Naval Facilities Engineering Command

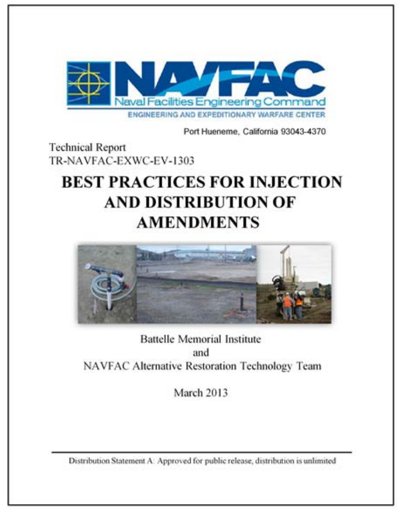
Best Practices for the *In Situ* Distribution of Amendments

RITS 2014

All photos courtesy of Battelle unless otherwise noted

Presentation Overview

- Introduction
- Refining the Conceptual Site Model
- Design Considerations
- Implementation Challenges
- Performance Monitoring and Verification
- Wrap Up


NAVFAC
Naval Facilities Engineering Command
ENGINEERING AND EXPEDITIONARY WARFARE CENTER
Port Hueneme, California 93043-4370

Technical Report
TR-NAVFAC-EXWC-EV-1303

BEST PRACTICES FOR INJECTION AND DISTRIBUTION OF AMENDMENTS

Battelle Memorial Institute
and
