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Starting Soon: Optimizing Injection Strategies and In Situ Remediation Performance

Poll Question

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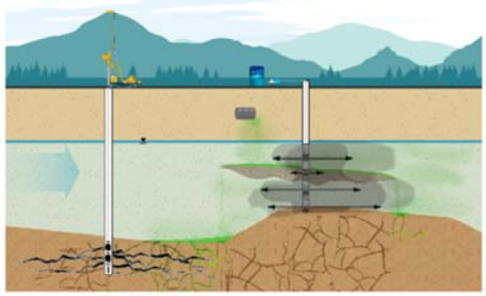
Optimizing Injection Strategies and In Situ Remediation Performance



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

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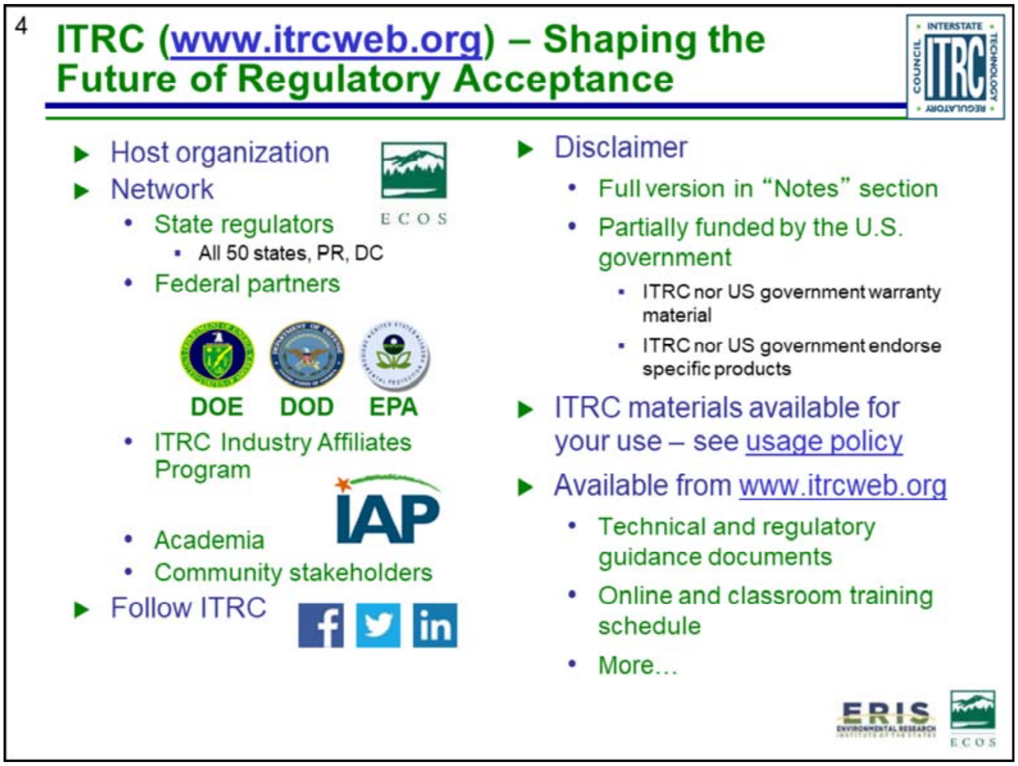

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Kristopher (Kris) McCandless has worked for the Virginia Department of Environmental Quality (DEQ) in Woodbridge, Virginia since 2015. As an Environmental Geologist in the petroleum storage tank remediation division, he manages the characterization and remediation of numerous leaking petroleum storage tank sites, as well as assists the Land Protection Program with chlorinated solvent sites. Kris has spent most of his career as a project manager and hydrogeologist in the environmental consulting field. In the past two decades, his projects were focused on investigating and managing petroleum and chlorinated solvent sites in the Mid-Atlantic Piedmont states. Kris spearheaded investigations for Alternate Water Supplies for the DEQ Petroleum Program for State Lead sites as a contractor for DEQ, including locating new supply well locations, tracking groundwater flow through fractured media, performing packer testing to sample and isolate impacted zones within a supply well, performing pump tests in fractured rock, and assessing bedrock sites for remediation of chlorinated solvents. While reaping the benefits of many ITRC webinars during his consulting career, Kris joined the Fractured Bedrock team soon after employment with DEQ. Kris is actively engaged as a chapter lead for the ITRC Optimization of In situ Remediation team beginning in 2018. Kris earned his Bachelor of Science degree in Geology from George Mason University in 1988 in Fairfax, Virginia and is a Certified Professional Geologist (CPG) in Virginia.

Richard Desrosiers is Vice President/Hydrogeologist for GZA GeoEnvironmental, Inc. in Glastonbury, Connecticut. Beginning his environmental career in the mid-1980s, Richard has focused on large complex geologic, hydrogeologic and geochemistry fate & transport problems associated with soil and groundwater contamination. He designed and led site investigations and remediation actions at a site with chlorinated solvents and hexavalent chromium encompassing a one square mile using high resolution site characterization and designing in-situ remediation remedies using chemical oxidation for VOC and biochemical reduction to treat hexavalent chromium and volatile organic compounds. Richard has completed RCRA/CERCLA hazardous waste investigations/closures; implemented in-situ innovative recirculation well technology to capture, treat and reinject remediate groundwater within the same well; identified and developed high yielding groundwater supplies in surficial and bedrock aquifers; completed numerous hydrogeologic evaluations and groundwater models; and has provided depositions, bench and jury expert testimony regarding litigation issues. Most recently, Richard leads GZA's PFAS initiative and has participated on CT PFAS Task Force Committees. Since 2015, Richard has been an active member on the Interstate Technology & Regulatory Council (ITRC) "Characterization and Remediation in Fractured Rock", "Optimization of In-Situ Remediation and Injection Strategies" and "Per- and Polyfluoroalkyl Substances (PFAS)" teams. Richard earned a bachelor's degree in Geology from Northeastern University in Boston, Massachusetts in 1982. He is a Licensed Environmental Professional in Connecticut and a licensed Professional Geologist in New Hampshire and Tennessee.

Suzanne O'Hara is a senior contaminant hydrogeologist with Geosyntec Consultants based in Ontario Canada. She has over 20 years of field and project management experience focusing on remediation of groundwater and soil containing recalcitrant compounds using innovative and more conventional technologies. She has directed, managed, or provided technical support for multiple projects ranging from overall strategy development, site investigation, remedial design, costing and implementation, contaminant fate and transport, and conceptual site model (CSM) development. Her technical experience involves dense non-aqueous phase (DNAPL) fate and transport in fractured media and the design, implementation and interpretation of innovative in situ remediation technologies for complex contaminated sites. Suzanne's remediation technology experience includes enhanced in situ bioremediation (EISB), in situ chemical oxidization (ISCO) and reduction (ISCR), Self-sustaining Treatment for Active Remediation (STAR) thermal remediation, passive treatment using zero-valent iron barriers, and reductive dechlorination using emulsified zerovalent iron (EZVI) for DNAPLs. Suzanne has been involved in ITRC since 2017 as a team member of the Optimizing Injection Strategies and In Situ Remediation Performance team. Suzanne earned a bachelor's degree in Earth Science (geology) from the University of Waterloo, Ontario, in 1994 and a master's in Hydrogeology from the University of Waterloo, Ontario, in 1997. Suzanne is a Professional Geoscientist in Ontario and a Professional Geologist in New York.

Elizabeth Rhine is an Independent Consultant in Greenville, South Carolina. She has more than 25 years of professional experience focused on the characterization and remediation of impacted sites in the chemical, oil and gas, and transportation sectors. She is adept at developing creative and cost-effective remediation strategies for clients to meet the objectives of project stakeholders including responsible parties, regulatory agencies, potential developers, and the public. Her work has focused primarily in groundwater remediation of sites under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and Resource Conservation and Recovery Act (RCRA), developing site conceptual models, evaluating site conditions for in situ groundwater remedies, indoor air quality, regulatory compliance, environmental liability valuations, transactional due diligence, and brownfield redevelopment. Elizabeth is the author or co-author of more than a dozen peer-reviewed technical papers and has presented at a number of conferences and universities. Elizabeth earned a bachelor's degree in biology from Furman University in Greenville, South Carolina in 1989 and a master's in business administration with an emphasis in data management in 1998.

