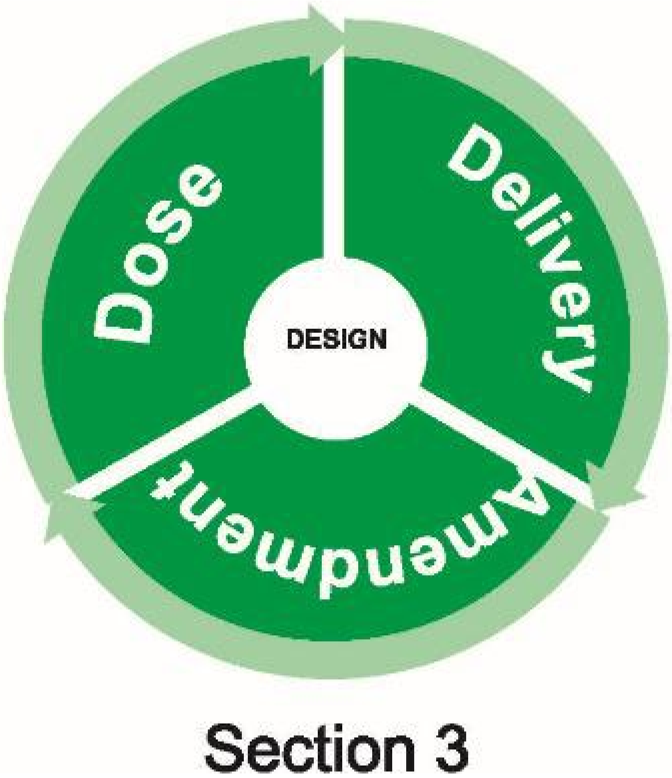
Presentation Road Map



- Optimizing Process
- Remedial Design Characterization
- **Design: Amendment, Dose & Delivery**
- Implementation, Monitoring & Interpretation
- Regulatory & Stakeholder Considerations

Learning Objective: Determine amendment, dosing and delivery options

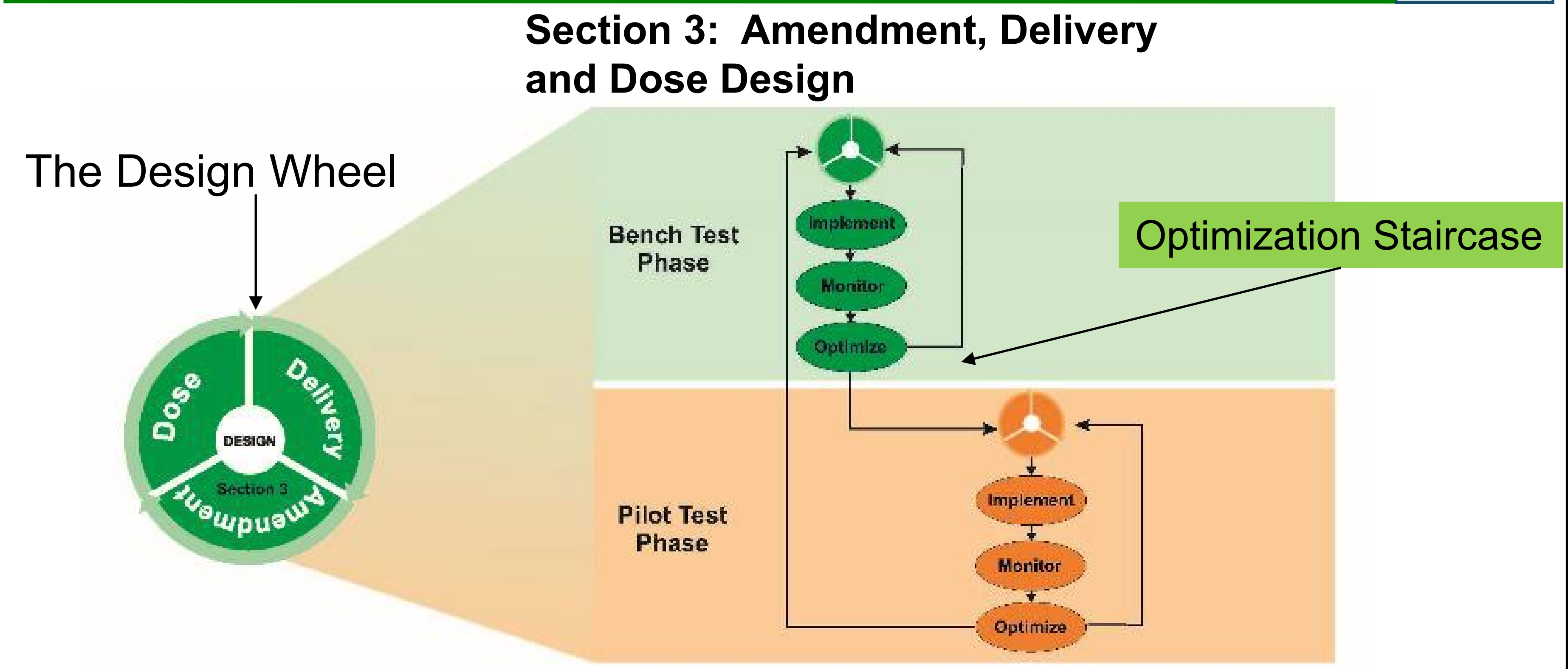
Amendment Delivery and Dose Design – The Design Wheel



- Involves consideration of the proposed amendment, delivery method and dose applied simultaneously throughout the in situ RDC design and implementation and monitoring process
- Any step in the sequence can be repeated as new information becomes available

ITRC OIS-ISRP-1 Modified from Figure 3-1

Iterative Nature of Design



- Refinement of design following selection of amendment and delivery strategy may involve various tests, all applying the dose, delivery and amendment design feedback;
  - Results of each test feeding refinements into a subsequent test

ITRC OIS-ISRP-1 Modified from Figure 3-1

Determine Target Treatment Zone

- Target Treatment Zone (TTZ)
  - Definition of TTZ often iterative
  - Considers collateral effects, performance, costs, etc.
  - May be revised as design is developed
- Key Considerations for defining TTZ
  - Cleanup objectives
  - Spatial and temporal relationship to other (combined) remedies
  - Uncontrolled amendment discharge
  - Geological, hydrogeological, and geochemical characteristics

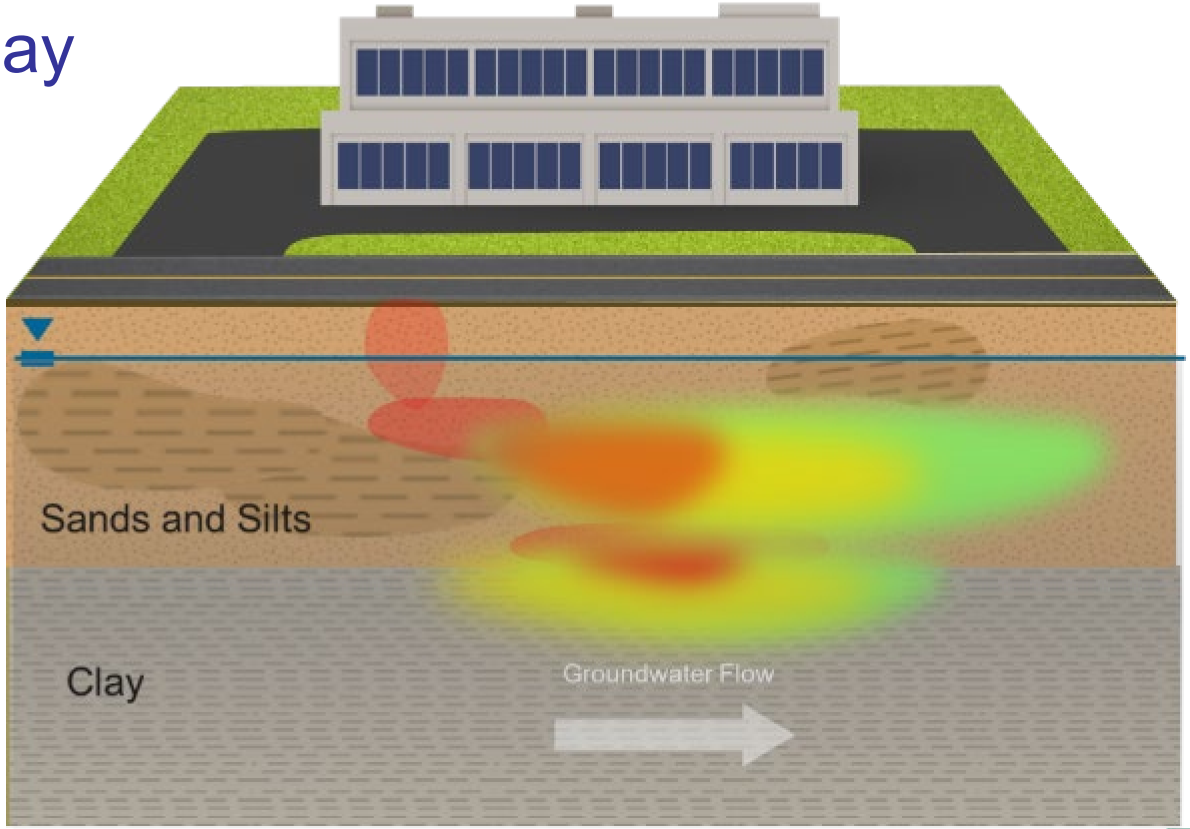
Design Support Elements

- Design elements to support remedial design are an extension of the CSM and RDC data
  - Number one source of failure for amendment injection is lack of adequately detailed characterization of TTZ and reliance on overly simplified CSM
- Design elements used to support design include:
  - Modeling and analytical tools
  - Laboratory bench testing, and
  - Field pilot tests

CSM – Contaminated Industrial Site

Case Study

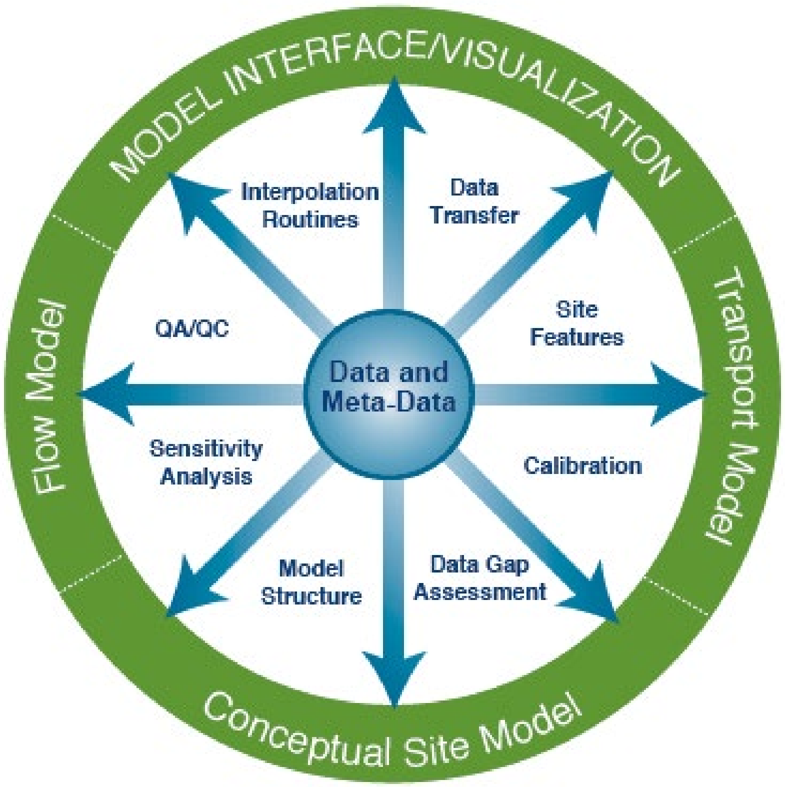
- Solvent release
- Sand and Silt
- Underlying Clay



Example Case Study – image prepared using Health Canada CSM Builder Tool 2015

Modeling and Analytical Tools

- Modeling and Analytical Tools
  - Parameter estimation,
  - Groundwater flow and transport
  - Geochemical reactions
- Can range from simple spreadsheet calculations to complex 3D models
- Some of the software is public domain and others are commercially available and require a license



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Laboratory Treatability Bench-scale Testing

- Determine type and dosing of amendments
- Provide data to support remediation technology or series of specific treatments
- Using site-specific materials, confirm that treatment is effective for a specific site's chemistry

See ITRC OIS-ISRP-1 Table 3-2 for a listing of bench testing objectives and considerations

Images used with permission of SiREM.

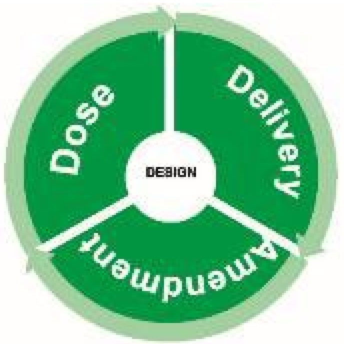
Consider Secondary Effects

- Secondary effects can occur over a wide range of time:
  - Transient shifts lasting hours or days
  - Long-term changes that may last years
- Consider potential secondary effects of the remedy design:
  - Evaluate and potentially mitigate secondary effects
  - Beginning with bench and field pilot tests

Example: The addition of sodium persulfate can affect the natural or anthropogenic chromium present in the soil or aquifer matrix, which may be oxidized to hexavalent chromium

Poll Question

- Have you used Bench Tests in your design for an in situ remedy?
  - Yes
  - No
- If you have used Bench Tests in your design for an in situ remedy did the results change your approach?
  - Yes
  - No

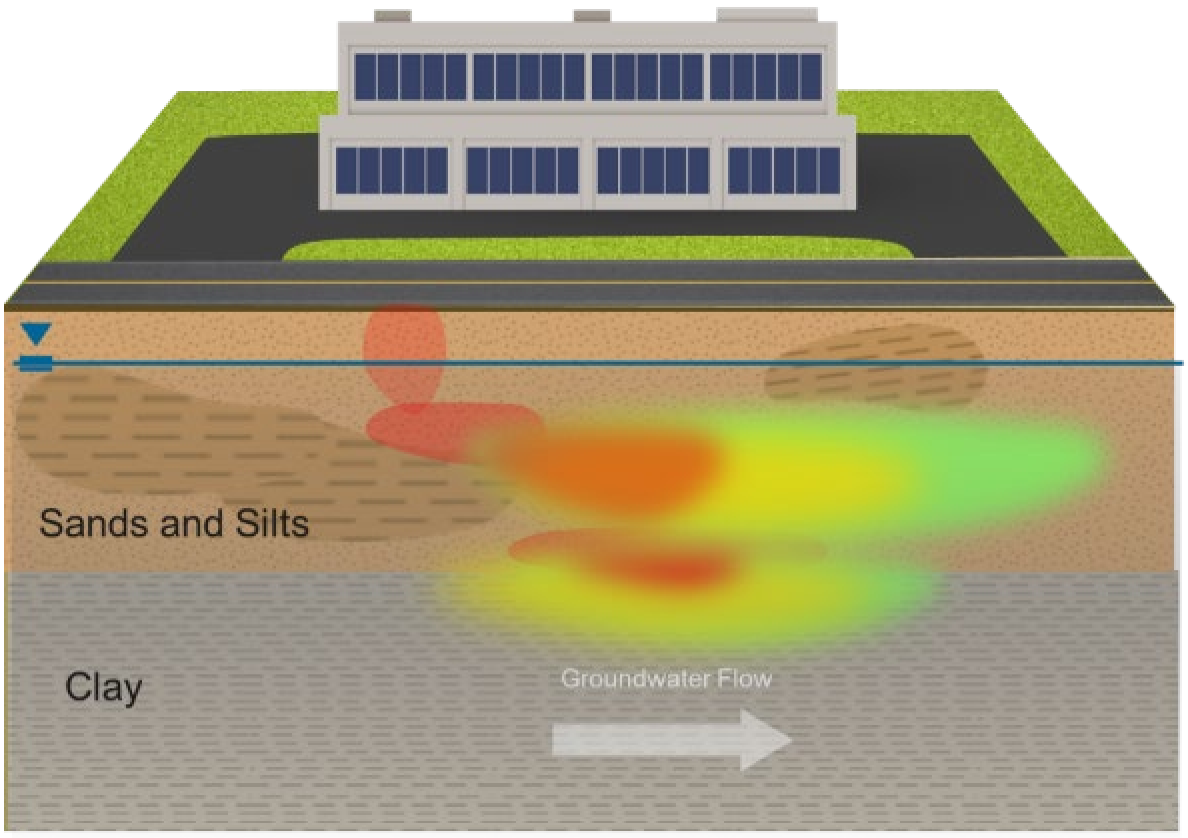


Section 3

Bench Tests Results

Case Study

- ISCO
  - Faster
  - More secondary effects
  - Higher oxidant demand than ideal
- Bio
  - Slower
  - Fewer secondary effects
  - Cheaper long term
  - Emulsified vegetable oil (EVO) as donor
  - Chosen option