NAVFAC Alternative Restoration Technology Team

March 2013

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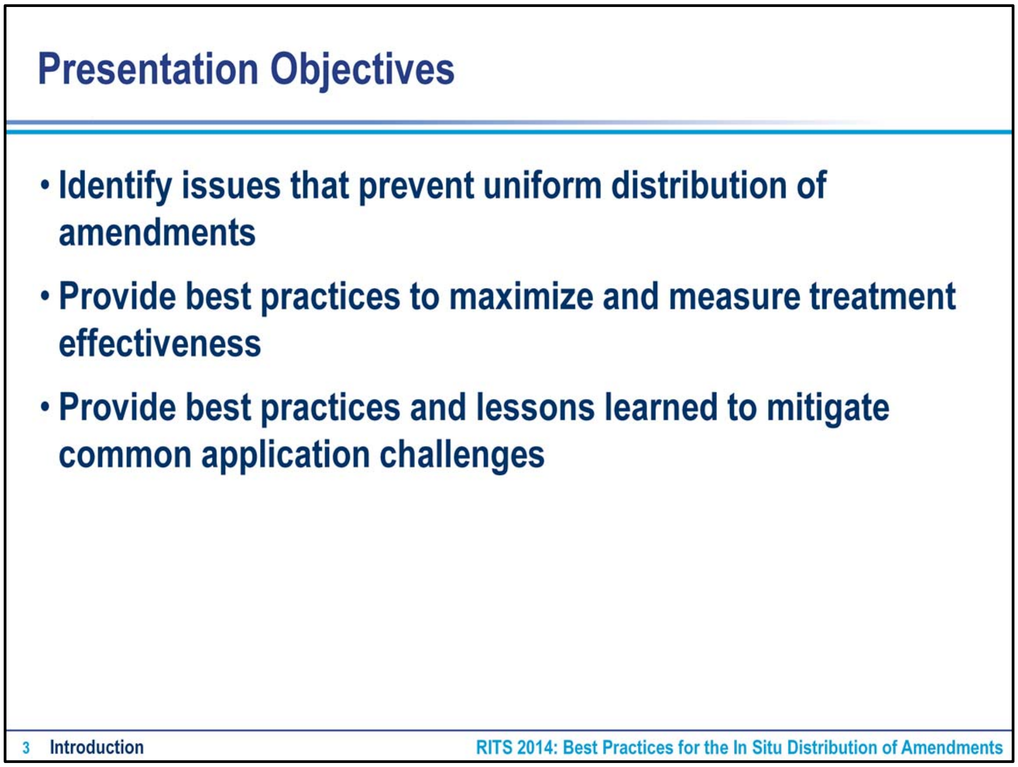
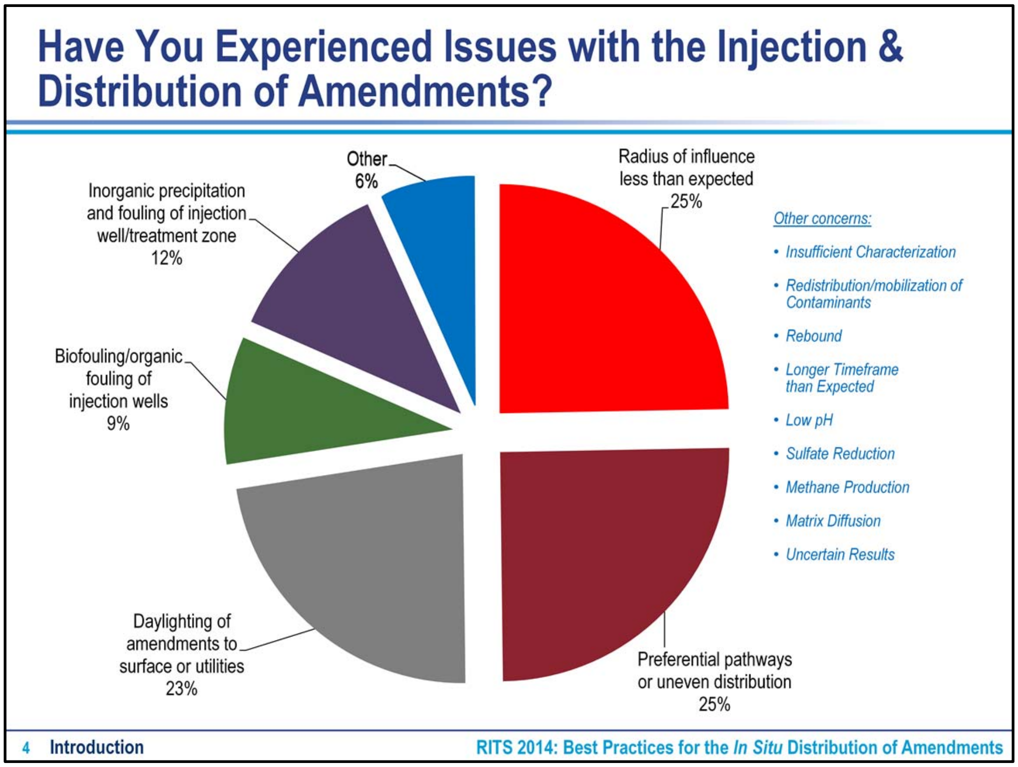
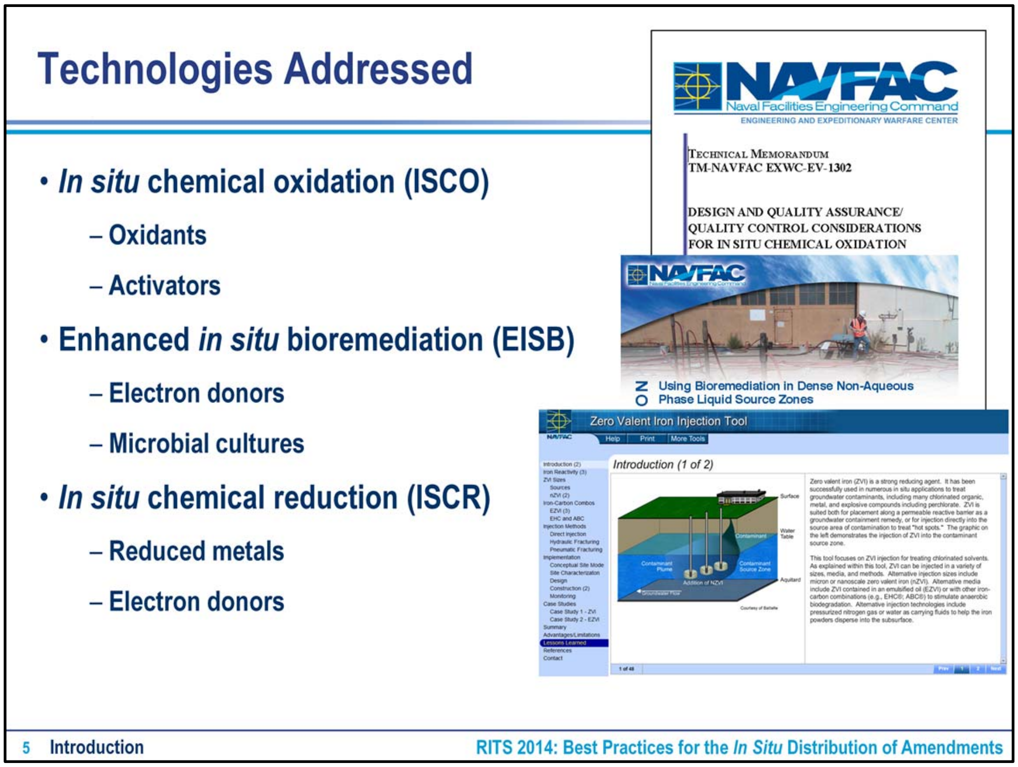


- Widely-used toolbox of technologies that rely on amendments
- Past experience has shown an inability to achieve adequate distribution and contact between amendments and COCs
- Lessons learned must be shared and standardized approaches must be developed

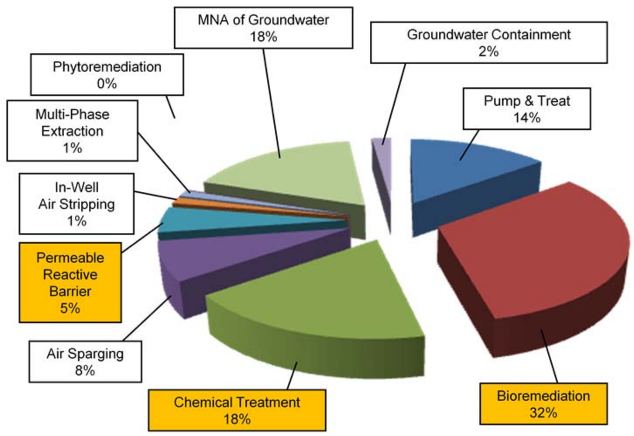


51% of those surveyed responded that they have had problems with the introduction and distribution of amendments