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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

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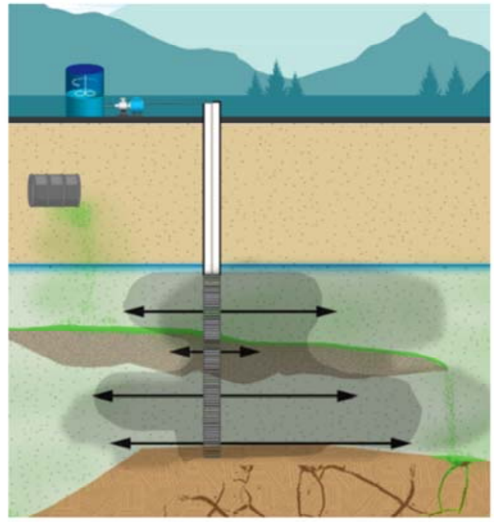
In Situ Remediation

- 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



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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

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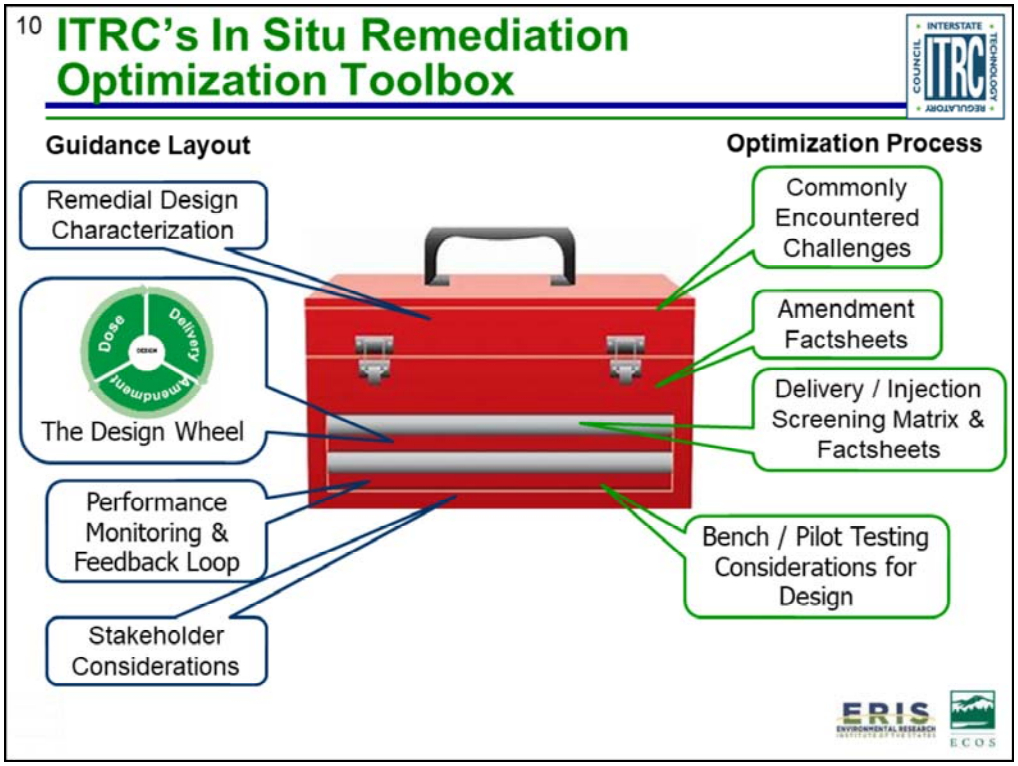
What is Optimization?

- 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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ITRC's In Situ Remediation Optimization Toolbox
Guidance Layout
Optimization Process
Remedial Design Characterization
Dose
Delivery
Amendment
DESIGN
The Design Wheel
Performance Monitoring & Feedback Loop
Stakeholder Considerations
Commonly Encountered Challenges
Amendment Factsheets
Delivery / Injection Screening Matrix & Factsheets
Bench / Pilot Testing Considerations for Design

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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

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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

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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

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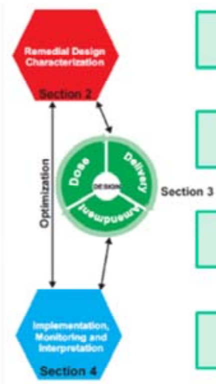
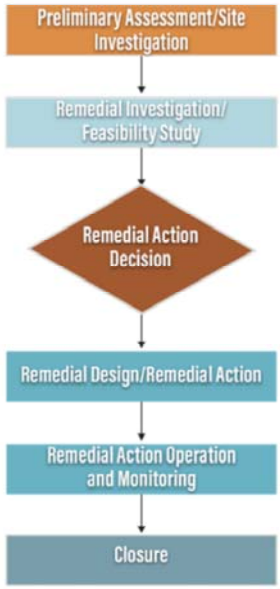
Presentation Road Map



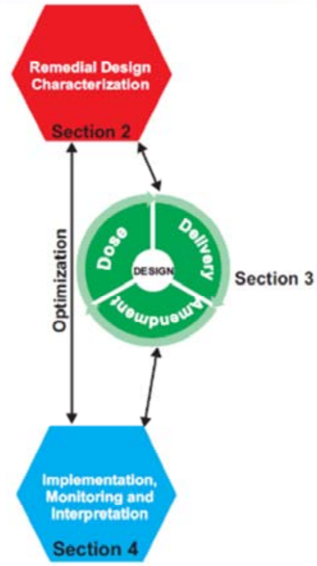
- **Optimization Process**
- Remedial Design Characterization
- Design: Amendment, Dose & Delivery
- Implementation, Monitoring & Interpretation
- Regulatory & Stakeholder Considerations

Learning Objective: Identify challenges

Linear Paradigm to Iterative Process

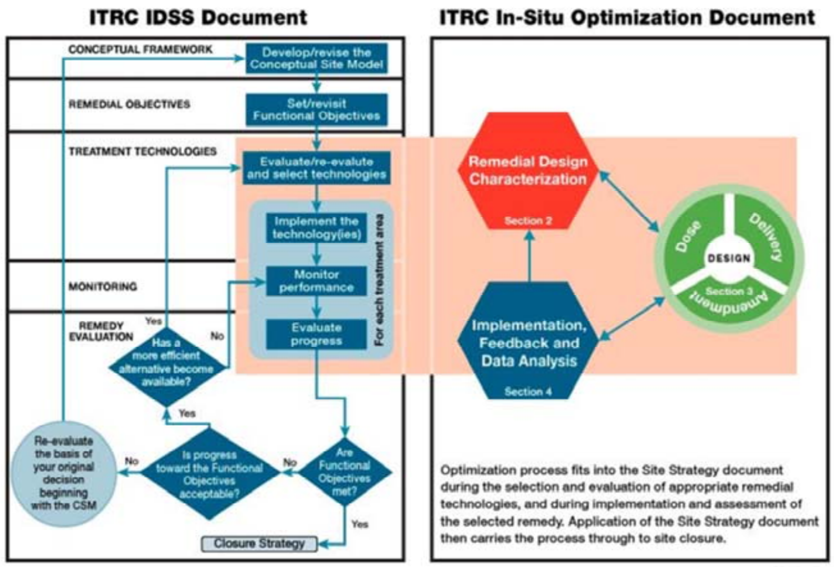


ITRC OIS-ISRP-1 Figure 5-1



ITRC OIS-ISRP-1 Figure 3-1

17 **ITRC Documents Support Interactive/Iterative Approach**



ITRC OIS-ISRP-1 Figure 1-1

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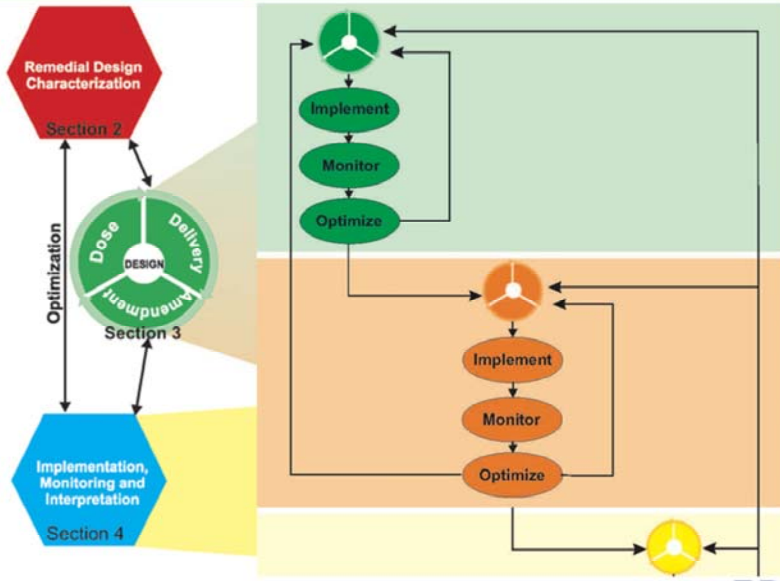
Iterative Approach to Optimization