Example Case Study – image prepared using Health Canada CSM Builder Tool 2015

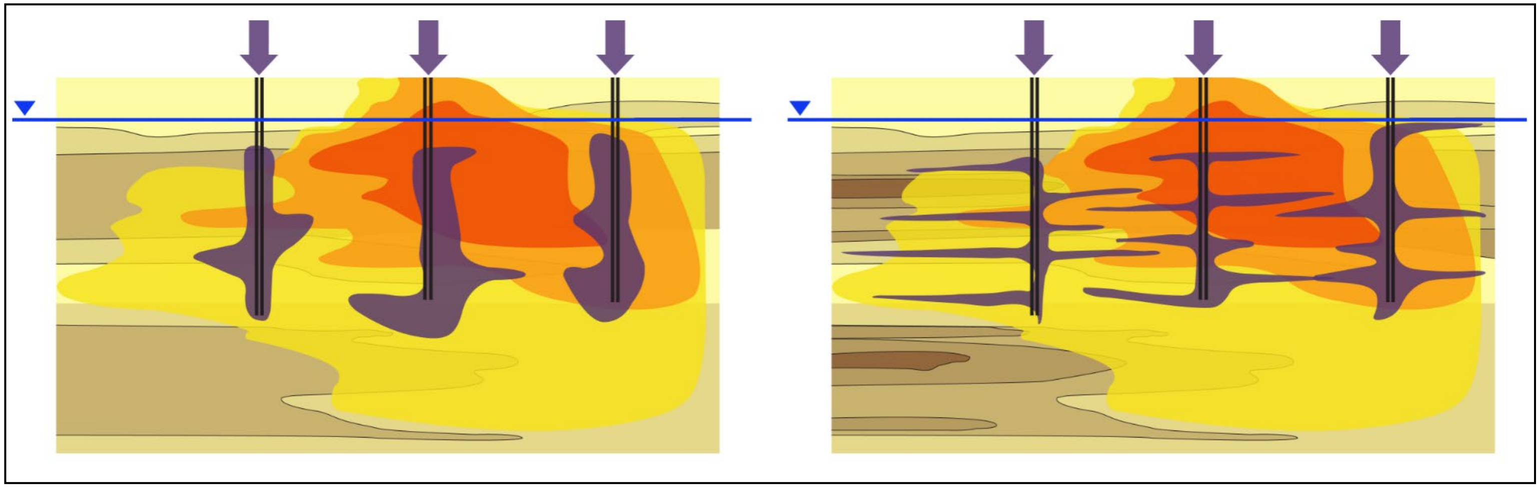
Field Pilot Tests Objectives

- Evaluate the impacts of heterogeneities on the performance of the remedial technology
- Evaluate remedy timeframe under real world conditions, combined effects of dilution, advective flow, diffusion, adverse chemical interactions, etc.
- Determine amendment distribution, ROI, injections rates and pressure, volume
- Evaluate secondary effects – metals mobilization, acid production
- Identify locations for sampling/performance evaluation

Used to test the assumptions incorporated into full-scale remedy design

Geologic Heterogeneity Affects Delivery

Geologic heterogeneity results in preferential flow through higher permeability zones. Unconsolidated (sedimentary) geologic deposits are stratified vertically.



The less heterogeneous case (left) results in delivery of amendment in the vicinity of each of the delivery points.

The more heterogeneous case (right) results in substantial variability in lateral influence versus depth.

ITRC OIS-ISRP-1 Figure 3-4
Graphic used by permission from Trihydro Corporation

Delivery Strategies - Distribution

Amendment distribution through a porous aquifer media is controlled by:

- The nature of the amendment
  - Soluble,
  - Semi-soluble, or
  - Insoluble
- Permeability of the formation
  - High permeability zones often receive the most fluids, allow broadest radial delivery
  - Back diffusion of contaminant mass storage in low permeability materials can be a significant source that contributes to plume longevity

Delivery Strategies - Pressure

- The pressure at which the fluid is applied to the formation
  - High-pressure emplacement technologies using hydraulic or pneumatic methods are required to deform the aquifer matrix and propagate seams (fractures) within the aquifer matrix
  - Soluble amendments like organic carbon substrates and chemical oxidants can be delivered under gravity flow-low pressure and via high pressure fracturing methods

Delivery Strategies

"Widely used = ●", "Site-specific = ▣", and "Not applicable = NA"

Hydrogeologic Classification System	Direct Push Injection (DPI) [D1]	Injection Through Wells & Boreholes [D2]	Electrokinetics This is injection through wells. [D3]	Solid Injection [D4]		Permeable Reactive Barriers (PRBs) [D7]
				Hydraulic Delivery Through Wells & Boreholes [D5]	Pneumatic Delivery Through Open Boreholes [D6]	
Gravels						
Cobbles						
Sandy Soils (Sm, Sc, Sp, Sw)						
Silty Soils (Ml, Mh)						
Clayey Soils (Cl, Ch, Oh)						
Weathered Bedrock						
Competent/Fractured Bedrock						
K ≤ 10^{-3} to 10^{-4} (Low Perm Soils)						
K ≥ 10^{-3} (High Perm Soils)						
Depth > Direct Push Capabilities						

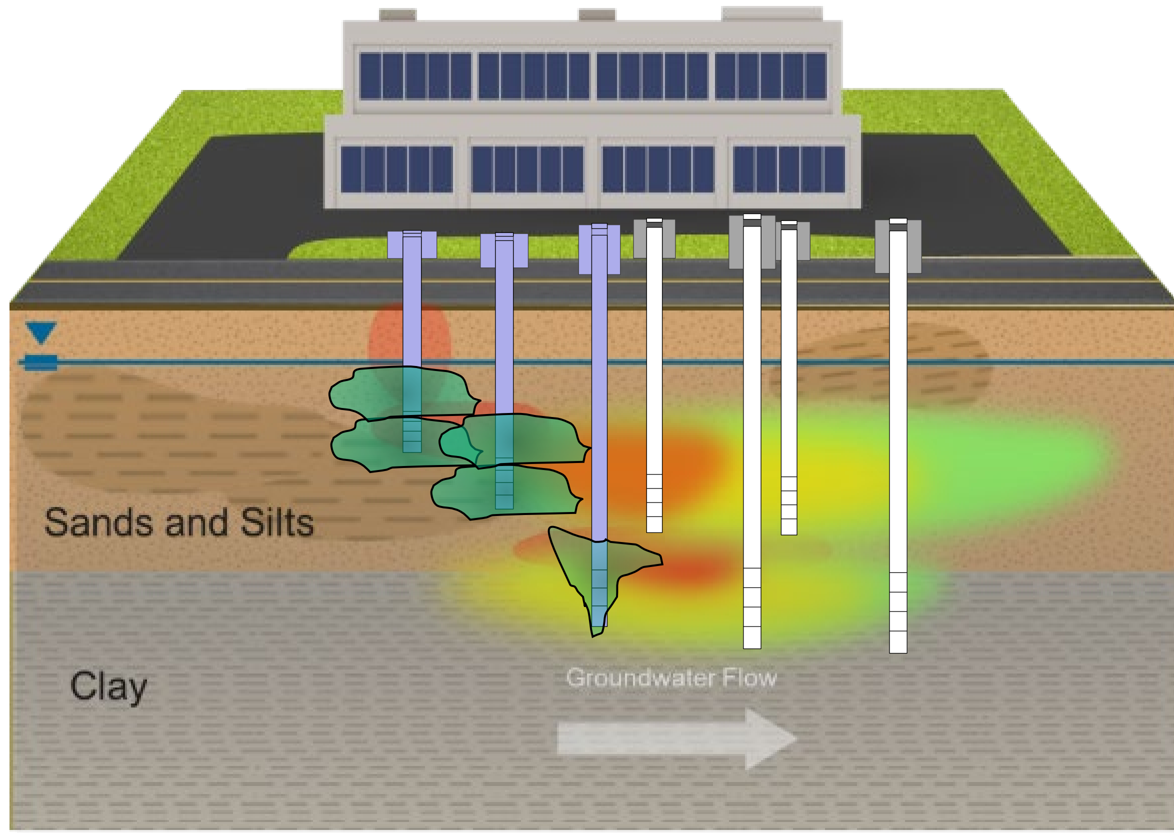
●	▣	●	●	●	●
●	▣	●	●	●	●
●	●	▣	●	●	▣
NA	●	NA	▣	▣	▣
●	▣	●	●	●	●
●	●	▣	▣	▣	●
NA	●	▣	▣	▣	▣

ITRC OIS-ISRP-1 Table 3-4

Pilot Test – Injection of Emulsified Vegetable Oil

Case Study

- Sand Layer
  - Good ROI at low injection pressures
  - Good distribution
- Clay Layer
  - High injection pressure
  - Evidence of short circuiting up into sand layer
  - Poor distribution
  - Uneven and very small ROI



Example Case Study – image prepared using Health Canada CSM Builder Tool 2015

Poll Question

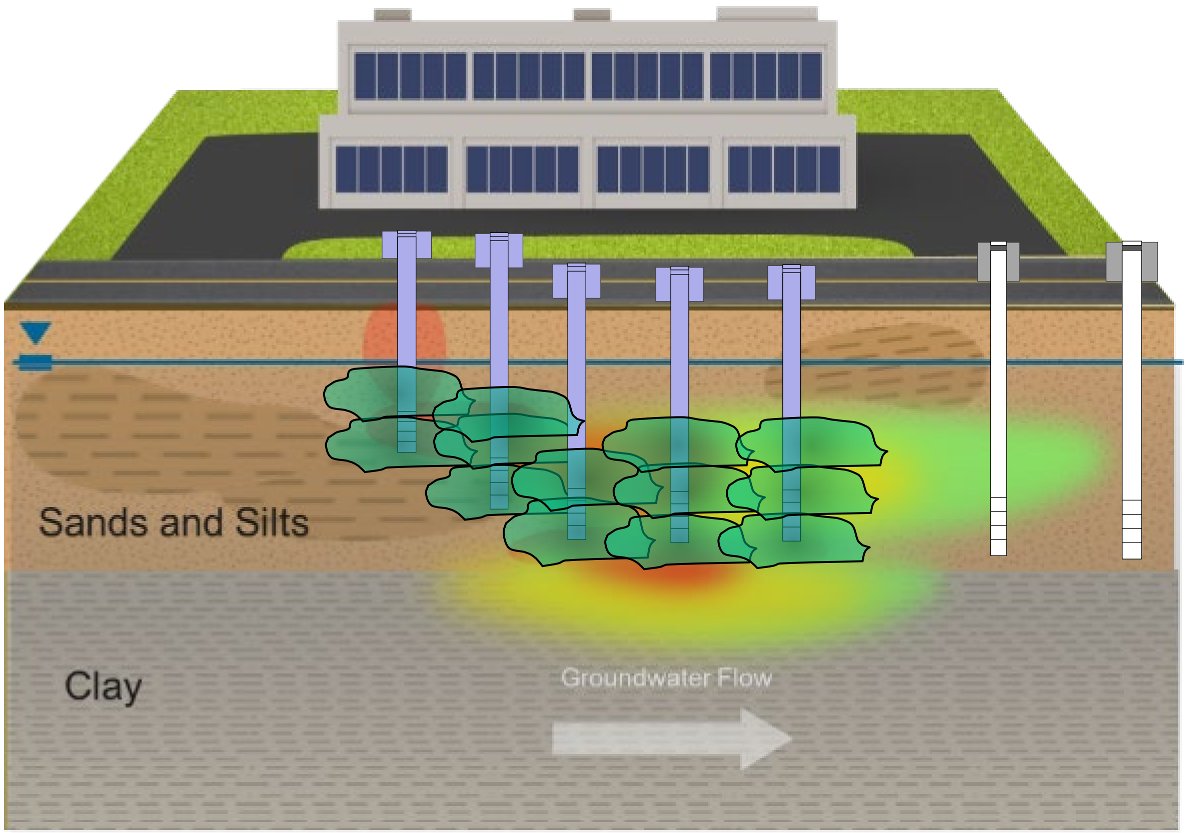
- Have you used Pilot Tests in your design for in situ remedy?
  - Yes
  - No
- If you have used Pilot Tests in your design for in situ remedy, did the results change your design?
  - Yes
  - No

Section 3

Full Scale – Injection of Emulsified Vegetable Oil (EVO)

Case Study

- Sand Layer
  - Direct Injection of EVO
- Clay Layer
  - Switch to Electro kinetic (EK) - Bio?
  - Go back to Bench Test



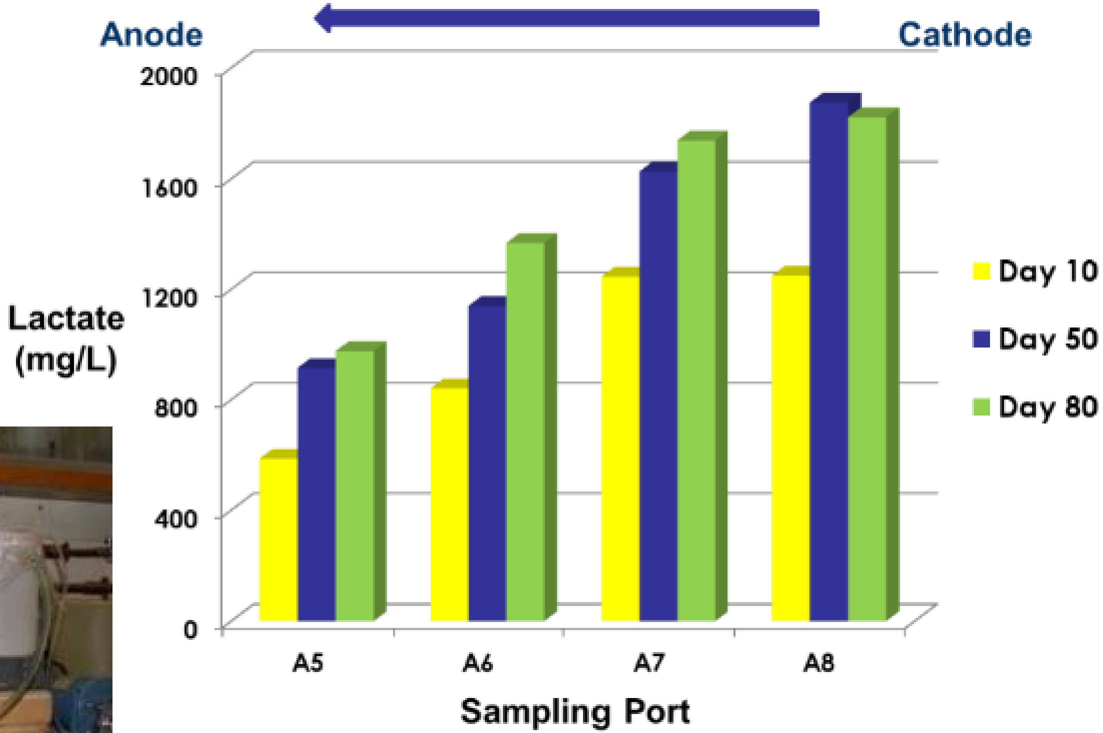
Example Case Study – image prepared using Health Canada CSM Builder Tool 2015