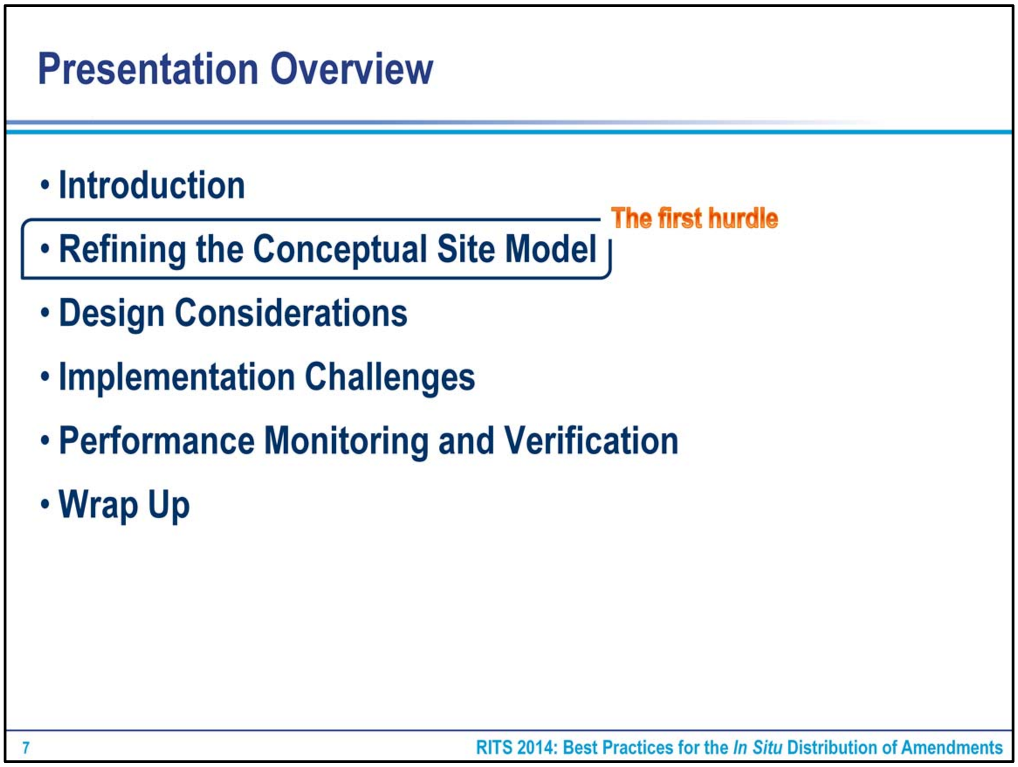


- ISCO is a chemical reaction induced by contacting a strong oxidant with contaminants to create harmless byproducts.
- EISB relies on the addition of organic substrates and sometimes microbial cultures to stimulate biodegradation.
- ISCR utilizes a reactive metal, typically elemental iron, to treat groundwater contaminants

Types/Percentages of Restoration Technologies Currently Used



Adapted from: Superfund Remedy Report, 14th Edition, EPA, 2013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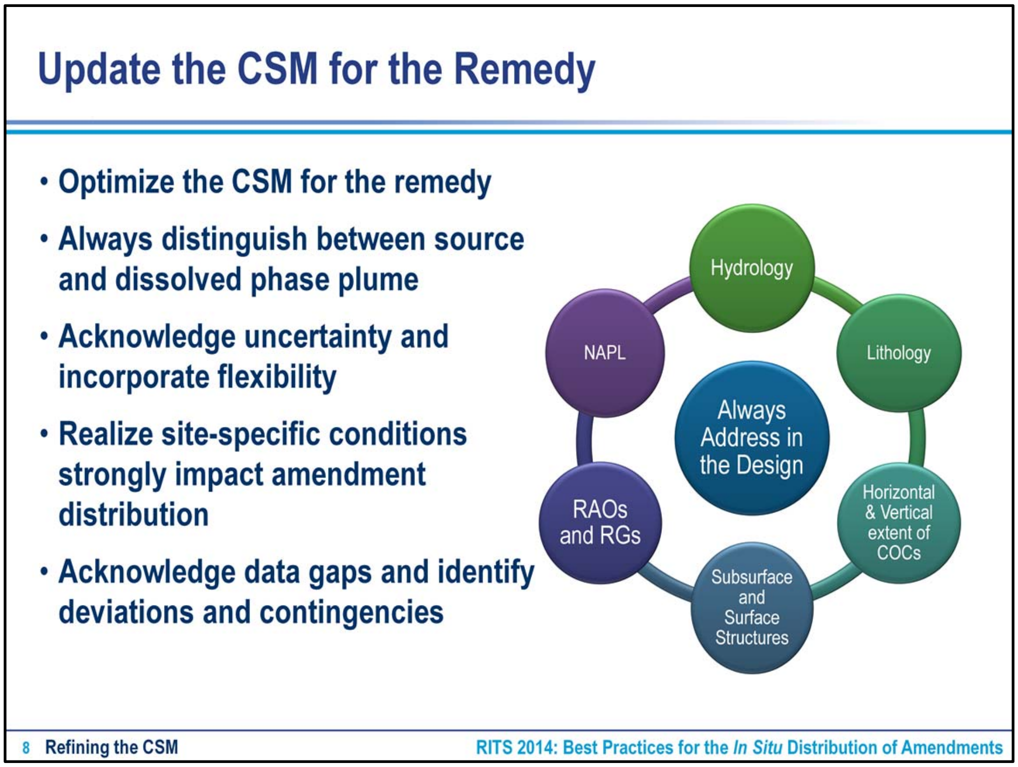