ITRC OIS-ISRP-1 Figure 3-1

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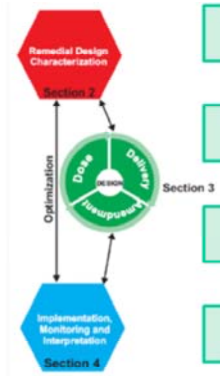
Presentation Road Map



- 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

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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

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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

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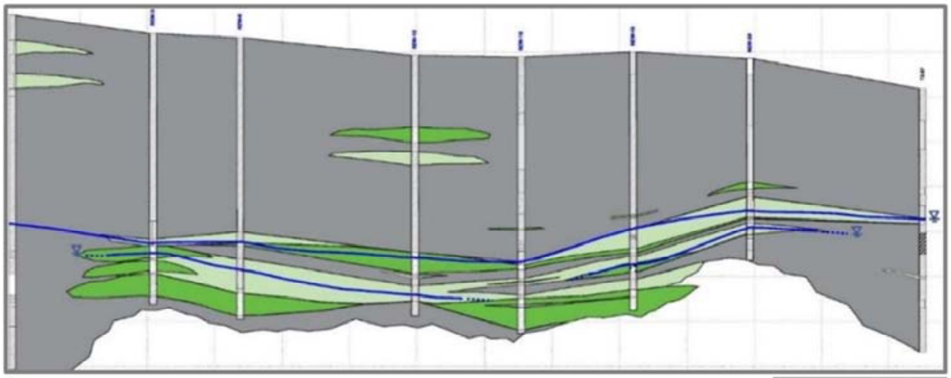
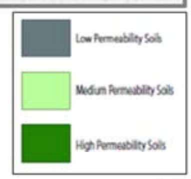
The Impact of Data



HYDROGEOLOGIC DATA:

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



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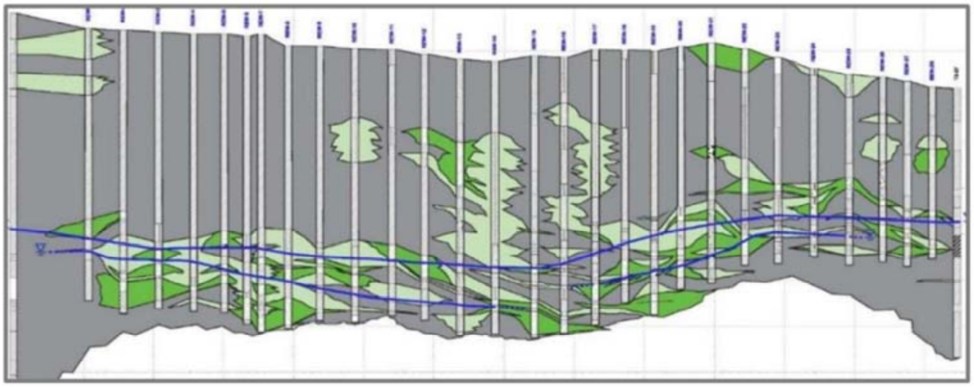
The Impact of More Data



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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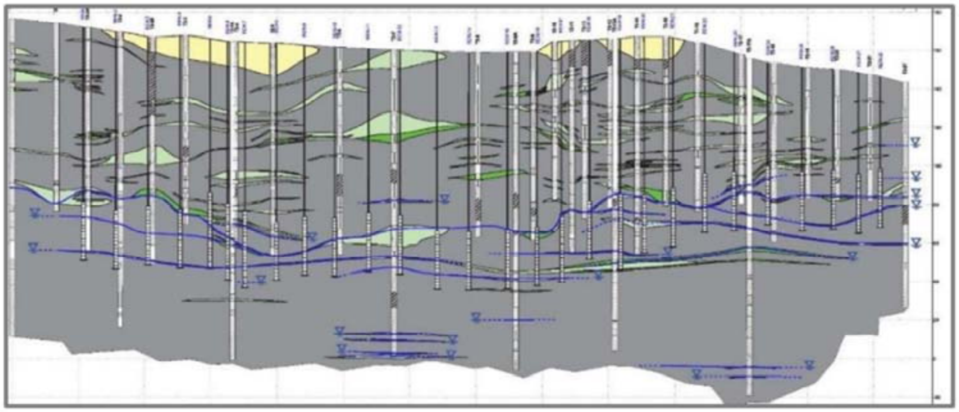
The Impact of More (and More) Data



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

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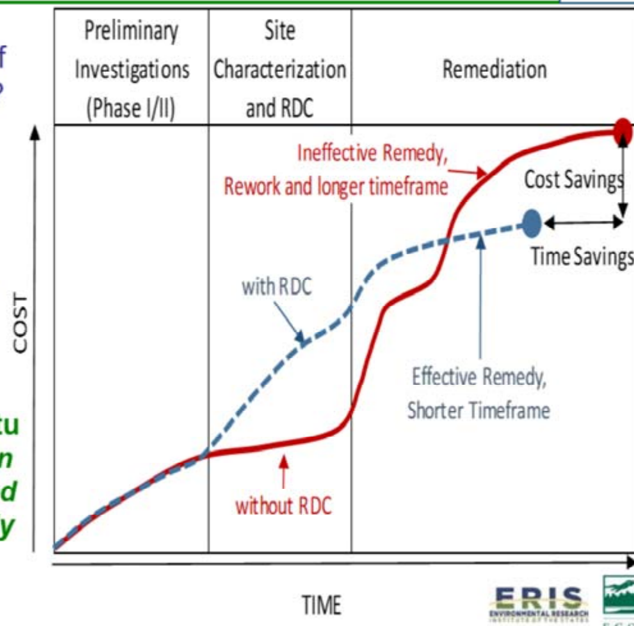
RDC - Why Do It? (Redux)

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

***Remember*: 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

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Value of Investigation (VOI) Case Study

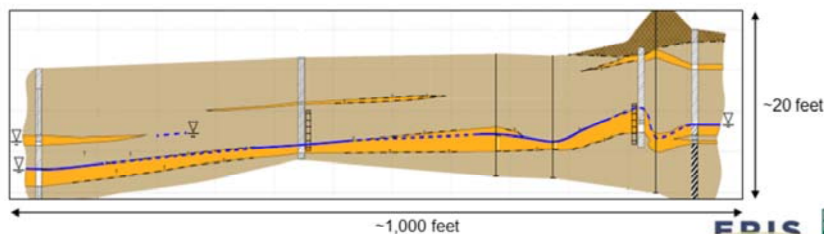
Case Study

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



ITRC OIS-ISRP-1 Section 2.1.2

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Value of Investigation (VOI) Case Study

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

Poll Question

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

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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

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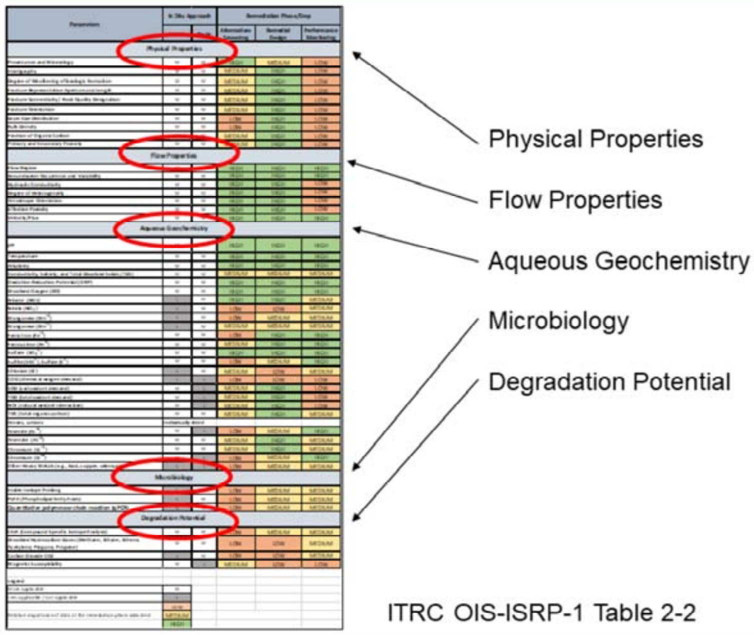
What Do We Need To Know? “THE TABLE” (2-2)



ITRC OIS-ISRP-1 Table 2-2

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and When? (Table 2-2)

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

ITRC OIS-ISRP-1 Table 2-2

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 ...n	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

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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.