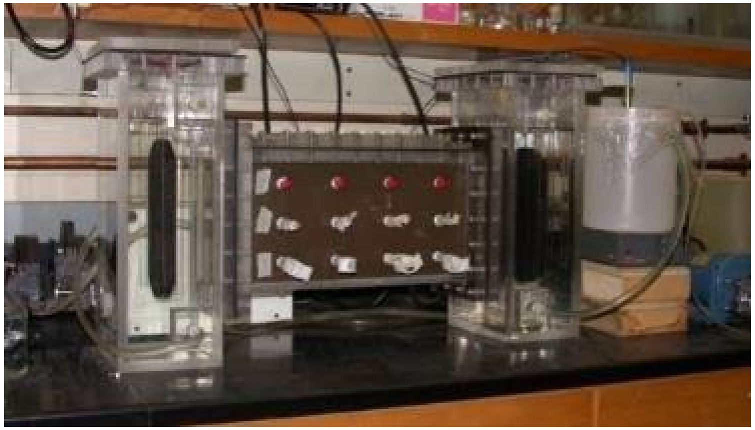
Return to Bench Testing

Case Study

- Clay Layer
  - Go back to Bench Test to make sure EK-Bio is an option

Lactate transport rate of 3.2 cm/day





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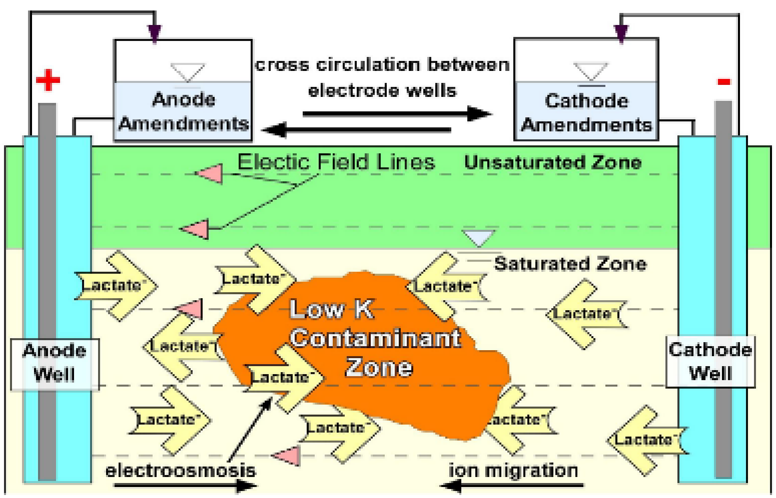
Return to Pilot Testing

- Clay Layer
  - Do pilot test to confirm design parameters and applicability
  - Dipole Test
  - Small Scale Test



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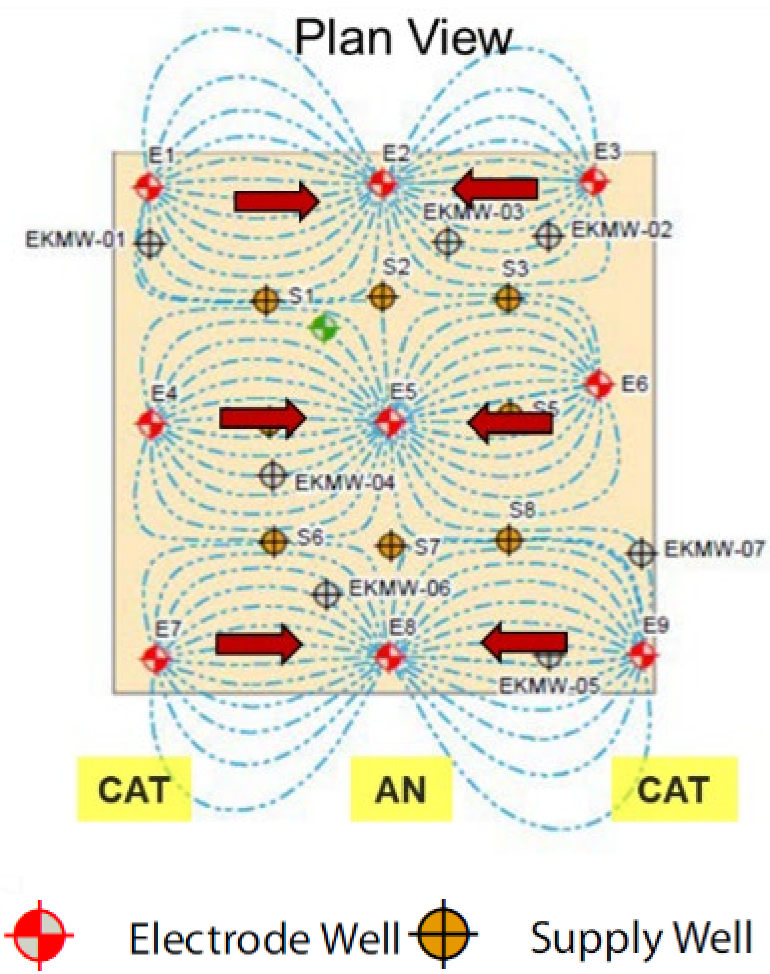
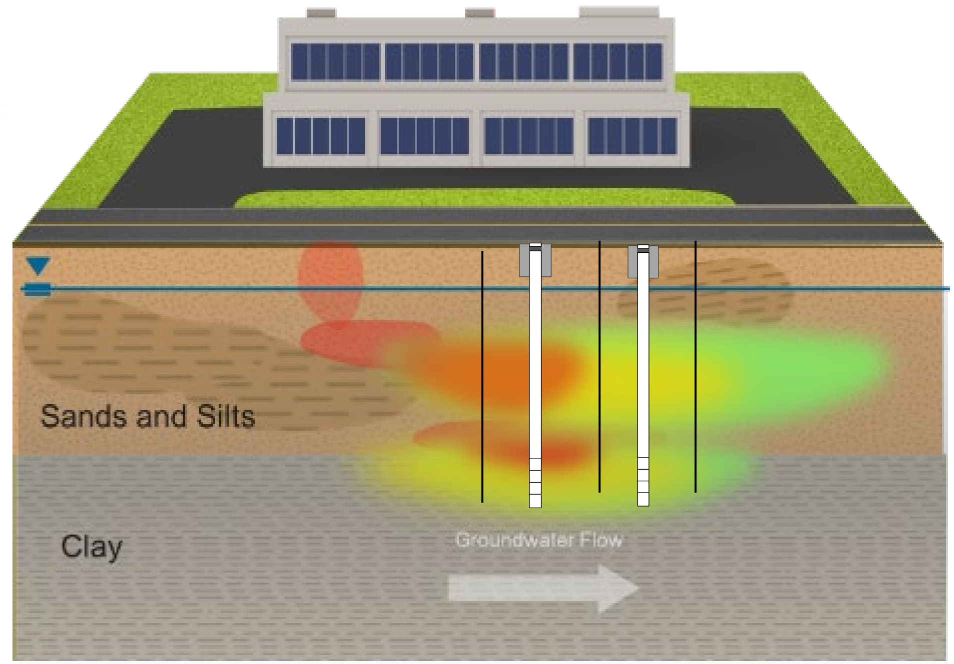
Full Scale Clay Layer– EK-Bio

Case Study

- Clay Layer
  - EK-Bio Implementation



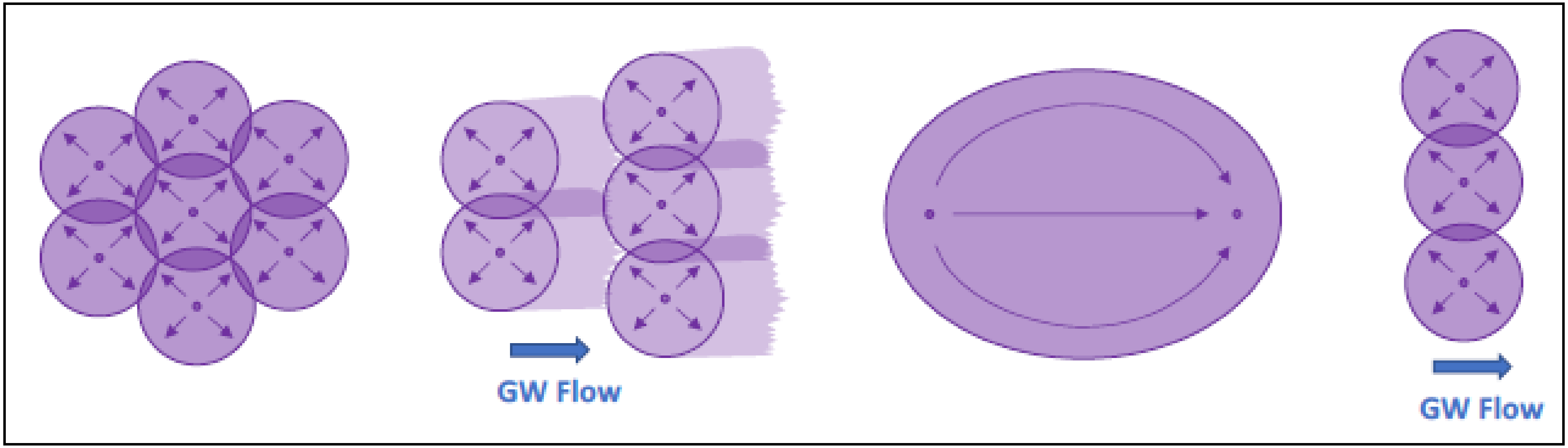


Example Case Study – image prepared using Health Canada CSM Builder Tool 2015; Graphics used with permission of Geosyntec Consultants.

Electro kinetics: OIS-ISRP Appendix D3

Amendment Delivery Optimization

The refinement of number and spacing of injection points, injection transects, and recirculation wells for minimization of cost or time using one of the delivery strategies:



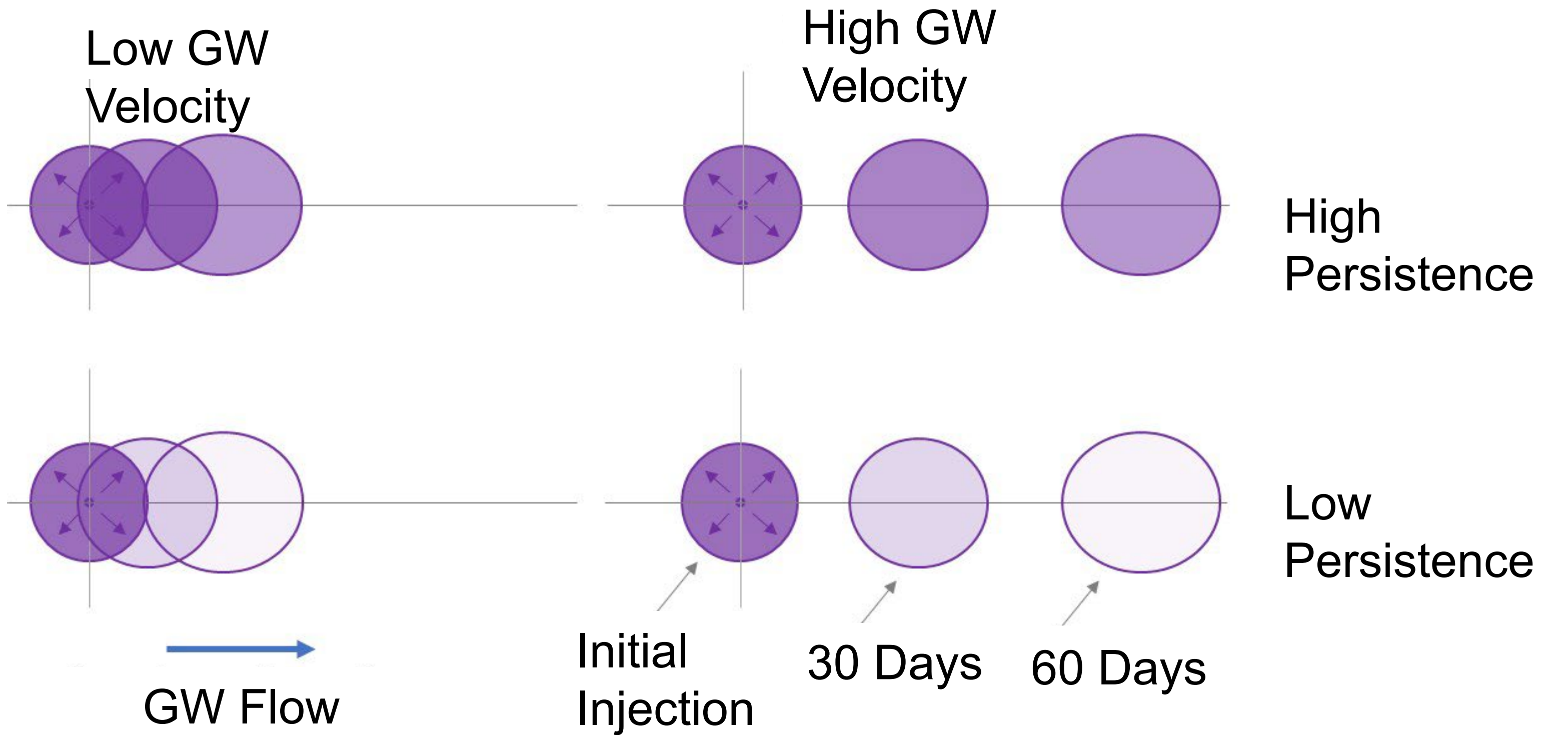
Grid Pattern | Inject and Drift | Recirculation | Barrier

ITRC OIS-ISRP-1 Figure 3-3

Graphic used with permission from Trihydro Corporation

Amendment Behavior and Persistence

Behavior and persistence of the amendment once injected must be understood and estimated:

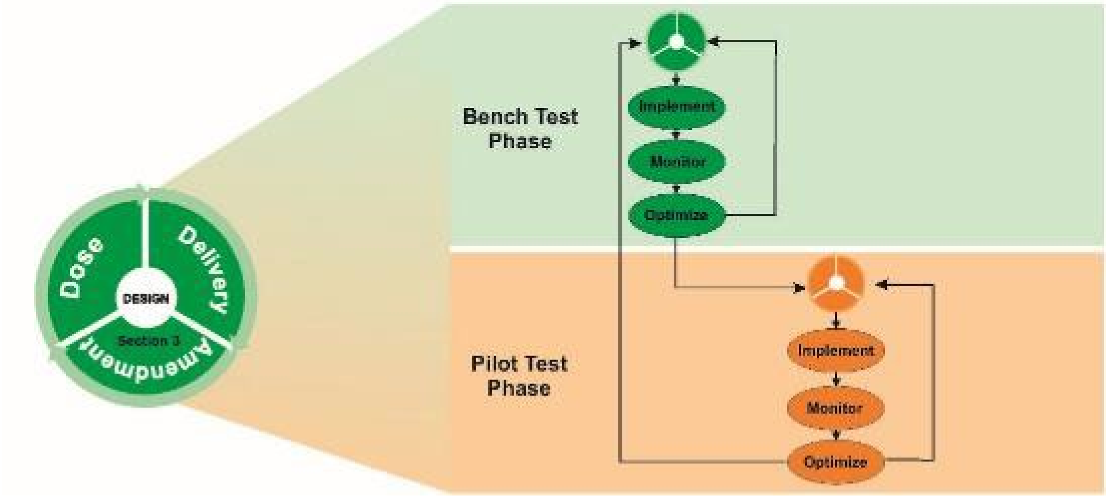


ITRC OIS-ISRP-1 Figure 3-2

Amendment persistence at natural flow using 4 scenarios. Graphic used with permission from Trihydro Corporation

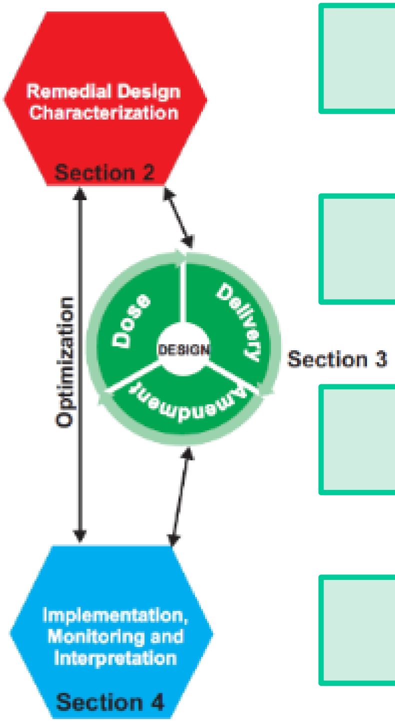
Remedial Design is Iterative

- Need to constantly evaluate the data you have
- Refinement of design following selection of amendment and delivery strategy may involve bench and pilot tests
  - Results of each test needs to feed back refinements into a subsequent test or next version of design
- Iterative approach and constant evaluation of new data will provide a strong design and more successful remedial effort



ITRC OIS-ISRP-1 Modified from Figure 3-1

Presentation Road Map



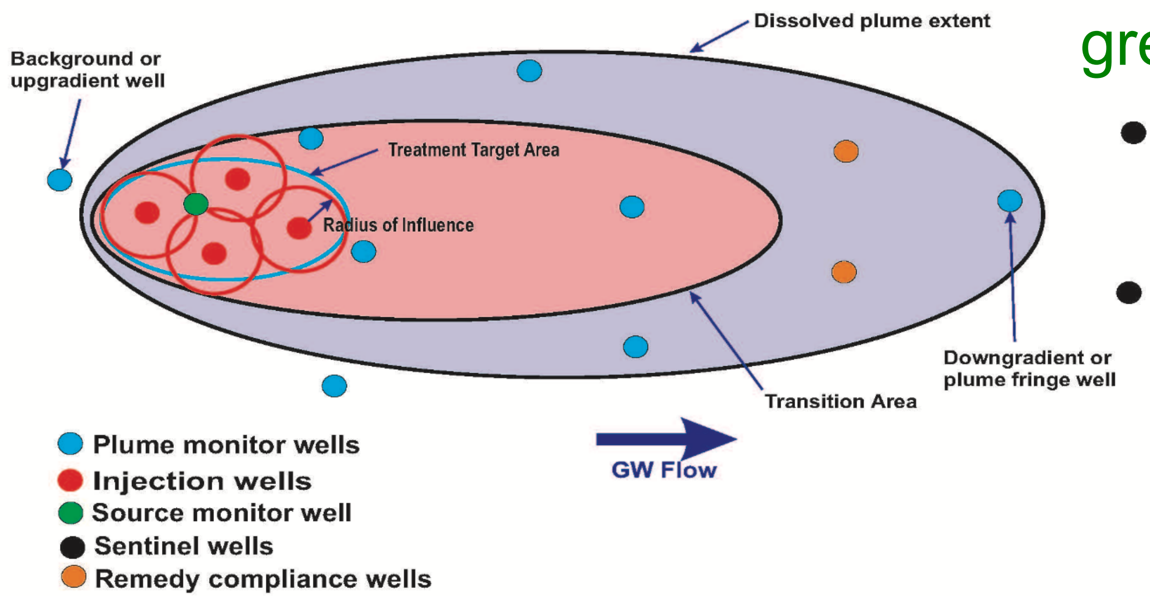
- Optimization Process
- Remedial Design Characterization
- Design: Amendment, Dose & Delivery
- **Implementation, Monitoring & Interpretation**
- Regulatory & Stakeholder Considerations

Learning Objective: Using performance monitoring to make optimization decisions.

Implementation and Feedback Monitoring Optimization

- Baseline monitoring
- Compliance monitoring
- Process monitoring
  - Frequency and parameters vary with amendment
  - Field parameters are inexpensive and have great value

Example of Network Well Locations



Suggested Analytical Parameters

Table 4-2. Analytical parameters for anaerobic biostimulation (with or without bioaugmentation).

PARAMETER	INTERPRETATION GUIDELINES	RECOMMENDATIONS
Contaminant concentrations	Progress is denoted by a reduction of parent COC concentrations and an increase in degradation products; build-up of degradation products could signal stalling.	If parent concentrations are declining but degradation products are not produced, there may be an alternate pathway (e.g., abiotic instead of reductive dechlorination).
Contaminant breakdown products	Breakdown products should be short-lived and reduce with time if the degradation is continuing to the desired end products. Changes in total molar concentrations of the parent and breakdown products should be assessed to verify full degradation.	If undesirable breakdown products continue to increase, then adjustments may be needed to stimulate greater transformation toward the desired end products.
Ultimate end products (e.g., methane, ethene, ethane, chloride, propene)	Presence confirms degradation of chlorin… or conditions suitable for sulfate reductio… methanogenesis.	
Field parameters—pH	Microbes typically require neutral pH (opti… 6.8–7.5; generally required range is 6.0–8.5).	low pH environments. Amend with sodium bicarbonate, sodium carbonate, or other additives to adjust pH; verify distribution if amendment is unsuccessful.
Field parameters—DO and ORP	DO should be <0.5 mg/l and ORP should be negative; if DO and ORP values are conflicting, the treatment zone may not be properly buffered or gases formed by injected materials may be causing instruments to read incorrectly.	If high DO or high ORP is observed in pockets, anisotropy may be hindering distribution by lowering the ROI in certain areas. Evaluate injection spacing in these areas to improve … to −400 mV.
Field parameters (e.g., temperature, specific conductance)	An increase in temperature or specific conductance may indicate injection reagents transport and could be used to evaluate ROI.	Each species of bacteria has an optimal range of temperature for growth. Verify that selected consortia meet site characteristics during the selection process because aquifer temperature cannot be changed.
Water level and NAPL thickness	Mounding or increased hydraulic gradients can be induced during injection events. NAPL can also be mobilized.	Determine groundwater flow direction and the hydraulic connection between injection wells and monitoring wells.
TOC	TOC includes both naturally occurring organic carbon (such as humus) and organic carbon contamination, e.g., benzene. TOC values above approximately 50 mg/L indicate carbon levels that, if biologically	Over time TOC will decline again to pre-remediation levels. This, combined with aquifer flow and transport information, can indicate when the substrate is depleted.

If sulfate reduction and methane are not observed and ORP is greater than -120 mV, conditions do not exist for sulfate reduction

methanogenesis occurs at -200 mV to -400 mV

Table 4-4. Analytical parameters for chemical oxidation

PARAMETER	INTERPRETATION GUIDELINES	RECOMMENDATIONS
Contaminant concentrations	Progress is denoted by a reduction of parent COC concentrations.	If COC concentrations are unchanged, evaluate distribution and effectiveness of selected oxidant (e.g., permanganate will not oxidize ethanes).
Contaminant breakdown products	Breakdown products should be short-lived and reduce with time if the degradation is continuing to the desired end products.	If undesirable breakdown products continue to increase, then adjustments may be needed to stimulate greater transformation toward the desired end products
Ultimate end products (e.g., acetone, carbon disulfide, carbon dioxide, chloride)	Presence confirms degradation.	
Field parameters (e.g., pH, temperature, specific conductance, DO, ORP, pressure, ferrous iron, hydrocarbon gases, LEL, CO_2)	Certain reactions require low pH (ideal range i… 4–6); amend if necessary. In the case of alkaline activation of some oxidants, pH should be confirmed to be above targets, typically in the range of greater than 10.5 and < 12.	…conductivity are often elevated during ISCO application and can be used to evaluate ROI during process monitoring.
Water level and NAPL thickness	Mounding or increased hydraulic gradients can be induced during injection events. NAPL can also be mobilized.	Determine groundwater flow direction and the hydraulic connection between injection well locations and monitoring wells.
Metals (e.g., arsenic, chromium, lead, zinc, and other site-specific or amendment-specific metals)	Metals can leach from the geology/soil at concentrations that exceed regulatory standards.	Monitor secondary effects of ISCO application.
Natural oxidant demand (NOD)	Determine the oxidant demand of the existing biogeochemistry and account for it when calculating the amount of amendment needed. A high NOD may preclude the selection of ISCO as cost-effective. COD, soil oxidant demand (SOD), and total oxidant demand (TOD) are related terms.	Evaluate oxidant demand required to overcome properties of the aquifer. This is typically a design parameter not used during performance monitoring. Multiple applications of a chemical oxidant may be required to overcome NOD such that COD can be adequately addressed.
TOC	TOC provides a general indication of the amount of oxidant that will be needed, if a soil sample cannot be collected for testing.	It is best to rely on NOD, COD, or TOD when using chemical oxidation amendments.
Amendment-specific parameters (e.g., manganese, sulfate, sodium, potassium, ozone), amendment components (H_2O_2, persulfate, permanganate, ozone)	Amendments can be used as a tracer to evaluate ROI and calculate travel times if the reaction with contaminants and soil minerals or organics is accounted for. May need to monitor for components of amendments if there are components that present a water quality concern.	Evaluate ROI and travel times.
Water quality parameters—TDS	TDS is a measure of the combined organic and inorganic substances in water, primarily	Some states have compliance values for TDS and/or individual salts or minerals.

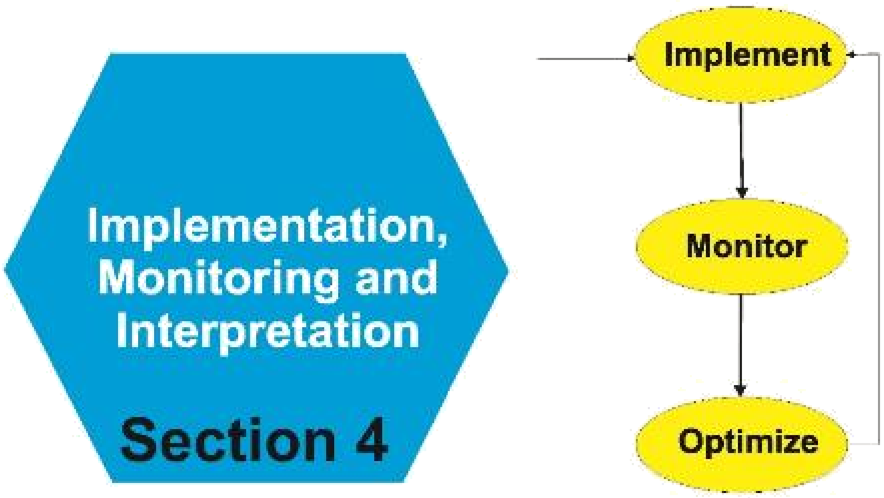
These end products may quickly dissipate in the vadose zone

Applying Optimization to Underperforming Remedies

- When should you optimize, select an alternate remedy, or transition to a polishing remedy (e.g., MNA)?
- Have you collected all of the data needed to evaluate progress?
- In what way is the remedy underperforming?
- Which Design Criteria needs to be addressed?
- Can it be optimized?
- Should a supplemental remedy be considered?

Case Study - Background

- Site Info:
  - Total area: ~380 acres
  - Plume extent: 12 acres, including off-site impacts
- Geology: Piedmont, heterogeneous with saprolite of varying thickness overlying transition zone of partially weathered rock and granitic schist



- Contaminants: Chlorinated solvents (carbon tetrachloride, trichloroethene (TCE), and daughter products)
- Existing Remedy: Pump and Treat
  - Ineffective after 13 years

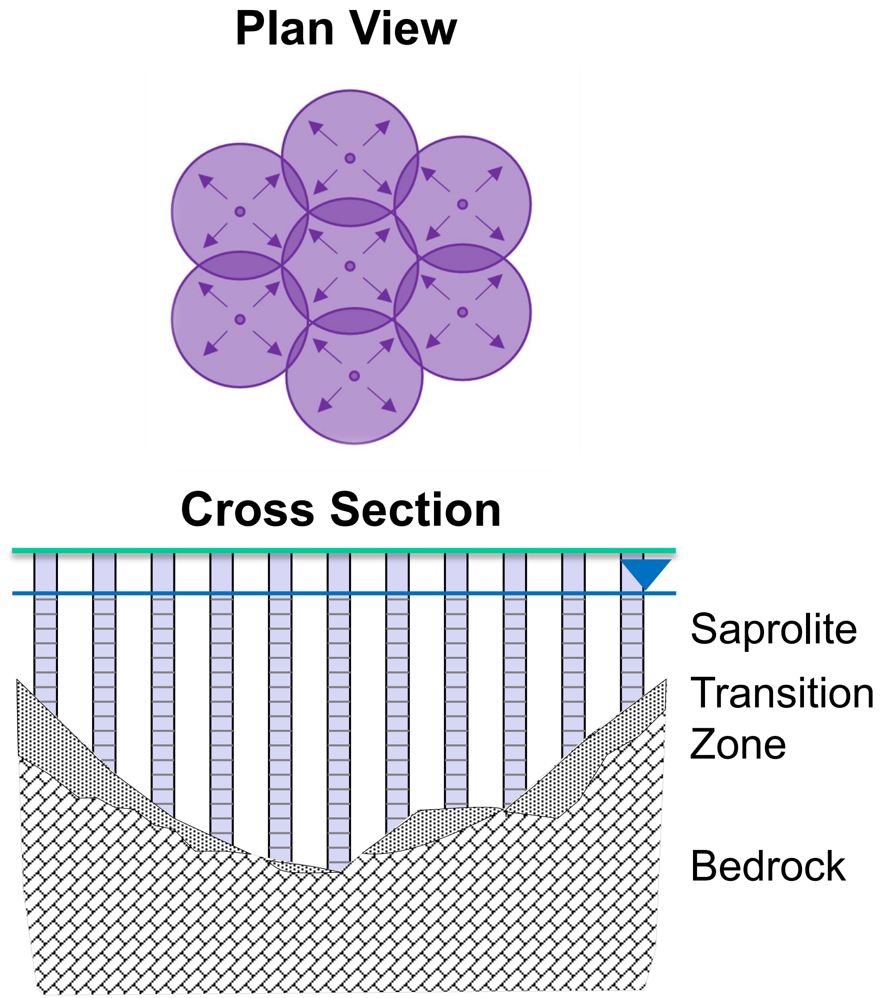
ITRC OIS-ISRP-1 Figure 3-1

Case Study – Multiple Optimizations

- Implemented anaerobic in situ bioremediation
- Optimized bioremediation remedy
  - Evaluate monitoring data monthly – don't wait for the annual report
  - Know when to anticipate changes in groundwater chemistry and respond early
- Incorporated hydraulic fracturing to improve distribution
- Relied on natural downward vertical gradient to distribute amendments to the bedrock
  - Also anticipated MNA once shallow groundwater impacts were addressed
  - But had a contingency plan to address bedrock