Impacts of Site-Specific Conditions on Ability to Introduce/Distribute Amendments

Hydraulic conductivity and aquifer anisotropy
- Groundwater and amendment flow follow path of least resistance. Low conductivity regions may not be adequately treated. Additional injections may be required in those regions.
- Impacts radius of influence and injection methods utilized

Lithology
- Fracturing may be required in low permeability aquifers
- Heterogeneities will influence flow pathways
- Presence of COCs in low permeability aquifer material can back diffuse over extended time

Presence of NAPL
- Impacts reagent demand
- Contributes to substantial rebound if only dissolve phase is treated
- Contributes to back diffusion (especially from low permeability areas)
- Mobility will impact type and extent of treatment

Horizontal extent of contamination
- Degree of treatment, which could include only the source area, a portion or all of the dissolved phase plume, or combination of both

Vertical extent of contamination
- COCs distributed across regions having low hydraulic conductivities are more difficult to treat
- Depth of contamination will influence cost and design (*i.e.*, direct push, recirculation wells, aboveground recirculation, *etc.*)

Subsurface utilities and conduits
- Potential pathway for groundwater and reagents
- Potential pathway for volatile gases generated

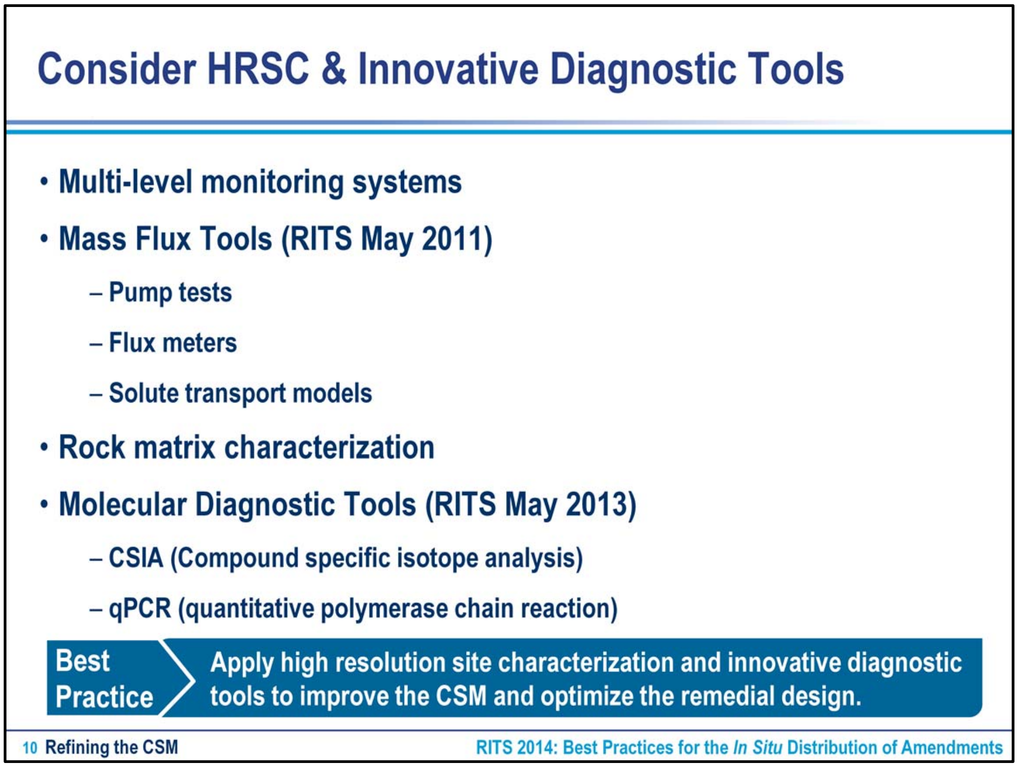
Aboveground structures
- Potential for vapor intrusion may impact dosages of reagents
- Number of well and well spacing may be limited in some areas