Parameters	In Situ Approach		Remediation Phase/Step		
	[illegible]	[illegible]	Alternatives [illegible]	Remedial Design	Performance Monitoring
[illegible]	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

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Flow Properties

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

Parameters	In Situ Approach		Remediation Phase/Step		
			...ves ...ng	Remedial Design	Performance Monitoring
				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

ITRC OIS-ISRP-1 Table 2-2

Flow Properties

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

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
De[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

ITRC OIS-ISRP-1 Table 2-2

Aqueous Geochemistry

ITRC OIS-ISRP-1 Table 2-2

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).

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

The Redox Ladder

Poll Question

Terminal Electron Acceptors	→	Associated Metabolic Byproducts
Oxygen (O_2)	Oxidizing	Water (H_2O)
Nitrate (NO_3^-)	Reducing	Nitrite (NO_2), Nitrogen (N_2)
Tetrachloroethene (PCE)		Trichloroethene (TCE), Chloride (Cl^-)
Manganic Manganese (Mn^{4+})		Manganous Manganese (Mn^{2+})
Ferric Iron (Fe^{3+})		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^{3-})		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.

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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
Sulf	M	M	LOW	MEDIUM	HIGH
Chloride Cl^-	L	M	MEDIUM	LOW	MEDIUM
[illegible]	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

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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 ...	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

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Q&A Break

Follow ITRC:

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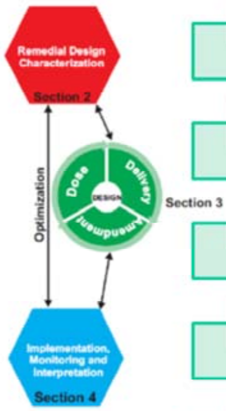
Presentation Road Map



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

Learning Objective: Determine amendment, dosing and delivery options

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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

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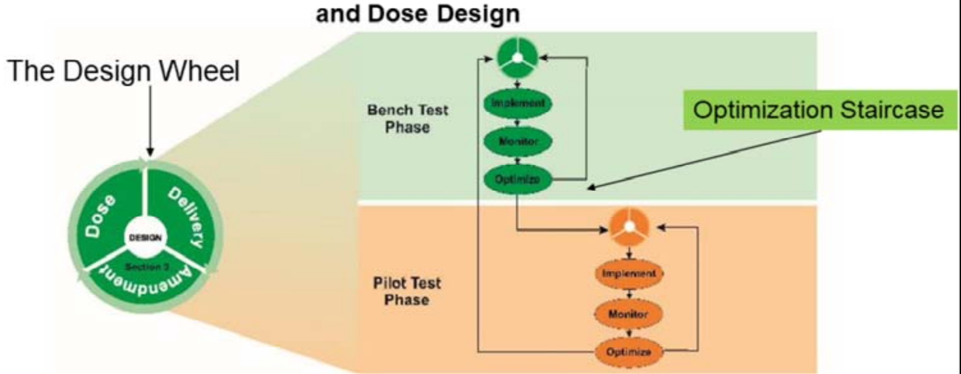
Iterative Nature of Design

Section 3: Amendment, Delivery and Dose 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

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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

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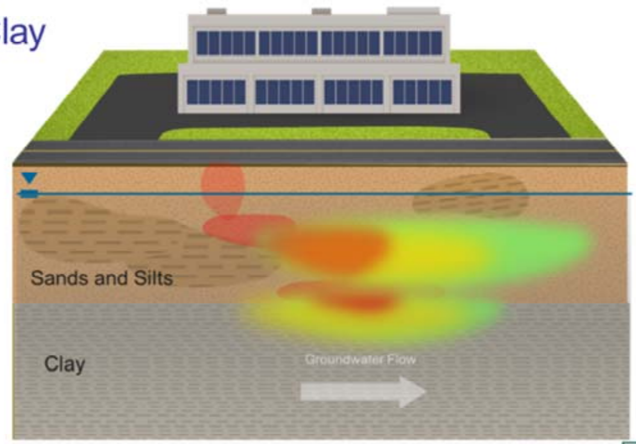
Design Support Elements

- 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

- Solvent release
- Sand and Silt
- Underlying Clay



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

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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

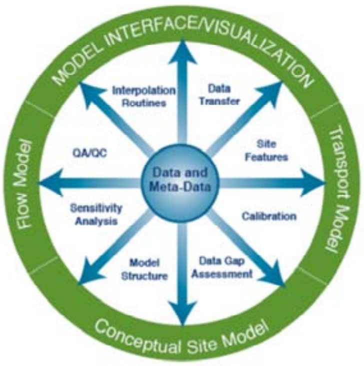

Image used with permission of Geosyntec Consultants.

50 **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

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Poll Question

Poll Question

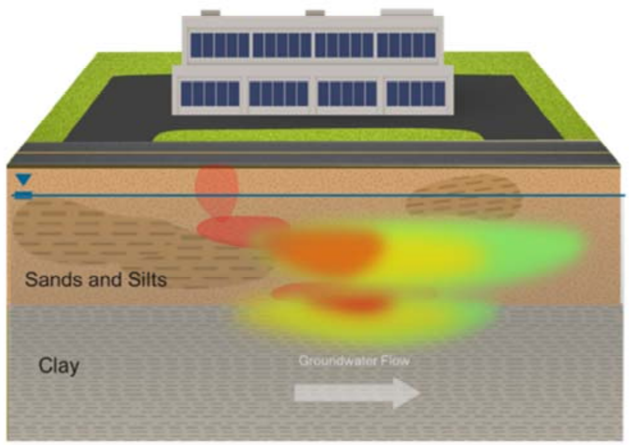
- Have you used Bench Tests in your design for an in situ remedy?
  - Yes
  - No
- If you have used Bench Tests in your design for an in situ remedy did the results change your approach?
  - Yes
  - No

Section 3

53

Bench Tests Results

- 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



Case Study

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

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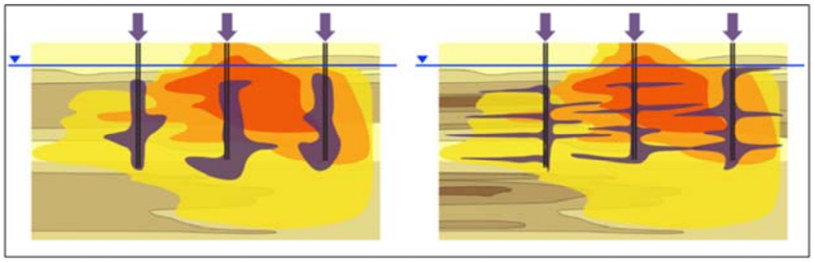
Field Pilot Tests Objectives

- 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

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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

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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

- 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

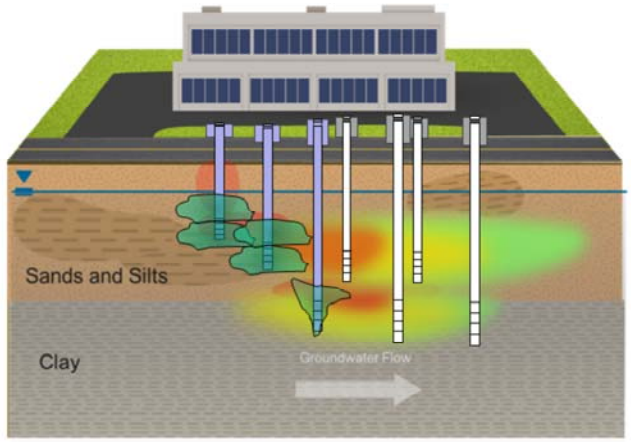
Direct Push Injection (DPI) [D1]	Injection Through Wells & Boreholes [D2]	Electrokinetics This is injection through wells. [D3]	Solid Injection [D4]: Hydraulic Delivery Through Wells & Boreholes [D5]	Solid Injection [D4]: Pneumatic Delivery Through Open Boreholes [D6]	Permeable Reactive Barriers (PRBs) [D7]
•	▣	•	•	•	•
•	▣	•	•	•	•
•	•	▣	•	•	▣
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