Case Study – Remedy Design

- Fixed injection wells on 25-foot centers in grid pattern
- 134 injection wells within 4.1-acre TTZ
- Injections in saprolite only, relying on downward vertical gradient for distribution to deeper zones
- Automated injection system

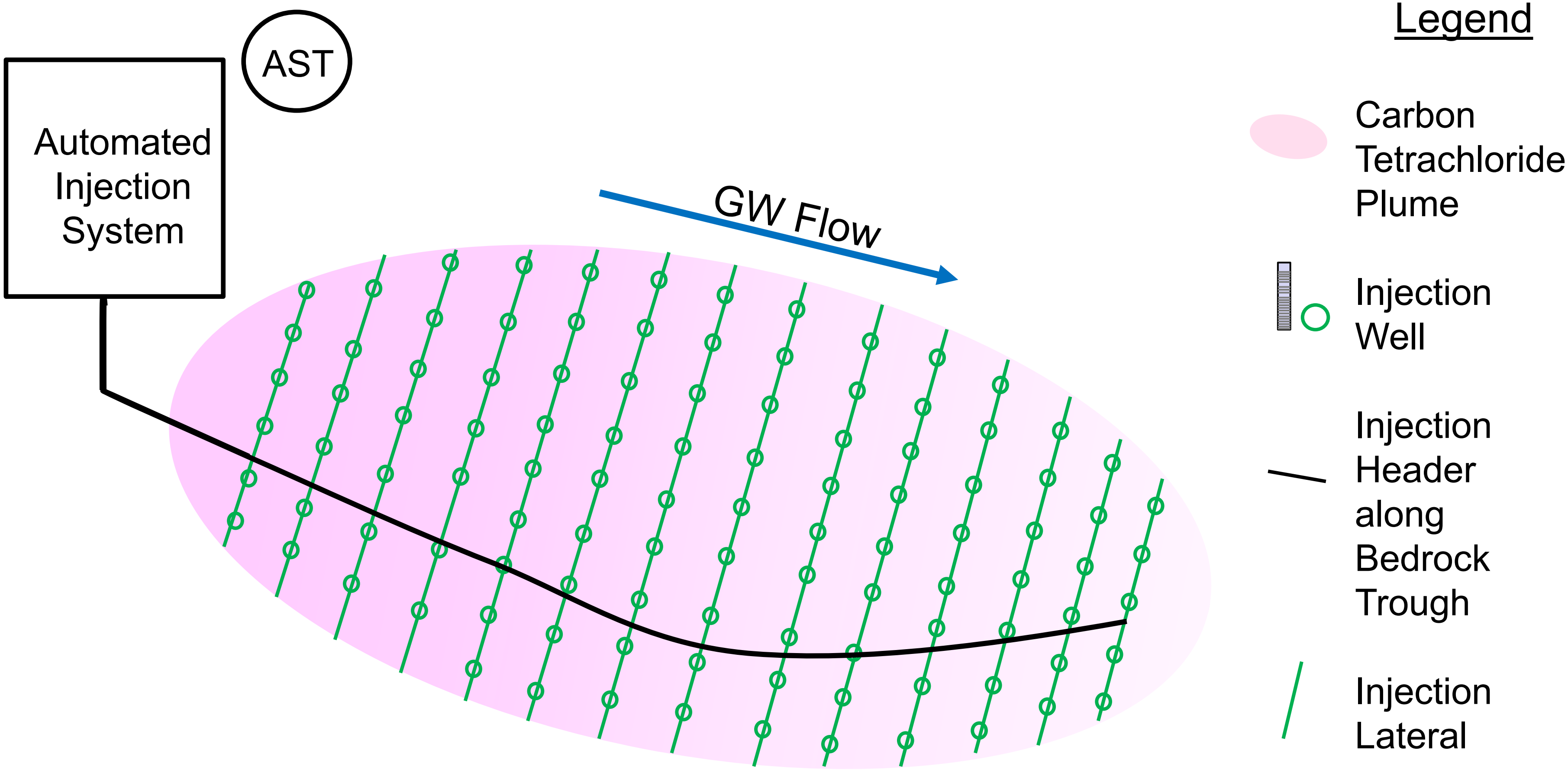


ITRC OIS-ISRP-1 Figure 3-3 (graphic used by permission from Trihydro Corporation); Cross section Figure used with permission of Elizabeth Rhine

Case Study

Injection Well Network

Case Study



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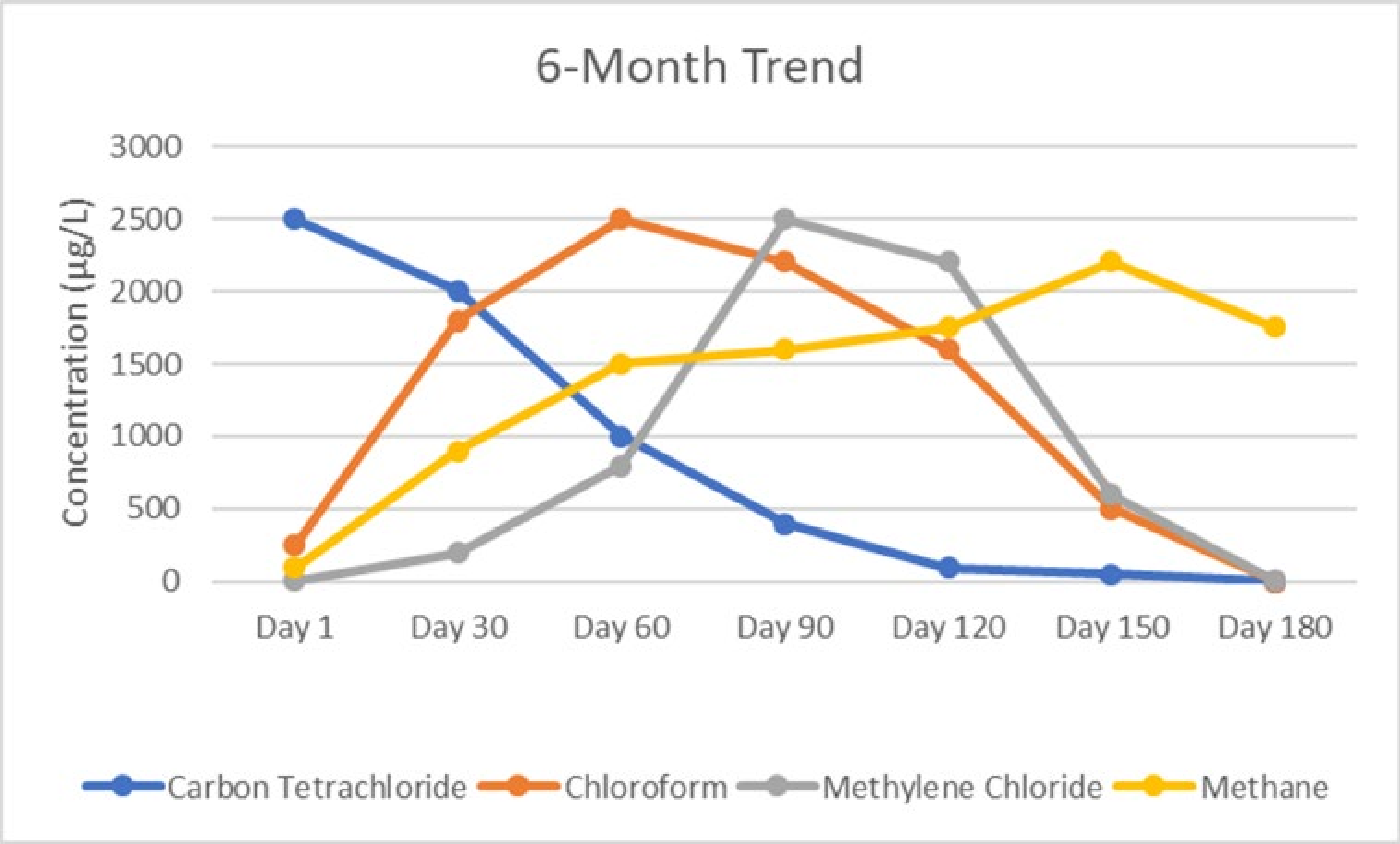
Good News…

Case Study

- In the Source Area, MCLs were met within 6 months in performance monitoring wells



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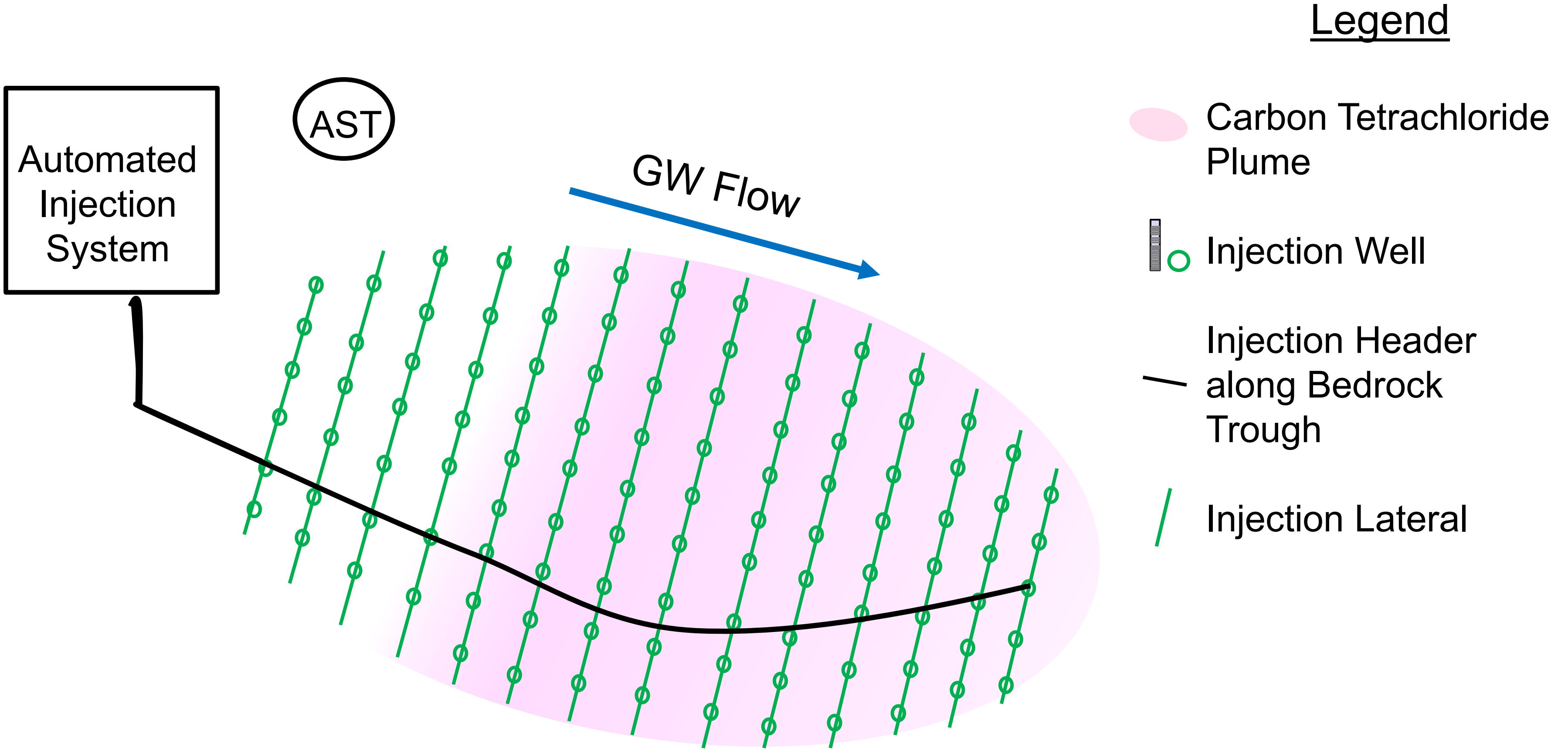
…But Not Quite the Expected

Injection Well Network



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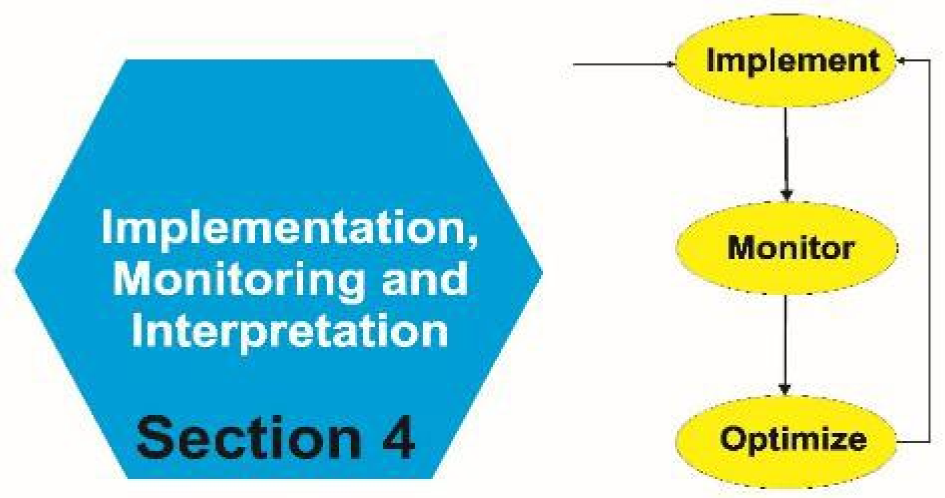
Data Evaluation after 6 months

Case Study

- Increase in daughter products
- The pH dropped slightly after 12 months
- Increased methane concentrations