RAOs and RGs
- Number and spacing of points
- Mass of amendments injected

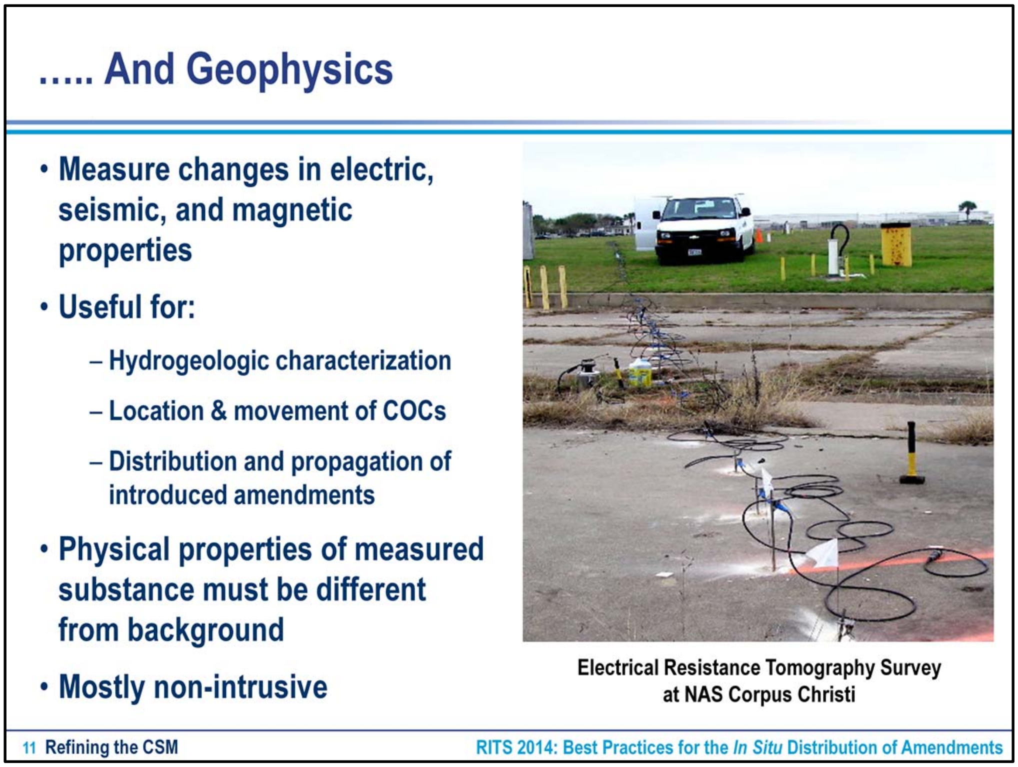
Site-Specific Impacts on Reagent Distribution Technique (from ESTCP ER-0623)

Parameter	Vertical Injection Wells	Vertical Recirculation Wells	Horizontal Wells	Direct-push Technology Injection	Hydraulic Fracture	Pneumatic Fracture
Amenability to Media Type						
Unconsolidated media	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
Consolidated media	Excellent	Good	Excellent	Not recommended	Excellent	Excellent
Fracture Continuity						
Good fracture continuity	Good	Good	Fair	Not recommended	Good	Good
Poor fracture continuity	Fair	Poor	Poor	Not recommended	Good	Good
Hydraulic Conductivity						
$>10^{-3}$ cm/sec	Excellent	Excellent	Excellent	Excellent	Poor	Poor
$<10^{-3}$ but $>10^{-4}$ cm/sec	Good	Fair	Fair	Excellent	Fair	Fair
$<10^{-4}$ but $>10^{-5}$ cm/sec	Fair	Poor	Poor	Good	Good	Good
$<10^{-5}$ but $>10^{-6}$ cm/sec	Poor	Not recommended	Not recommended	Fair	Excellent	Excellent
$<10^{-6}$ cm/sec	Not recommended	Not recommended	Not recommended	Not recommended	Excellent	Excellent
Lithology						
Homogeneous (Kmax/Kmin <1,000)	Excellent	Excellent	Excellent	Excellent	Excellent	Fair
Heterogeneous (Kmax/Kmin >1,000)	Fair	Fair	poor	Good	Fair	Fair
Type of Heterogeneity						
Layered heterogeneous	Fair	Fair	Poor	Good	Good	Good
Randomly heterogeneous	Fair	Fair	Fair	Good	Fair	Fair
Scale of Heterogeneities (distance between alternating lenses)						
Small (<0.3 m)	Good	Good	Poor	Good	Poor	Poor
Medium (0.3-1 m)	Fair	Fair	Poor	Fair	Fair	Good
Large (>1 m)	Fair	Fair	Fair	Good	Good	Good
Depth of Delivery						
<5 m bgs	Excellent	Excellent	Excellent	Excellent	Fair	Fair
<10 m bgs but >5 m bgs	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
<25 m bgs but >10 m bgs	Excellent	Excellent	Good	Fair	Excellent	Excellent
<50 m bgs but >25 m bgs	Good	Good	Poor	Poor	Excellent	good
>50 m bgs	Good	Good	Not recommended	Not recommended	fair	fair
Site Activity Disruption Intensity						
Buildings, active roads, restricted areas	Light	Moderate	Very Light	Moderate	Light	Light
Subsurface utilities, foundations, *etc.*	Light	Light	Light	Moderate	Moderate	Moderate