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

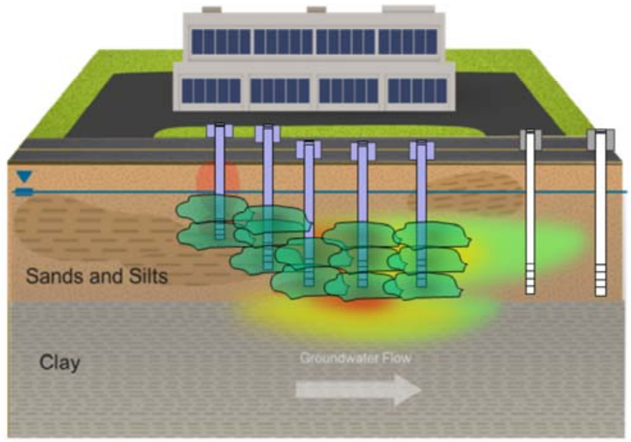
ERIS ENVIRONMENTAL RESEARCH INSTITUTE OF THE STATES

ECOS

61 **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

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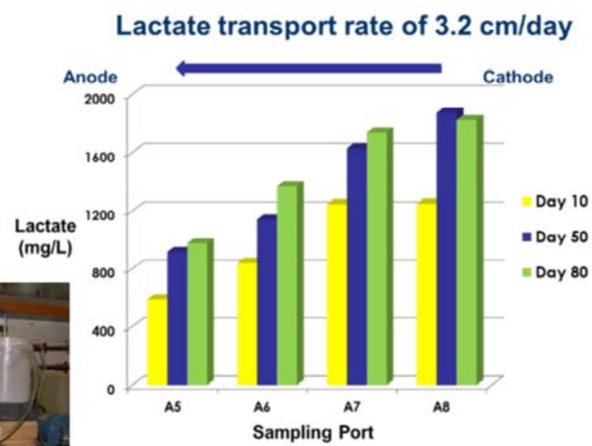
Return to Bench Testing

Case Study

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



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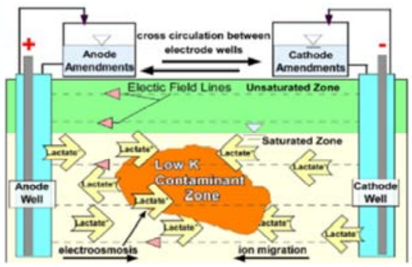
Return to Pilot Testing

Case Study

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



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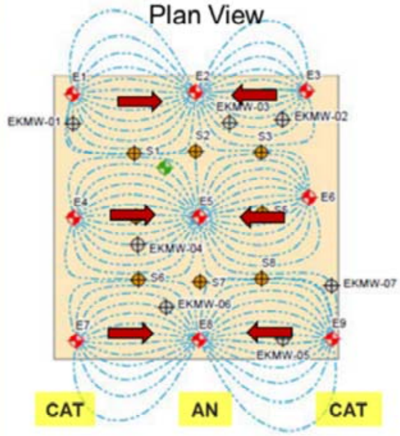
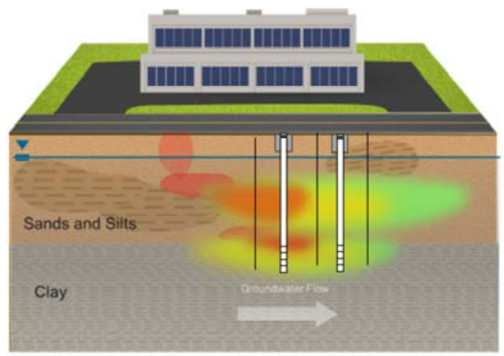
Full Scale Clay Layer– EK-Bio

Case Study

- Clay Layer
  - EK-Bio Implementation

Plan View





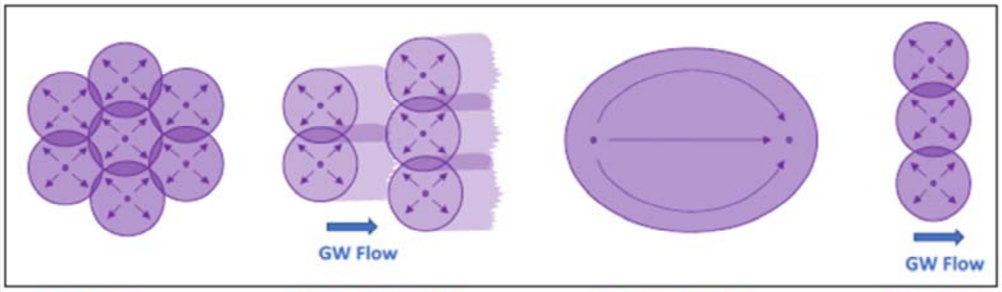
Example Case Study – image prepared using Health Canada CSM Builder Tool 2015; Graphics used with permission of Geosyntec Consultants.

Electrode Well Supply Well

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:



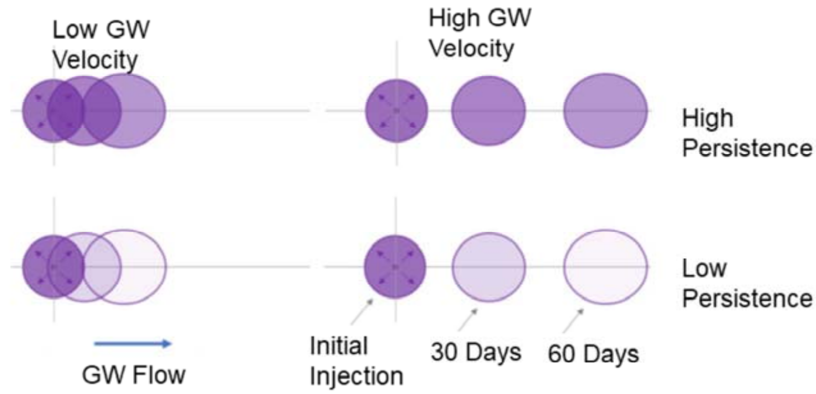
Grid Pattern | Inject and Drift | Recirculation | Barrier

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:

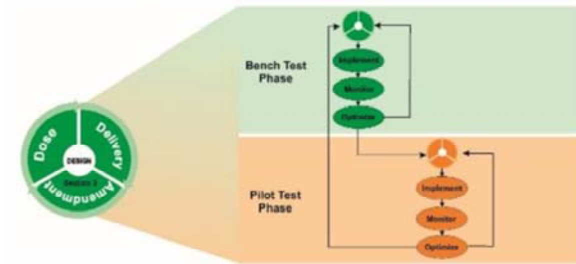


ITRC OIS-ISRP-1 Figure 3-2

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

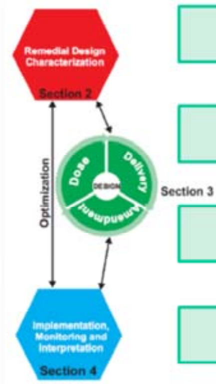
Remedial Design is Iterative

- 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.

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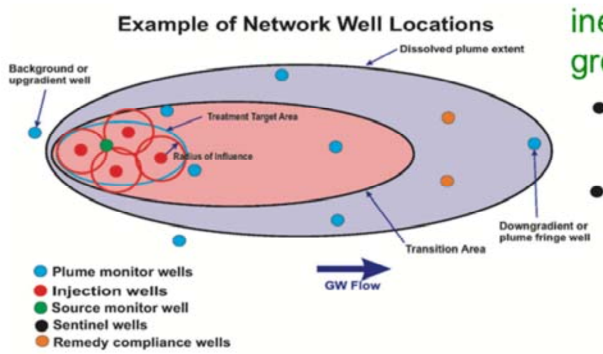
Implementation and Feedback Monitoring Optimization

- Baseline monitoring
- Monitoring at startup
- Compliance monitoring



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

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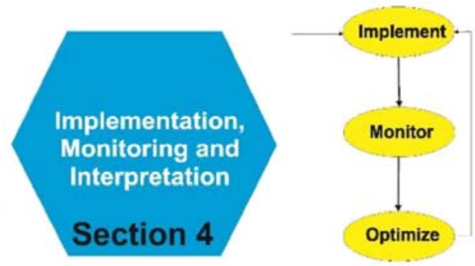
Applying Optimization to Underperforming Remedies

- 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

Case Study

- 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

Case Study

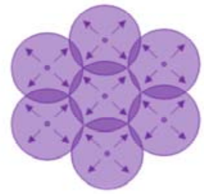
- Implemented anaerobic in situ bioremediation
- Optimized bioremediation remedy
  - Evaluate monitoring data monthly – don't wait for the annual report
  - Know when to anticipate changes in groundwater chemistry and respond early
- Incorporated hydraulic fracturing to improve distribution