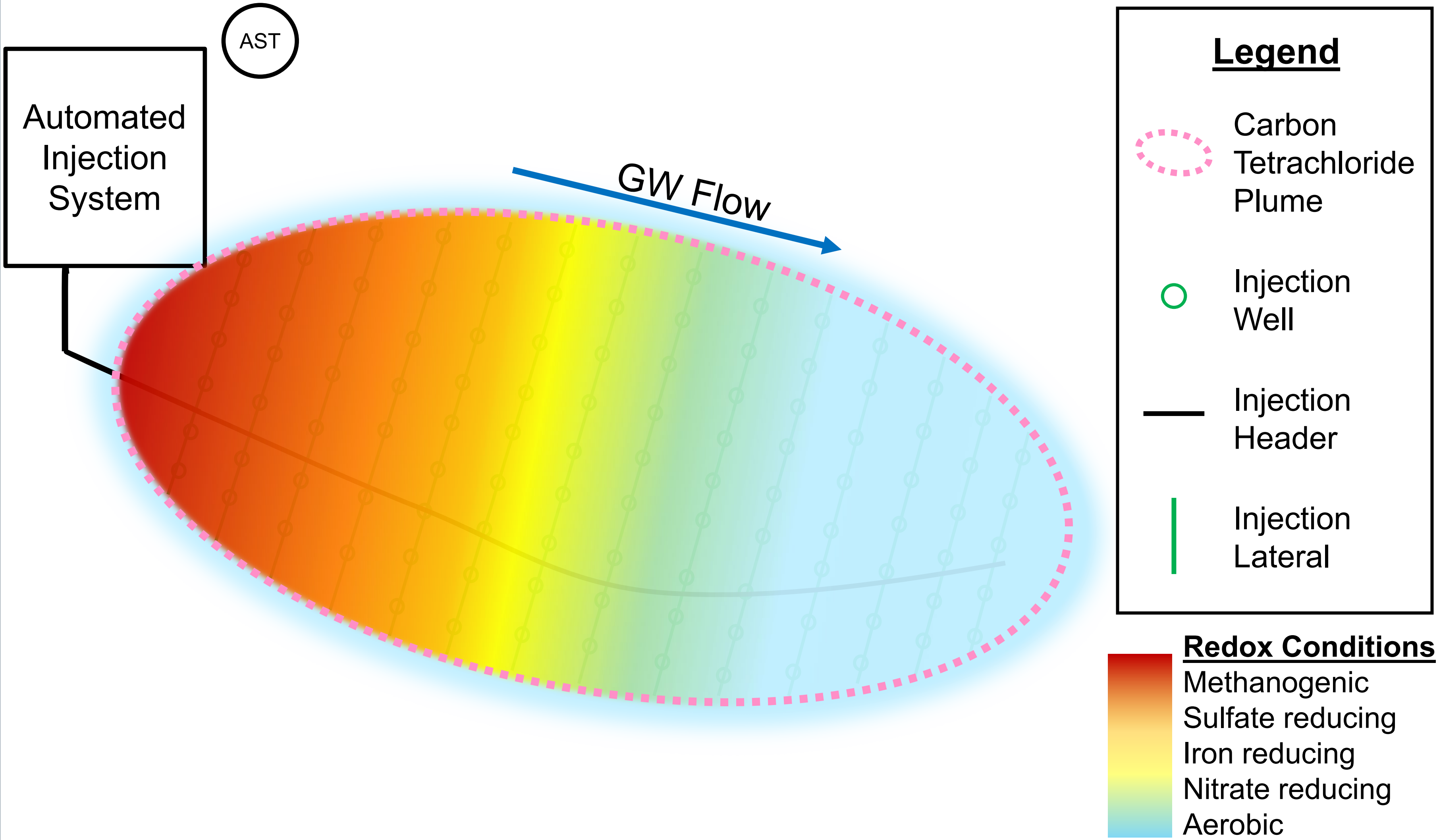


- Ideal redox conditions for biodegradation not generated uniformly across the plume
- Distal end of the plume exhibited no change
  - But it should have been easier to address low concentrations

ITRC OIS-ISRP-1 Figure 3-1
Graphic used with permission of Elizabeth Rhine

Redox Parameter Evaluation

Case Study



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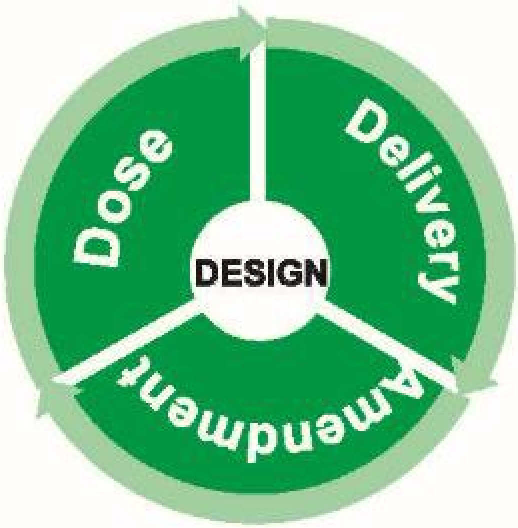
Poll

- Given the data just presented, what type of problem do we have? What needs to be optimized for success?
  - Delivery
  - Dose
  - Amendment
  - All of the above

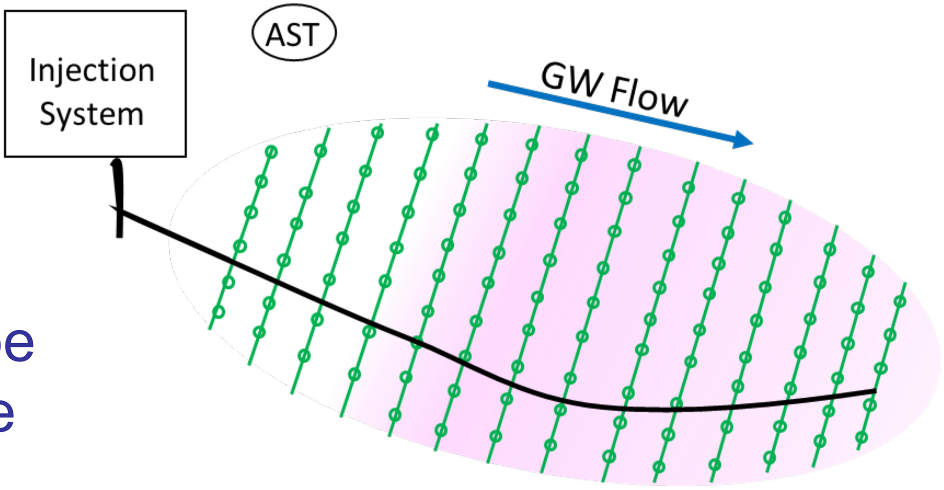


Optimization 1

Case Study

- Downgradient, anaerobic conditions not established
  - COC concentrations and pH stable in this area
- Degradation by-products not observed in the downgradient, low-concentration plume
- Low TOC compared to upgradient
- ROIs in downgradient monitoring wells appear to be less than observed in source area monitoring wells

- What should we do?
  - Revisit RDC
  - Revisit the Design Wheel
  - Increase the radius of influence (ROI) in the downgradient wells

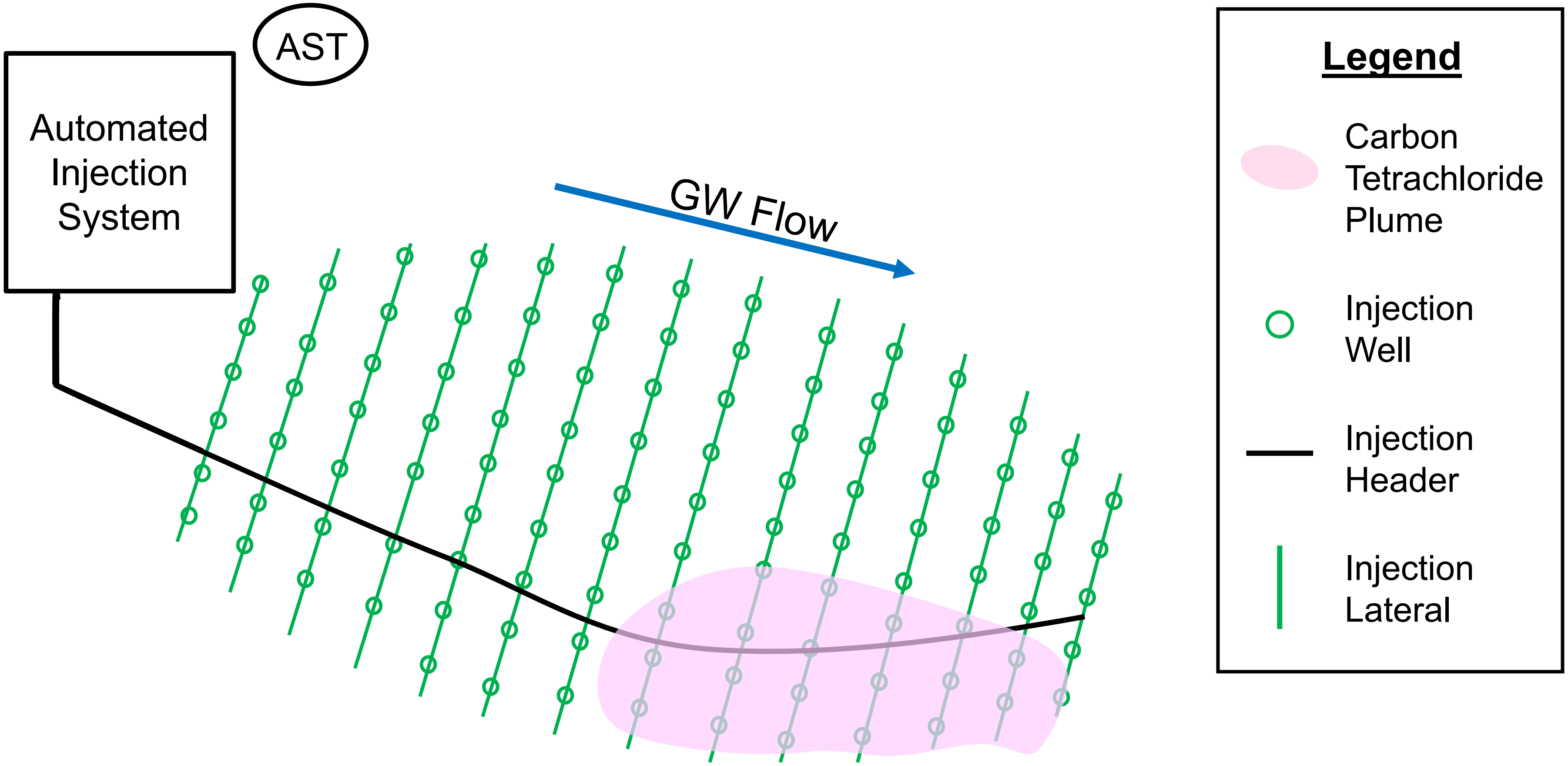


Optimization 1 – Operational Changes

	Problem	Resulting Optimization
Amendment	▶ Address the pH drop	▶ Lower carbon load from 10% to 5%
Dose	▶ Increase the radius of influence (ROI) of downgradient wells	▶ Decrease the frequency of injection ▶ Increased the volume from 10 to 25 gal/ft
Delivery	▶ Solve the fermentation issue in the holding tank	▶ Add a clean water flush ▶ Stir the holding tank

12 Months after Optimization 1

Case Study



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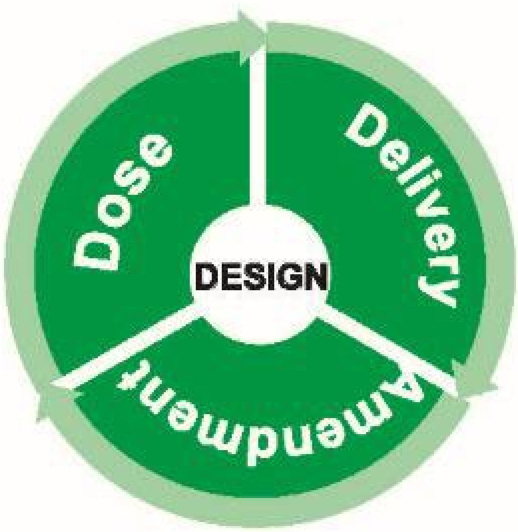
Poll

▶ Given the data just presented, what type of problem do we have? What needs to be optimized for success?

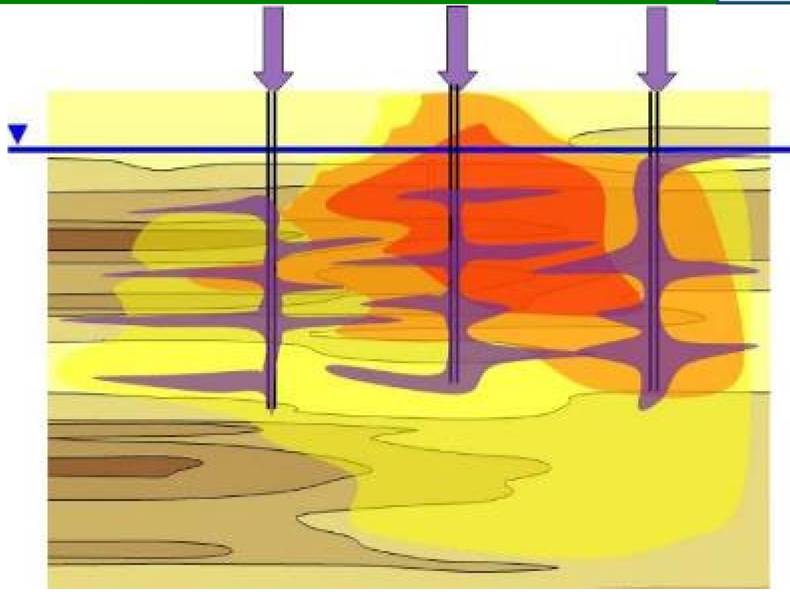
- Delivery
- Dose
- Amendment
- All of the above



Poll Question

Optimization 2 – Address Distribution

- Initial optimization helped in most areas
- Why did COCs persist in this area?
- Revisit RDC and Design Wheel
  - Review boring logs
  - Silts and clay lenses
  - Back-diffusion from clay acting as a long-term source



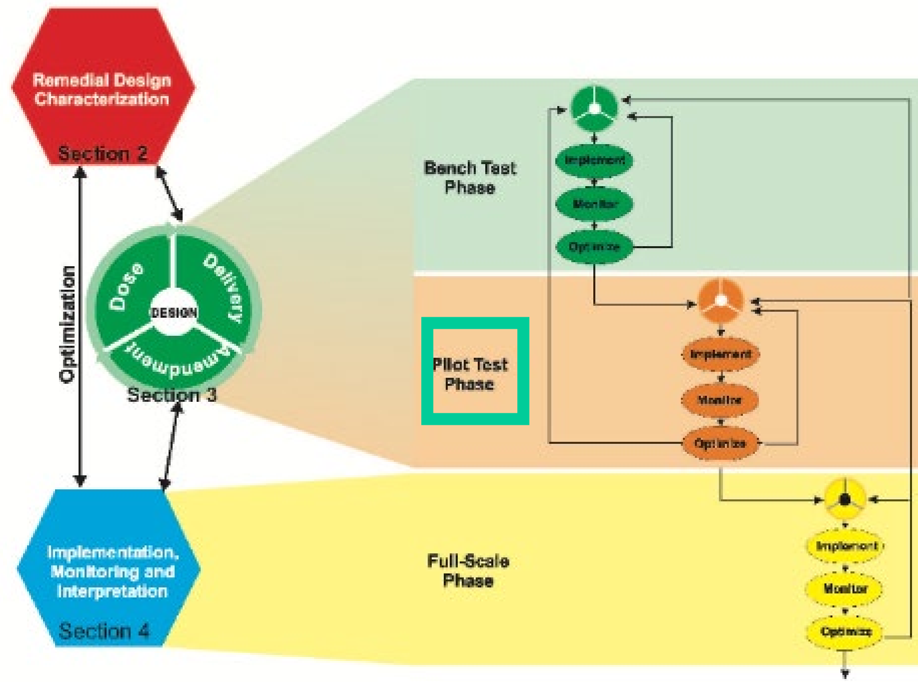
- Will hydraulic fracturing help?
  - Perhaps
  - Pilot study

ITRC OIS-ISRP-1 Figure 3-4
Graphic used by permission from Trihydro Corporation

Optimization 2 – Fracturing Pilot Test

Case Study

- Reagent takes path of least resistance, which in this case was the silty sands
- Hydraulic fracturing pilot test to evaluate potential to enhance distribution by creating additional sand layers