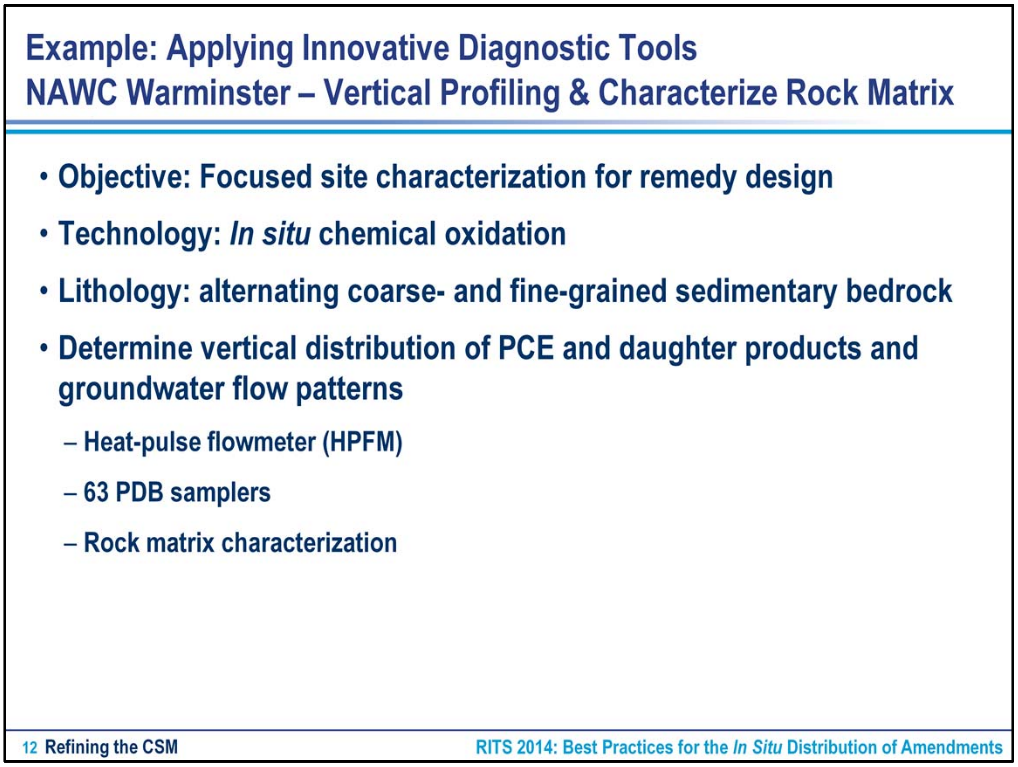
9 **Refining the CSM** RITS 2014: Best Practices for the *In Situ* Distribution of Amendments



- Multi level monitoring systems facilitate identification of preferential pathways (COCs and reagents)
- Mass flux tools measure source strength
- Rock matrix characterization determines distribution of contaminants of COCs and advective flow pathways in fractured media
- Molecular diagnostic tools can be used to evaluate abiotic versus biotic and chemical versus physical changes

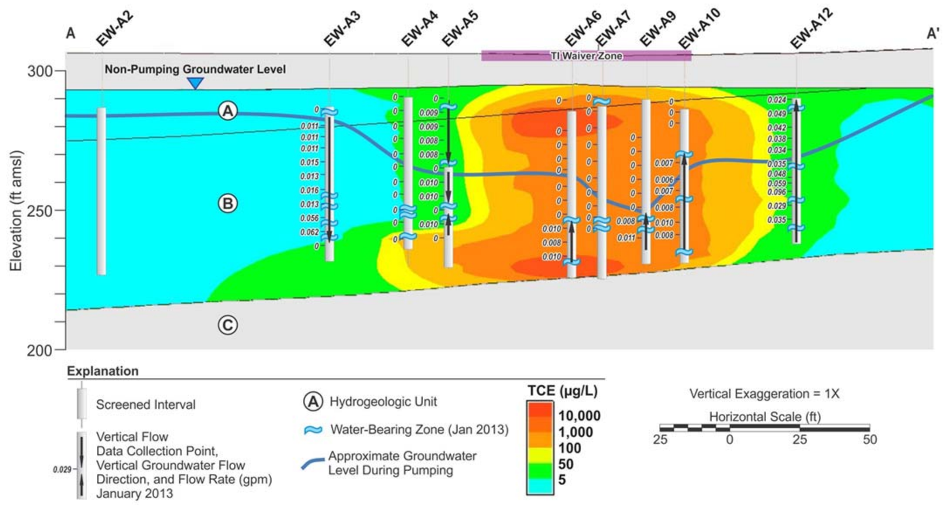


- Common geophysical methods employed include ground penetrating radar, electrical resistance tomography, seismic reflection, cross well radar, borehole flowmeters and electromagnetic induction techniques.
- Geophysics relies on the use of various sensors to detect changes in electric, seismic, and magnetic properties. Changes in these properties can be related to changes that occur in the aquifer during the application of a remedy.
- There is however, a tradeoff between depth and resolution. Good resolution can be achieved at deep depths; however, this requires using in-well electrodes, which result in greater cost than surface electrodes.



- Objectives of the Area A well profiling evaluation are to better understand the vertical distribution of dissolved chemicals, identify water-bearing zones, and evaluate the potential for vertical borehole flow in selected wells within the proposed study area at Area A.
- A HPFM is comprised of a heated grid located between two thermistors, and operates by diverting nearly all flow to the center of the device where the heating grid driven by electric current triggered from the ground surface lightly heats a thin zone of water (U.S. Geological Survey [USGS], 1998). Natural vertical flow rate and direction are calculated based on the time it takes for the heated water to flow between the two thermistors and the direction of the flow.
- Changes in fluid resistivity reflect changes in the concentration of dissolved solids in a well, which can be used to determine an entry or exit of water from the borehole
- fluid temperature data can be used to identify water-producing and water-receiving fractures as well as determine intervals of vertical fluid flow within a borehole
- Correlation of caliper logs with fluid-resistivity and fluid-temperature logs was used to identify water producing and water-receiving fractures or zones in the study area wells.
- Passive diffusion bag samples, ranged from five to eight samples per well
- 50 rock samples collected for VOC characterization

Warminster Vertical Profiling Results



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Best Practices for Refining the CSM

- Achieve an optimum level of characterization
- Distinguish between source and dissolved plume
- Know horizontal AND vertical extent of COCs and flows/directions
- Use high resolution site characterization techniques

Key Point: Perform additional characterization during the design phase to significantly reduce application and monitoring cost and time to achieve RGs.