Case Study – Remedy Design

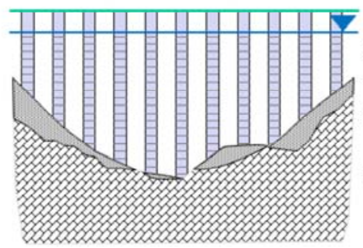
Case Study

- 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

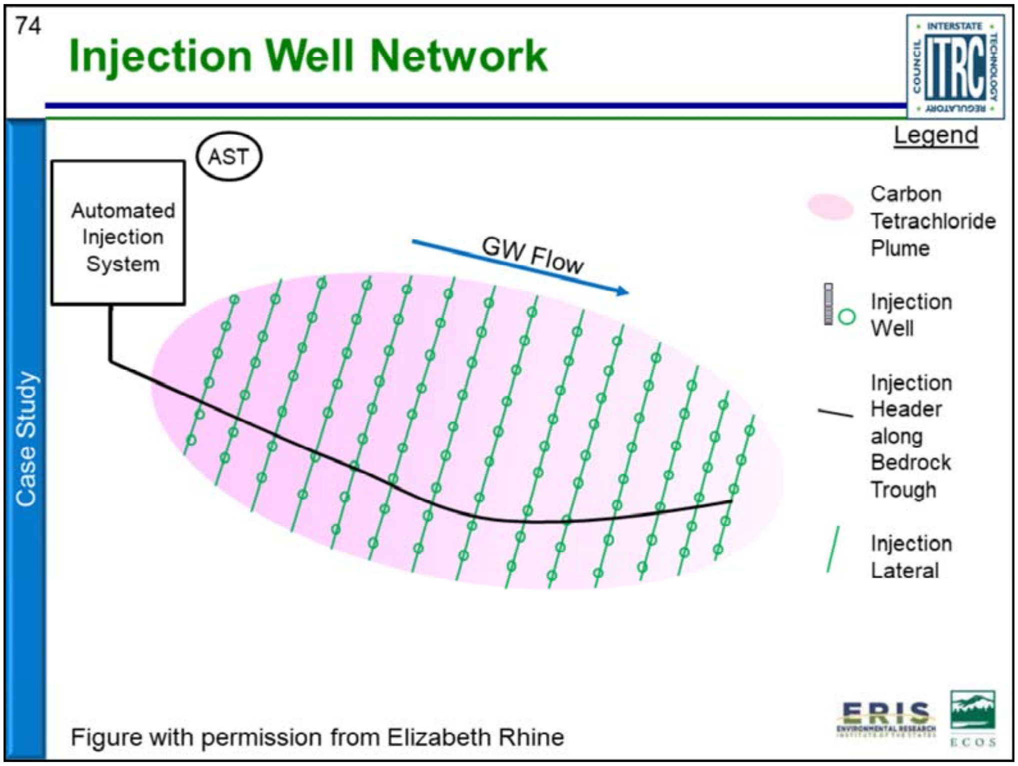
Plan View



Cross Section



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


74
Injection Well Network
Case Study
AST
Automated Injection System
GW Flow
Legend
Carbon Tetrachloride Plume
Injection Well
Injection Header along Bedrock Trough
Injection Lateral
Figure with permission from Elizabeth Rhine

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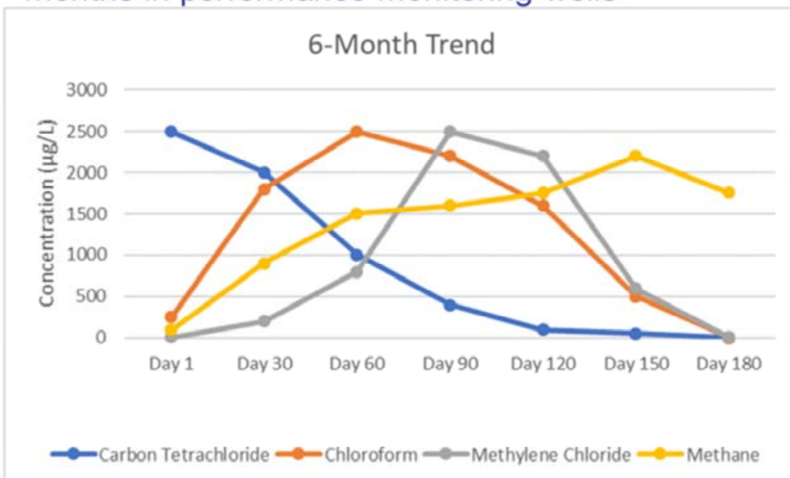
Good News…

Case Study

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



Graph with permission of Elizabeth Rhine

…But Not Quite The Expected

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
Graph with permission of Elizabeth Rhine

Resulting Plume Configuration

Case Study

Injection Well Network

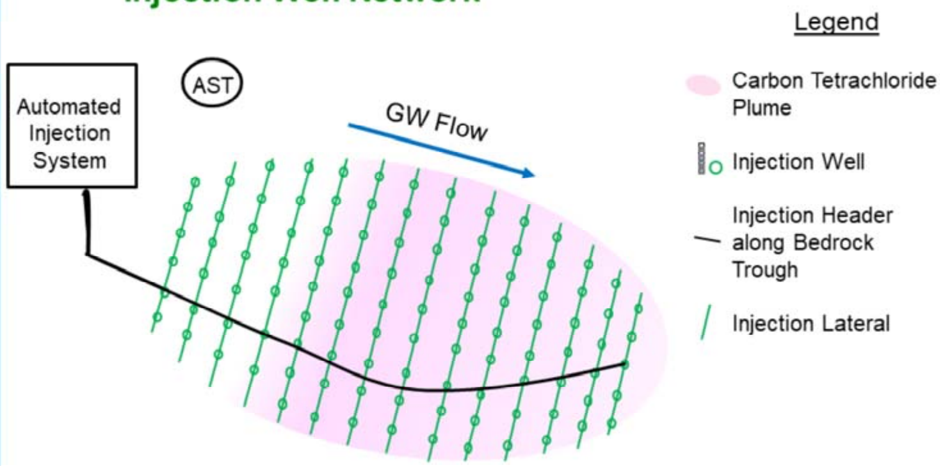


Figure with permission from Elizabeth Rhine

Redox Parameter Evaluation

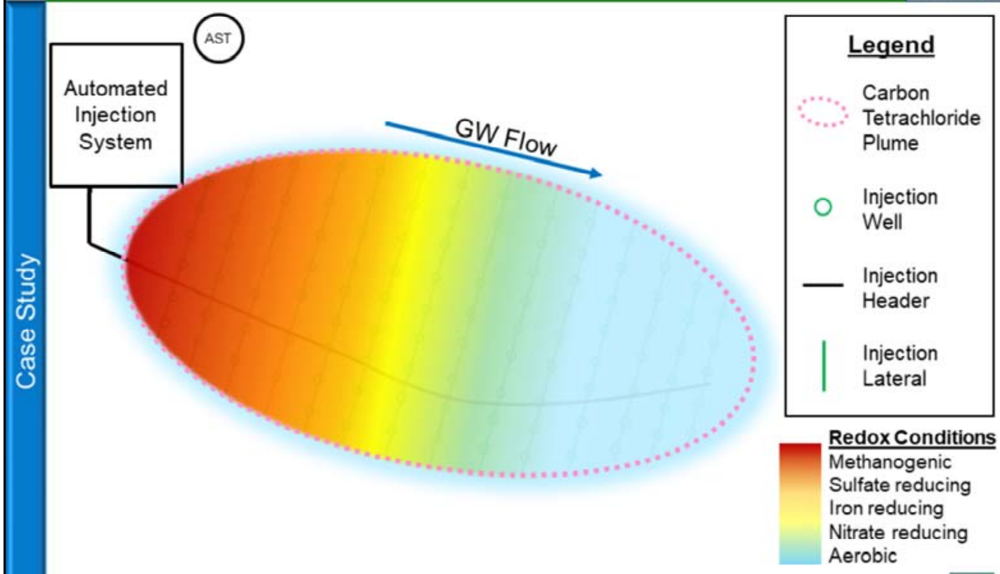


Figure with permission from Elizabeth Rhine

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Poll

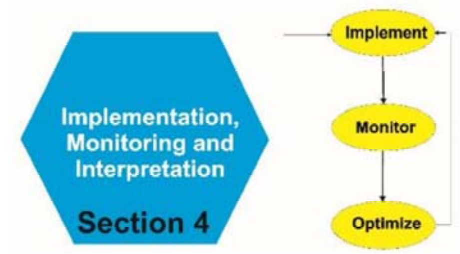
Poll Question

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



Full-Scale Phase

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Optimization 1 – Operational Changes

Case Study

	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

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12 Months after Optimization 1