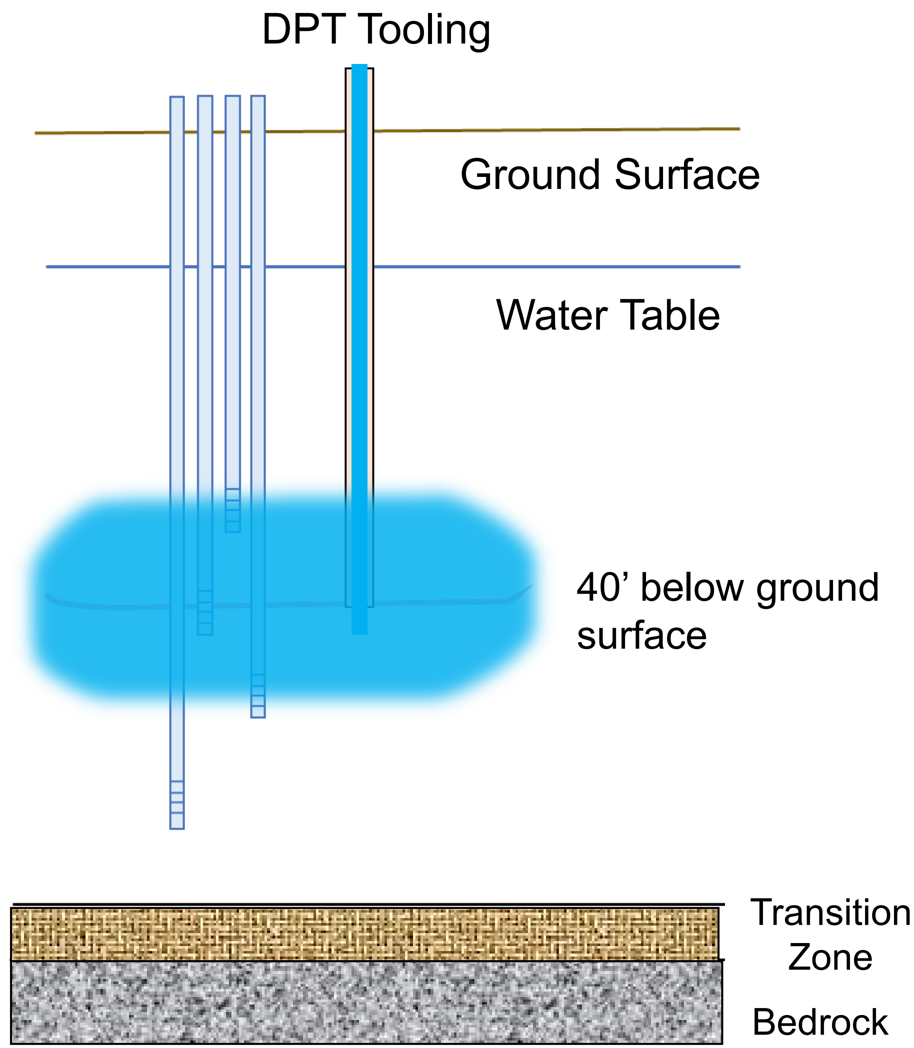


ITRC OIS-ISRP-1 Figure 3-1

Hydraulic Fracture - Prelim Pilot Test

Case Study

- Installed a single hydraulic fracture using sand suspended in food-grade guar gel using DPT tooling
- Installed piezometers at various depths and equipped with data loggers
- Injected water into fracture
- Influence was observed 3 to 4 feet above and below fracture



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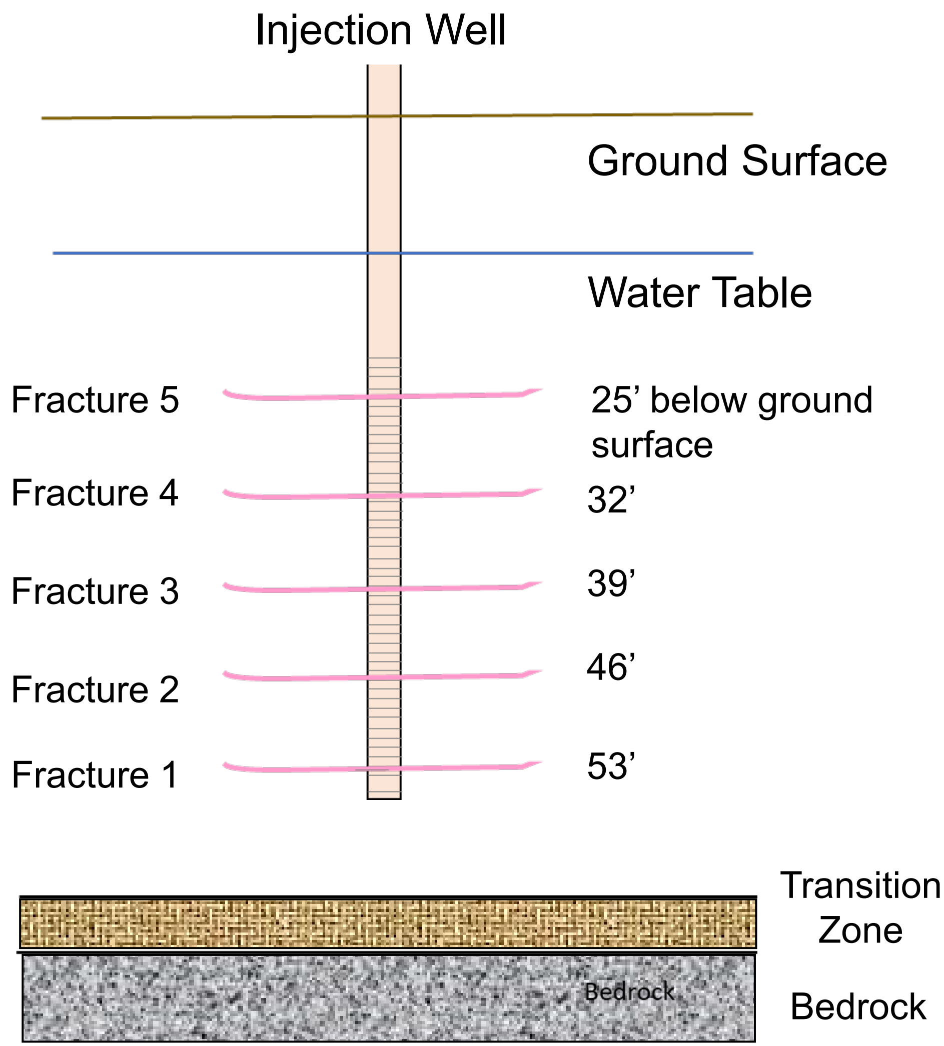
Hydraulic Fracture – Stacked Fractures

Case Study

- Implemented full-scale series of fractures at 7-foot intervals
- Installed a single injection well screened to intercept all 5 fractures
- Installed piezometers to measure ROI
  - 20-foot ROI
  - 40-foot ROI



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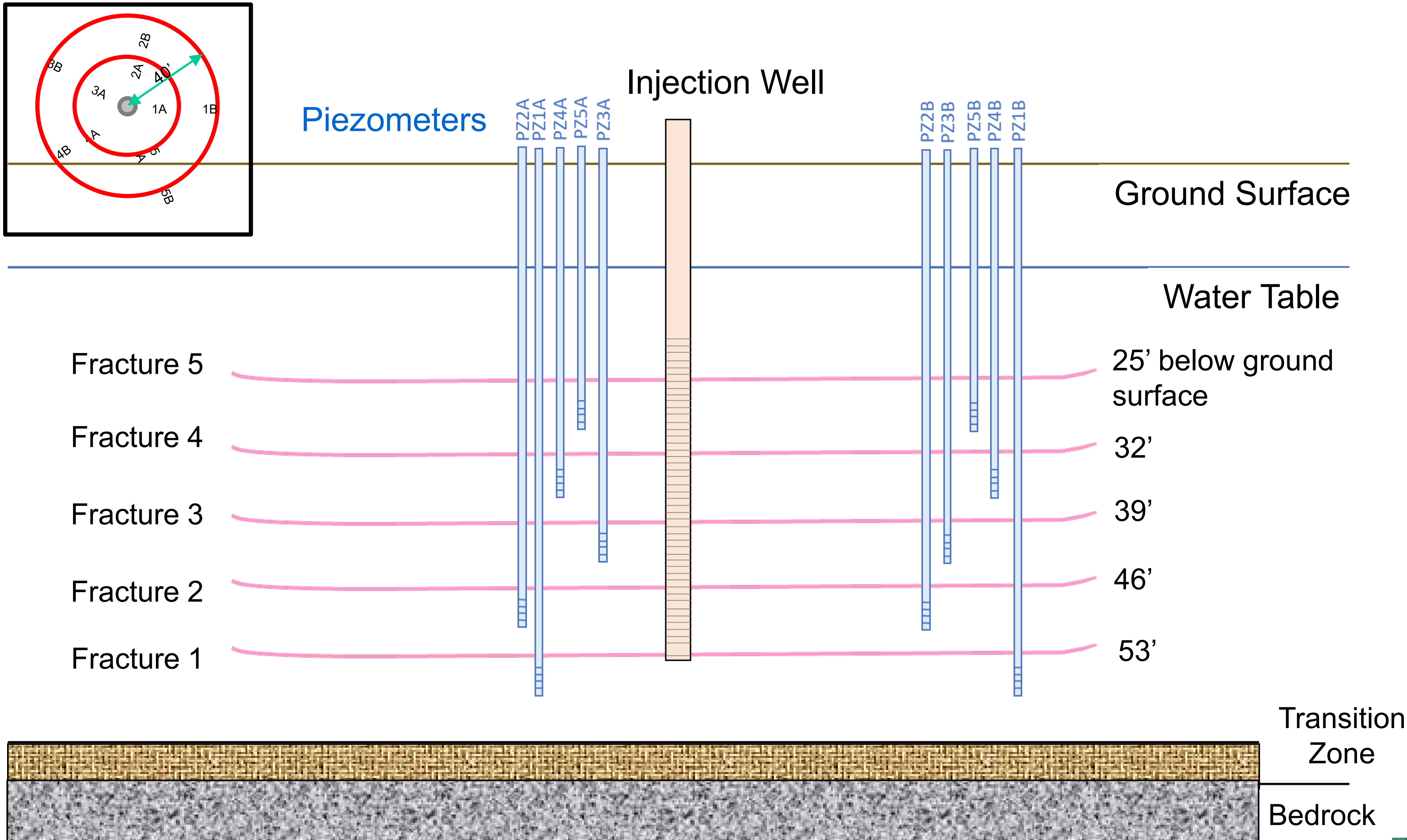
Hydraulic Fracture – Full Pilot Test

Case Study



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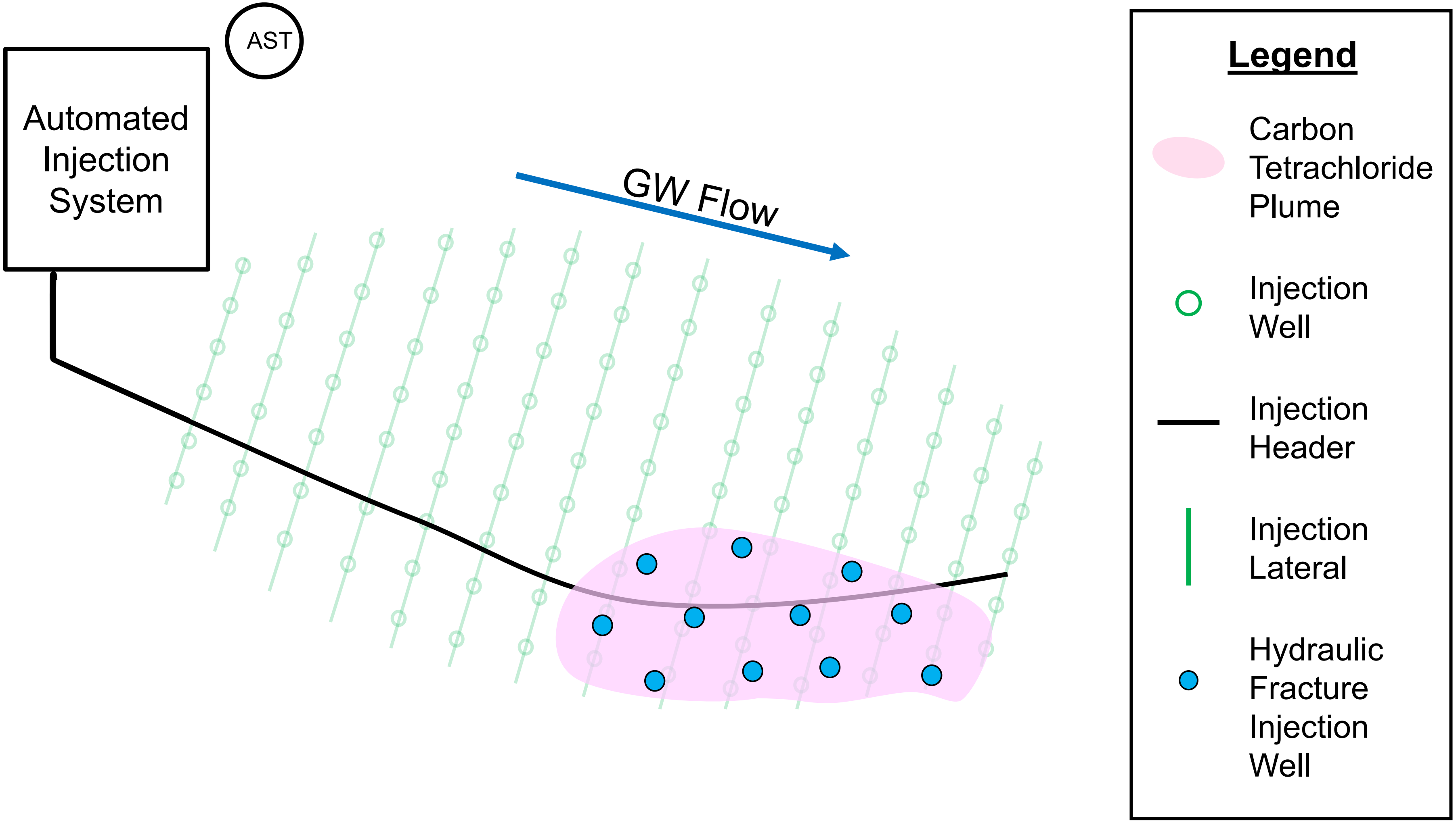
Optimization 2 – Startup



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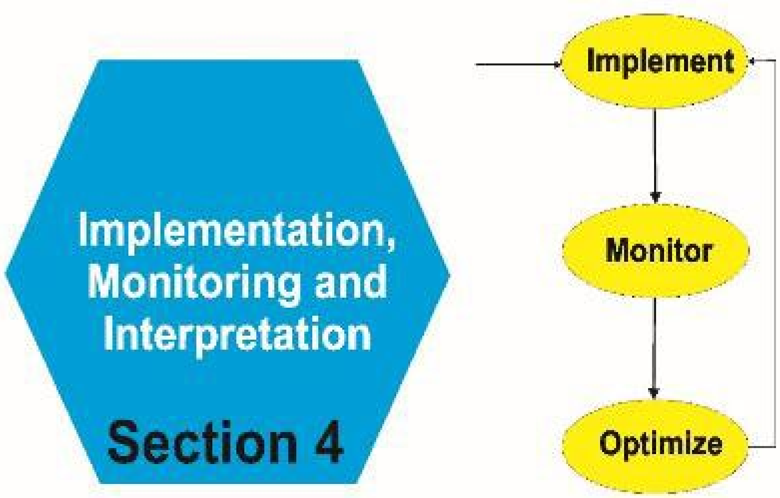
Rebound Study Conducted Elsewhere