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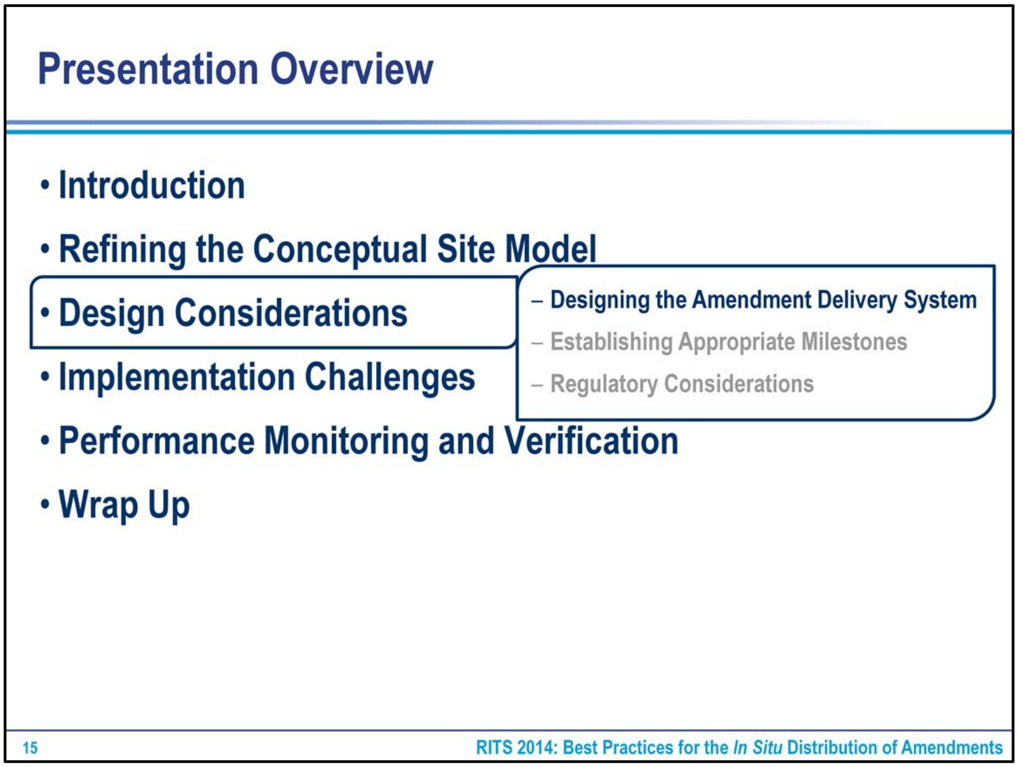
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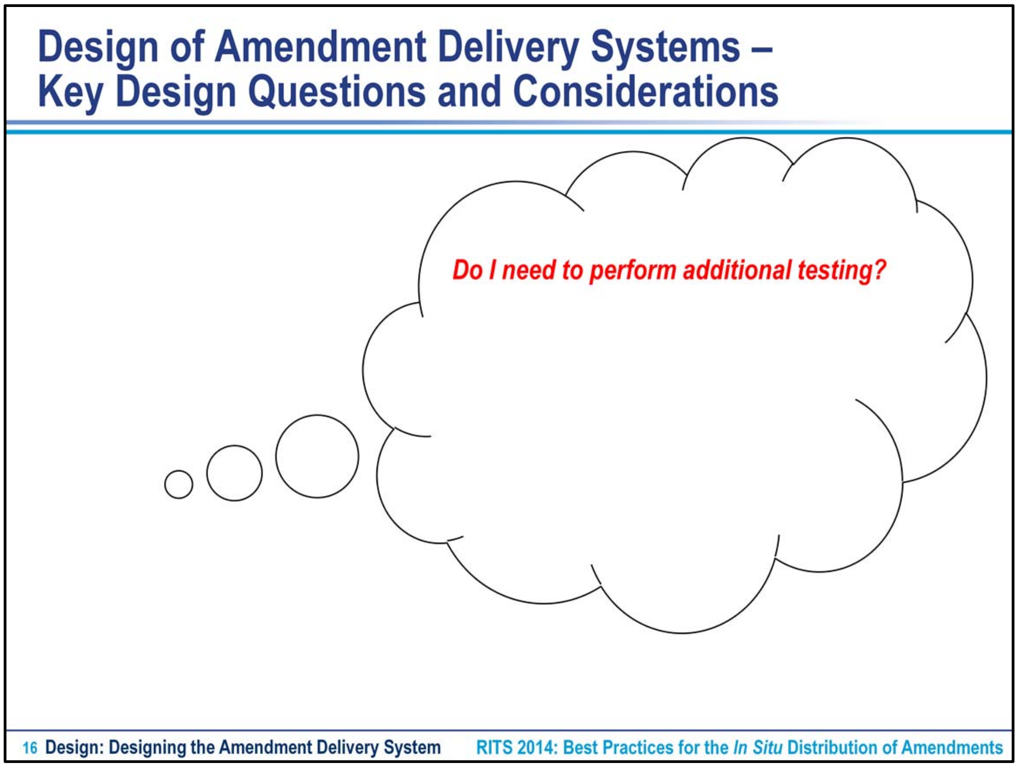
Design of Amendment Delivery Systems –