Case Study

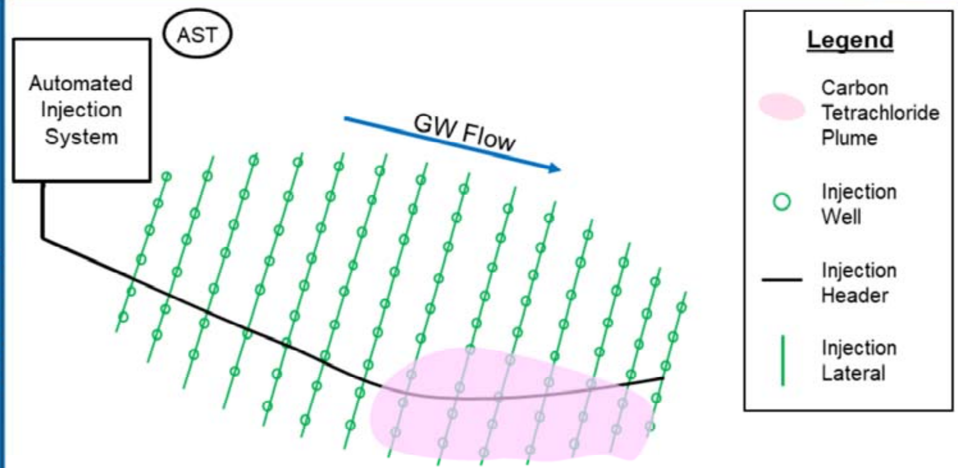

Figure with permission from Elizabeth Rhine

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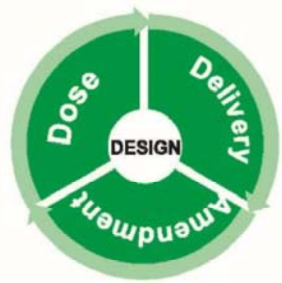
Poll

Poll Question

- 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



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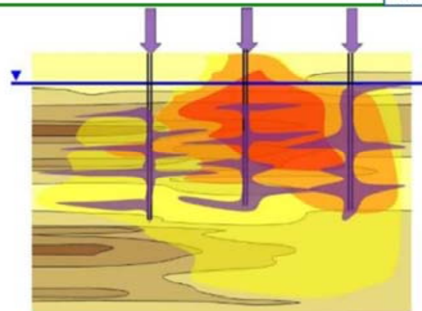
Optimization 2 - Concept

- 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

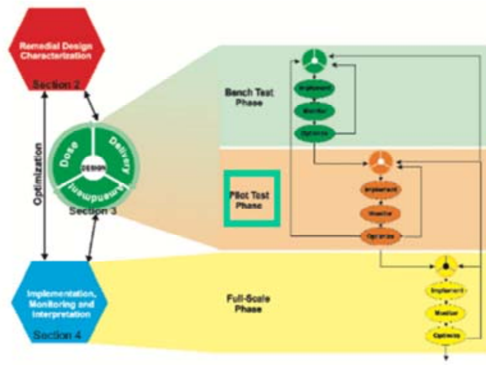
Case Study

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

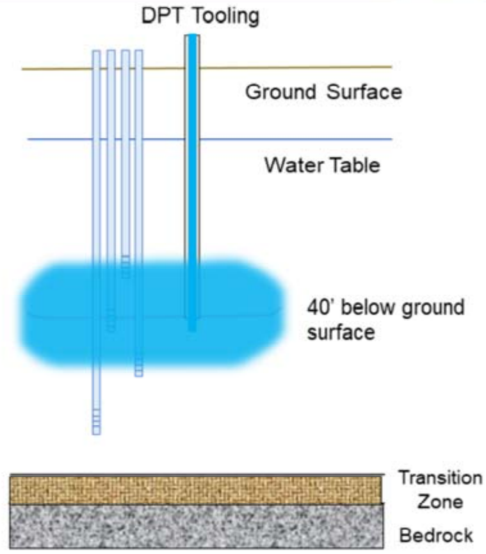


ITRC OIS-ISRP-1 Figure 3-1

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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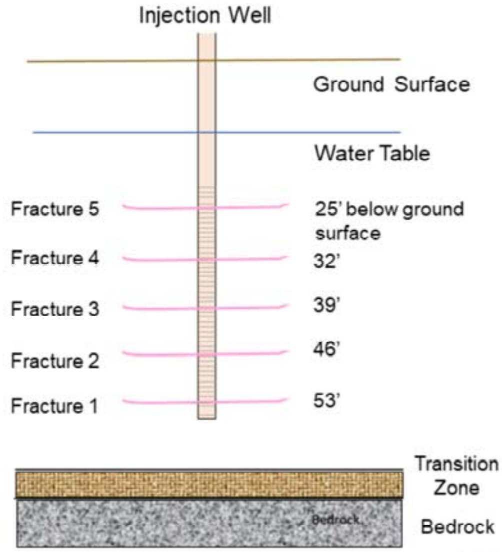
Hydraulic Fracture – Stacked Fractures

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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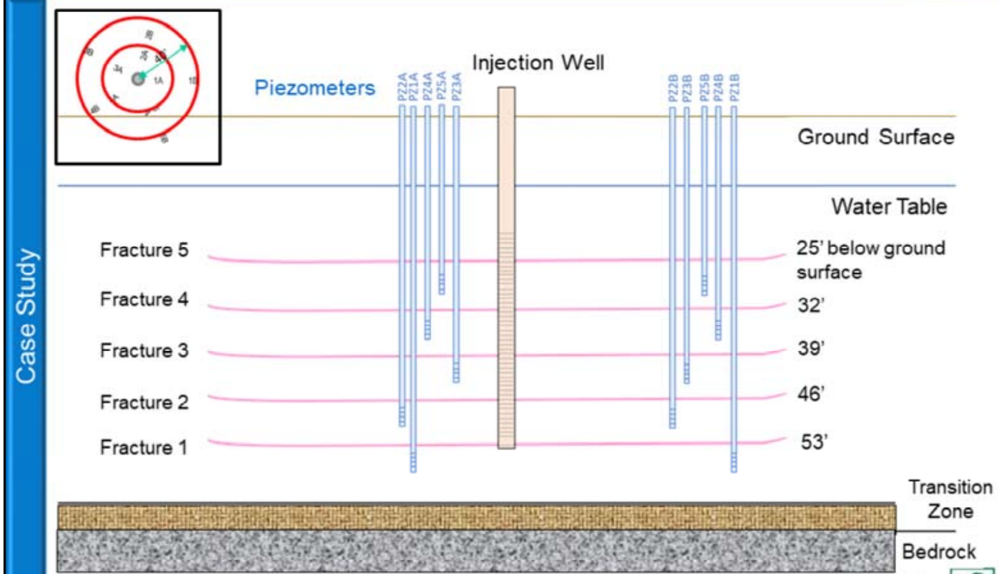
Hydraulic Fracture – Full Pilot Test



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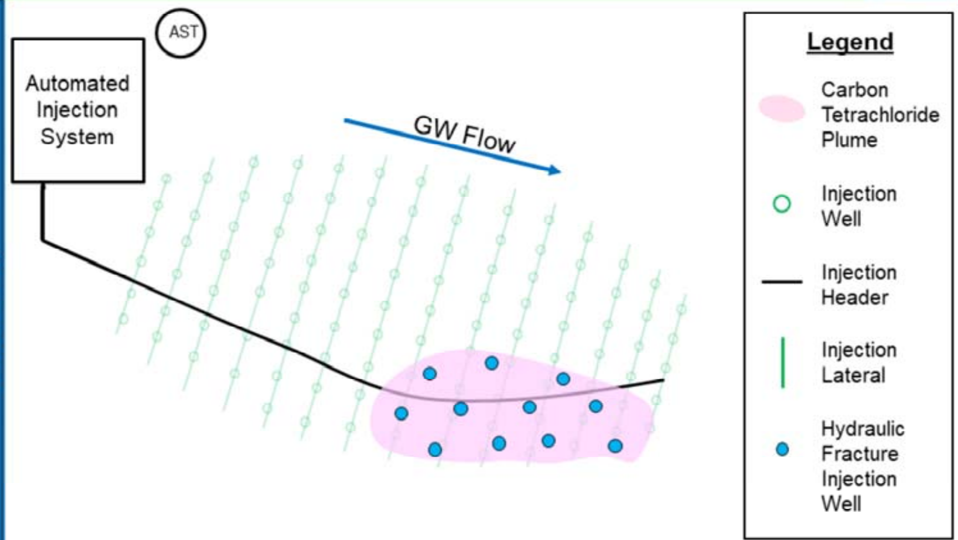
Rebound Study Conducted Elsewhere