- Nine months to complete the hydraulic fracture pilot study and install 11 fracture sets
- MNA monitoring during that period
- Nominal rebound in areas where MCLs were achieved
- Back-diffusion (e.g., equilibrium) limited to areas with high clay content per RDC borings

Recap of Hydraulic Fracturing

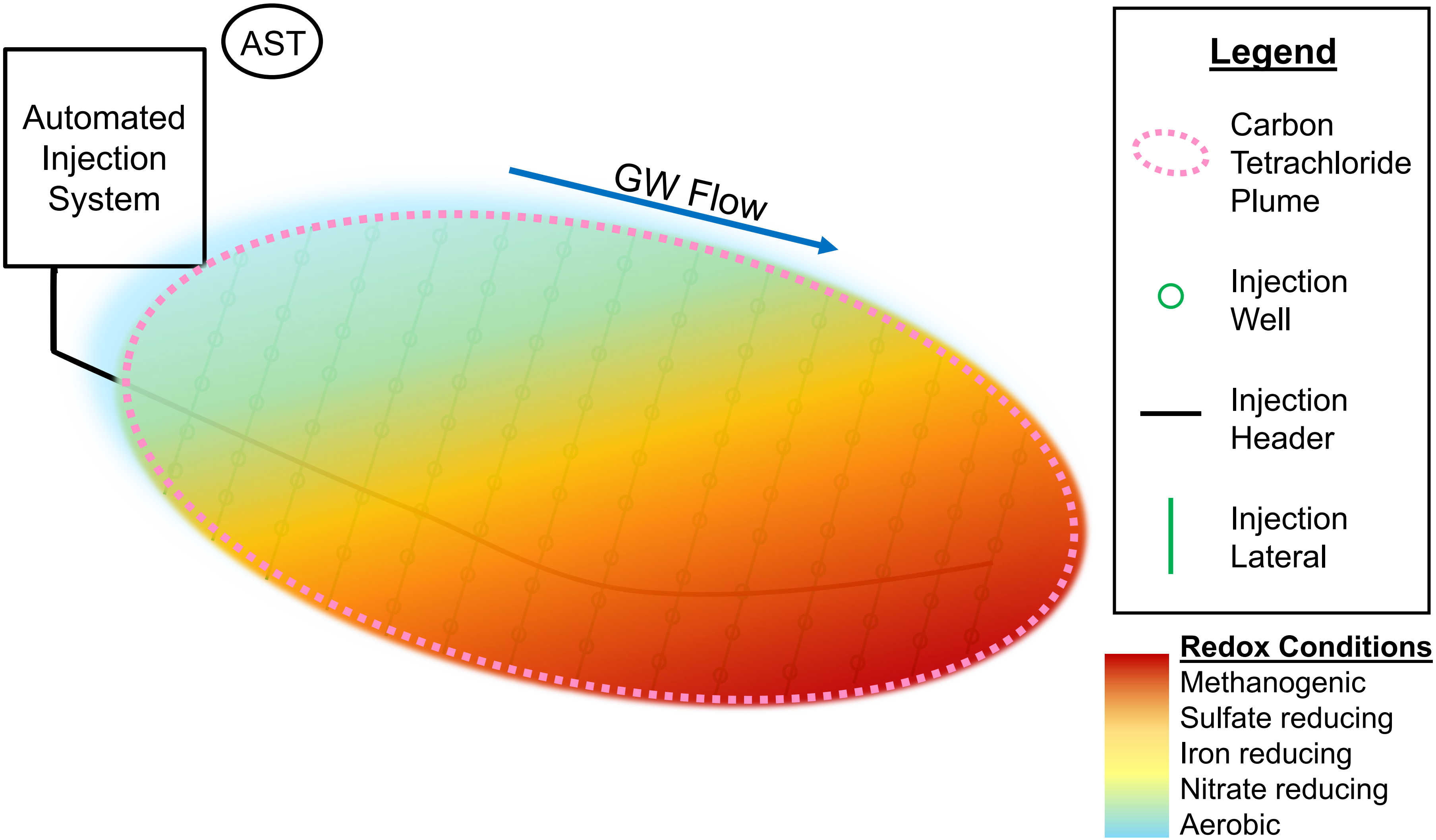
Case Study



- ROI of each fracture ~45 feet
- Installed 11 fracture sets and injection wells on 75-foot centers
- Automated injection system
- Injected once a month
- After two injection events, TOC concentrations at optimal levels
- Evidence of reductive dechlorination observed in 6 months
- After 9 months, transitioned to MNA

Redox Parameter Evaluation

Case Study



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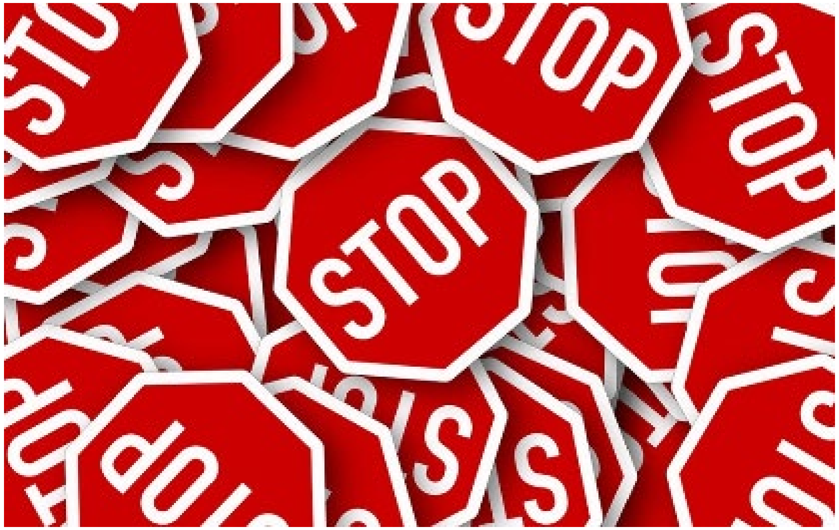
Optimization 3 – Transition to MNA

- Know when to stop
- Know when to transition to another technology or MNA
- Consider:
  - Cost/benefit of additional remediation
  - Point of diminishing returns
  - Regulatory framework
  - Final site use



Closure/Brownfield Redevelopment

Case Study

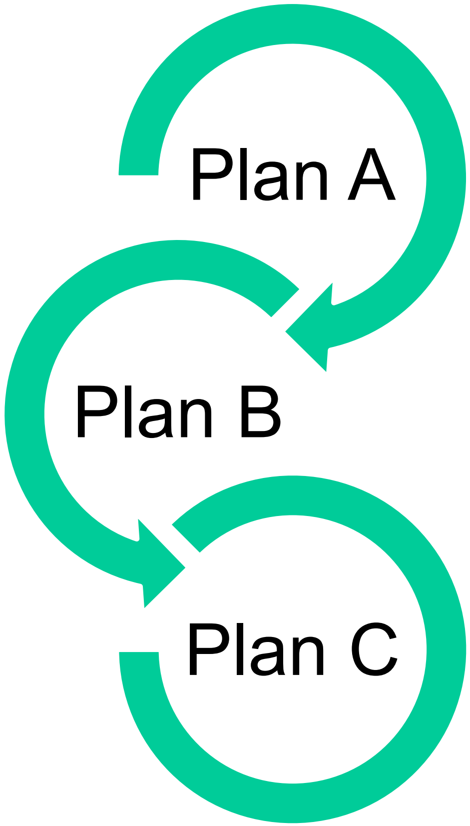
- Original Brownfield agreement restricted use to industrial
- Only buyer to express interested wanted to build apartments
  - More stringent criteria
  - Agreed to meet residential criteria because it was cheaper than holding on to the property
- With engineering controls, land use restrictions lifted and residential development allowed

Case Study Recap

- Treating the 4.1-acre TTZ achieved MCLs or close to MCLs throughout
- Natural attenuation in the remaining 8 acres downgradient
- Bedrock aquifer also naturally attenuated
- What's the future use of the property?
- For this site, transitioned to MNA when concentrations were below 5 times the MCL
- Different states may allow MNA at higher concentrations

Key Concepts from Case Study

- Including the original P&T remedy, there were 4 cycles of optimization to reach MNA
- Monthly evaluation was critical to maintain schedule for redevelopment
- Evaluate contingency plans up front, and be ready to implement if the data suggest it is needed



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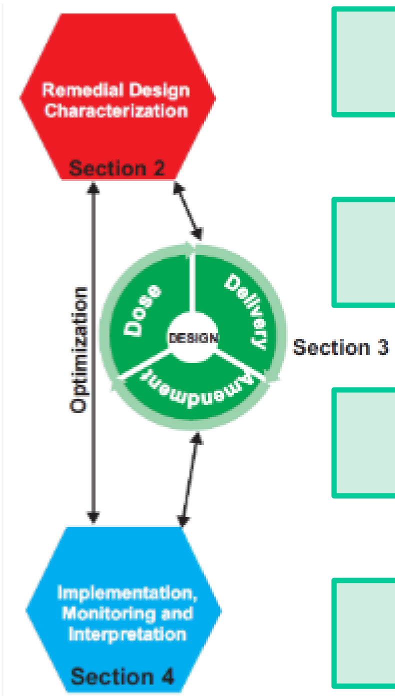
Section 4: Five General Strategies

- Anaerobic biostimulation
- Aerobic biostimulation
- Chemical oxidation (ISCO)
- Chemical reduction (ISCR)
- Surfactant/co-flushing

Strategy-Specific Monitoring

- Tables and Links to Fact Sheets
  - Monitor parameters appropriate for the remedy
  - Data interpretation guidelines
  - Optimization recommendations
- Sample Frequency
  - Dependent on site-specific conditions
  - Varies by reaction time of amendment
  - ISCO monitoring is very different from EISB
- Contingency Planning
  - Have one

Presentation Road Map

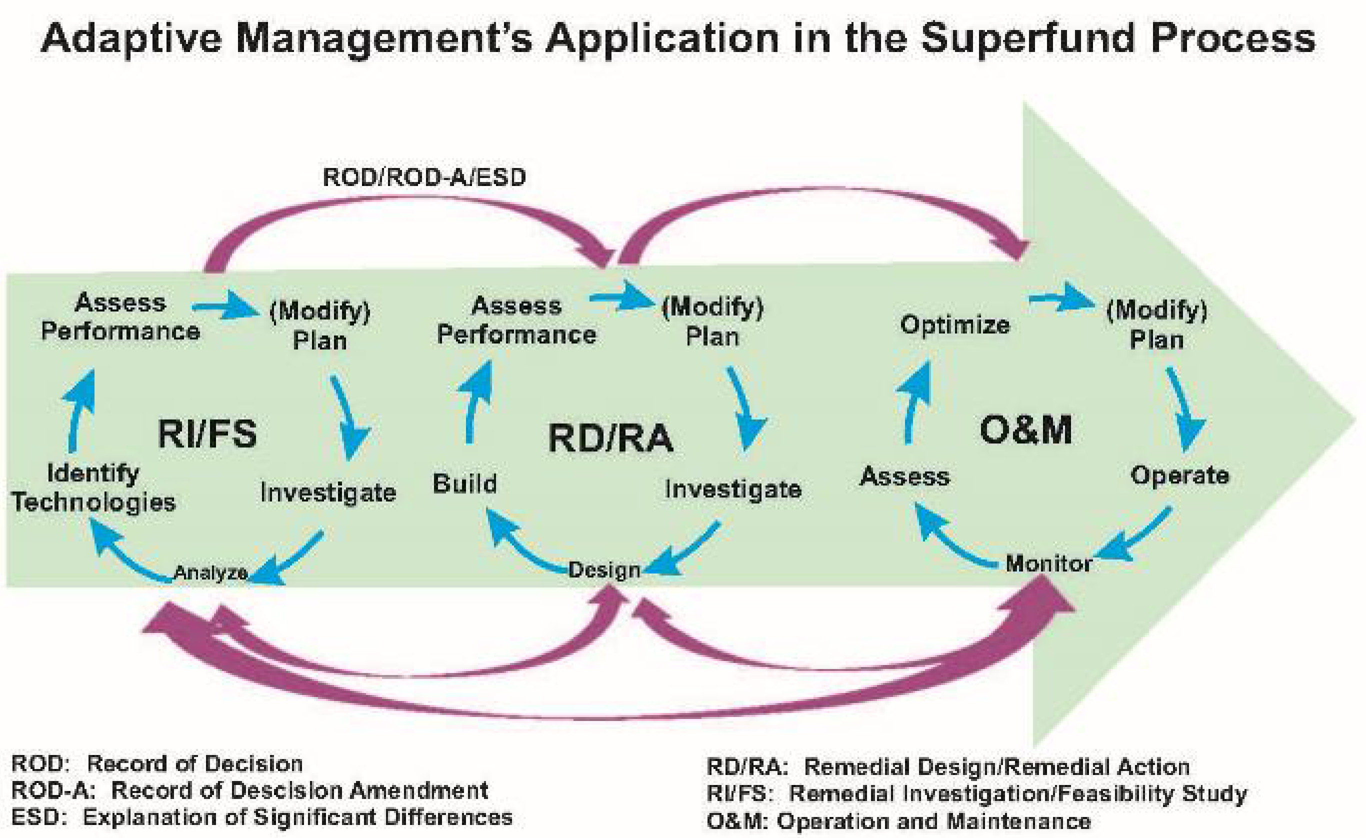


- Optimization Process
- Remedial Design Characterization
- Design: Amendment, Dose & Delivery
- Implementation, Monitoring & Interpretation
- **Regulatory & Stakeholder Considerations**

Learning Objective: Anticipate iterative refinement for remedy design and regulatory approvals

Regulatory Considerations

- Statutory Challenges
- Procedural Challenges
- Adaptive Management needs to become part of the regulatory process

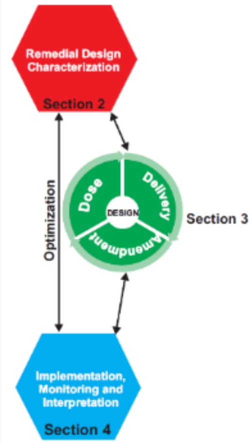


EPA www.clu-in.org/conf/tio/AdaptiveManagement-Stakeholders

Stakeholder Considerations

- Proactive Approach
  - Communicate all relevant information
  - Discuss unknowns and update as information becomes available
  - Regular communication
- Media
  - Single official point of contact with a professional, trusted relationship with media
  - Train all communicators and prepare for questions
  - Clear, concise fact sheets

Overall Course Summary – Call to Action



- RDC is key to developing detailed Conceptual Site Model
- Design of amendment, dose and delivery is an iterative process with multiple feedback loops
- Monitoring and data analysis to inform adaptive implementation and feedback optimization

Appendix F Checklist

Performance Evaluation & Optimization of In situ Remediation

Predictable and Optimized Outcome for In Situ Remedies using sound science and engineering

Thank You

Follow ITRC:

- 2nd question and answer break
- Links to additional resources
  - http://www.clu-in.org/conf/itrc/OIS-ISRP/resource.cfm
- Feedback form – *please* complete
  - http://www.clu-in.org/conf/itrc/OIS-ISRP/feedback.cfm

View Your Participation Certificate (PDF)

Need confirmation of your participation today?

Fill out the feedback form and check box for confirmation email and certificate.

Poll Question