Case Study

- 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

Optimization 2 – Startup

Case Study



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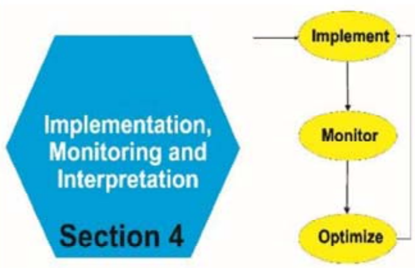
Recap of Hydraulic Fracturing

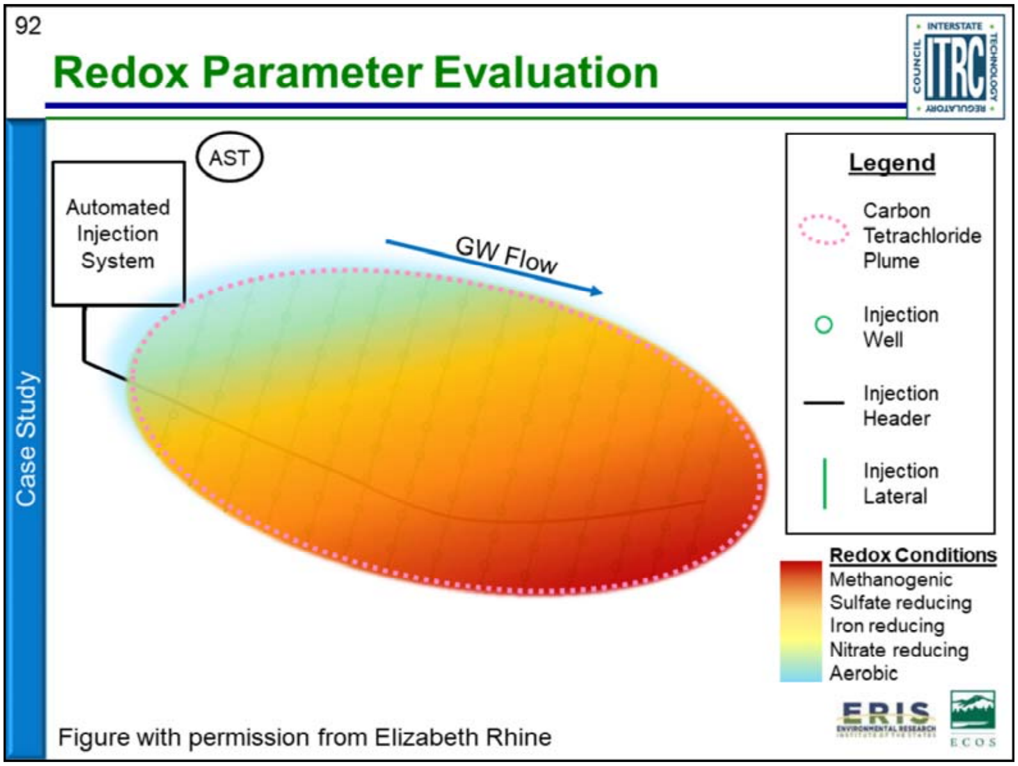
Case Study



- 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


92
Redox Parameter Evaluation
Case Study
AST
Automated Injection System
GW Flow
Legend
Carbon Tetrachloride Plume
Injection Well
Injection Header
Injection Lateral
Redox Conditions
Methanogenic
Sulfate reducing
Iron reducing
Nitrate reducing
Aerobic
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ERIS
ENVIRONMENTAL RESEARCH
ECOS

Optimization 3 – Transition to MNA

Case Study

- 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

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Optimization 3: MNA Phase

Case Study

- 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

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Closure/Brownfield Redevelopment

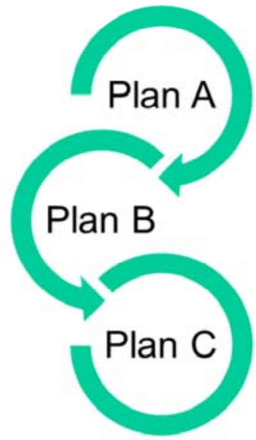
Case Study

- 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

Key Concepts from Case Study

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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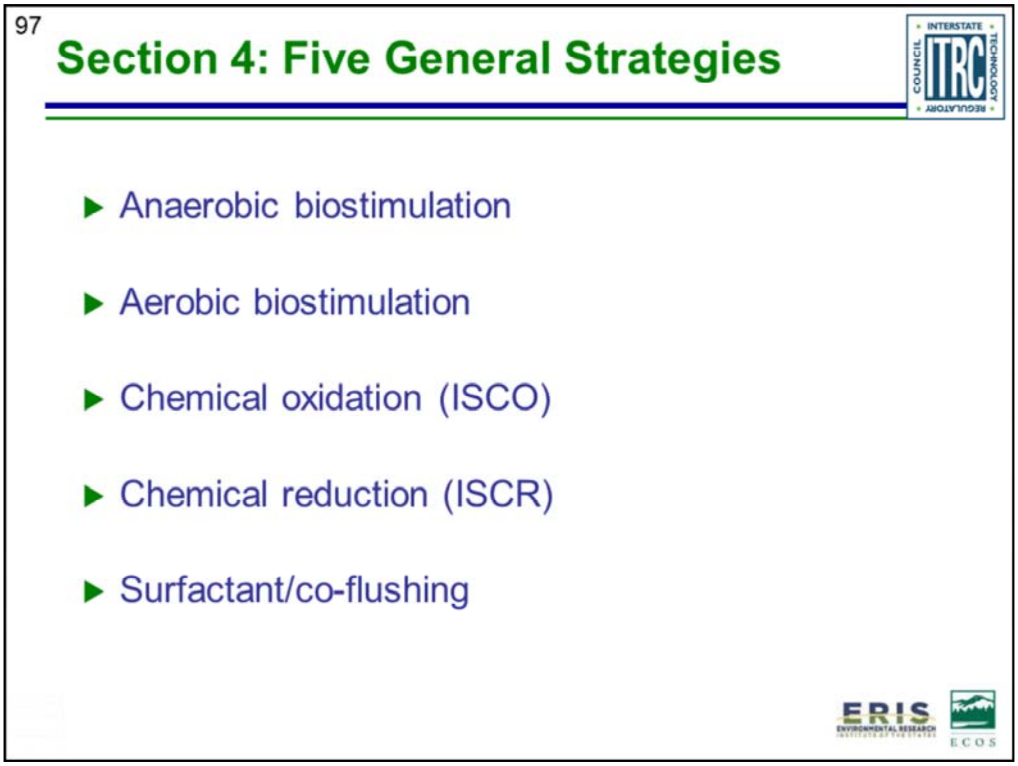
97
Section 4: Five General Strategies
Anaerobic biostimulation
Aerobic biostimulation
Chemical oxidation (ISCO)
Chemical reduction (ISCR)
Surfactant/co-flushing

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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

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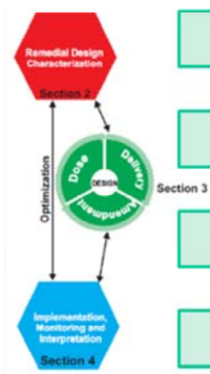
Presentation Road Map



- 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

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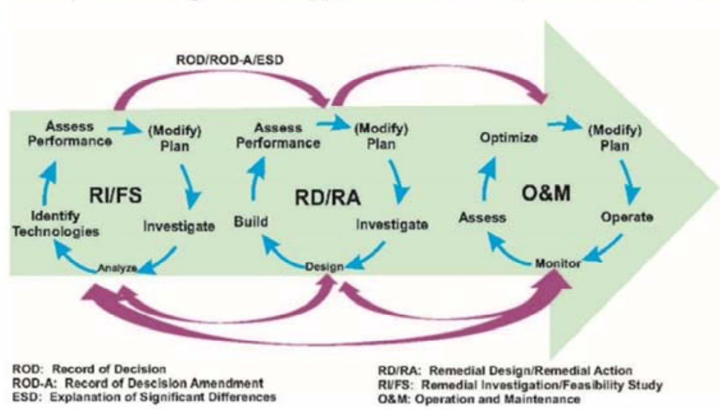
Regulatory Considerations

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

Adaptive Management's Application in the Superfund Process



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

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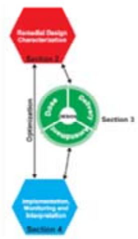
Stakeholder Considerations

- 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

102 **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

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Thank You

Follow ITRC:

Poll Question

- **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.