Key Design Questions and Considerations
Do I need to perform additional testing?
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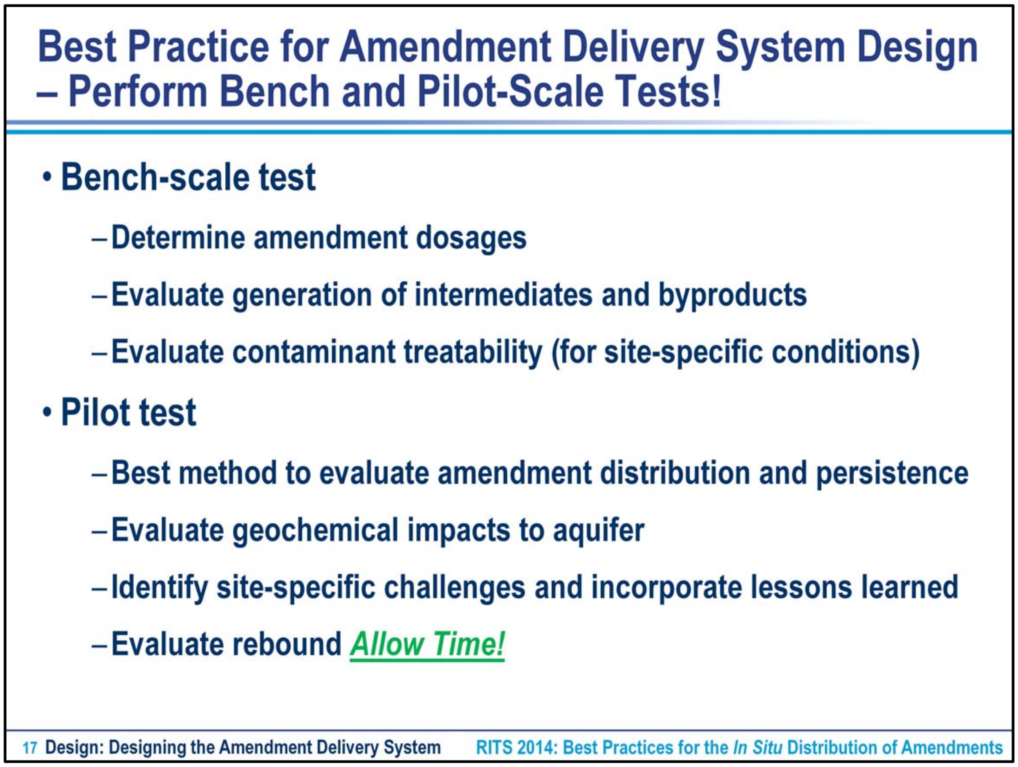
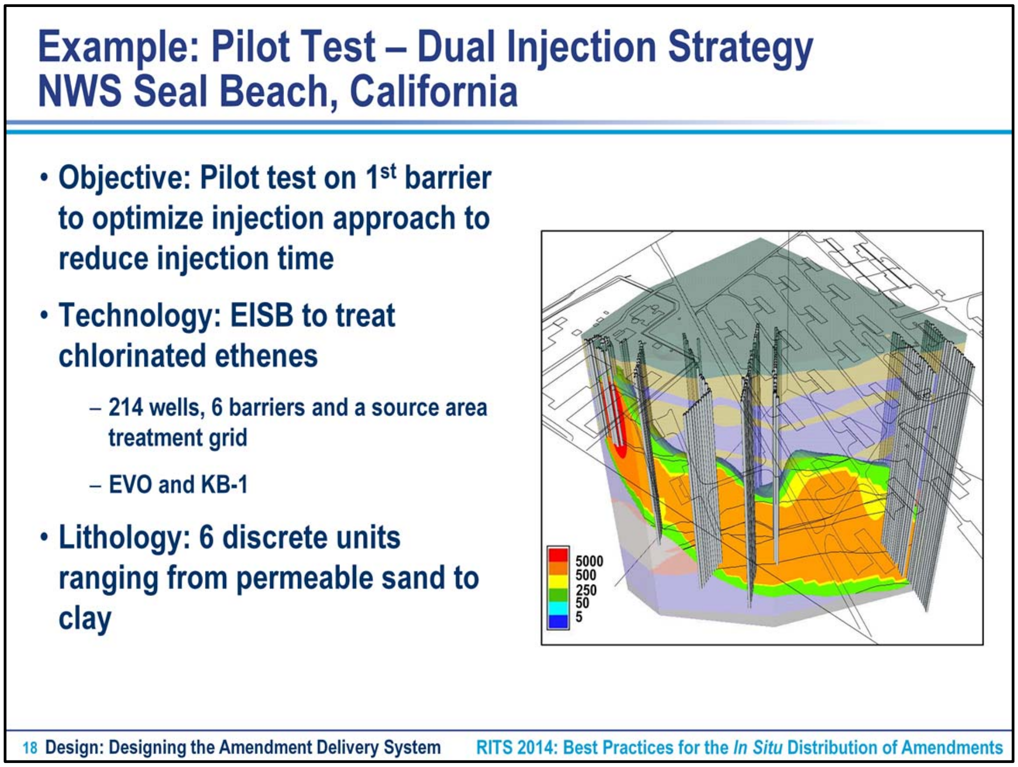
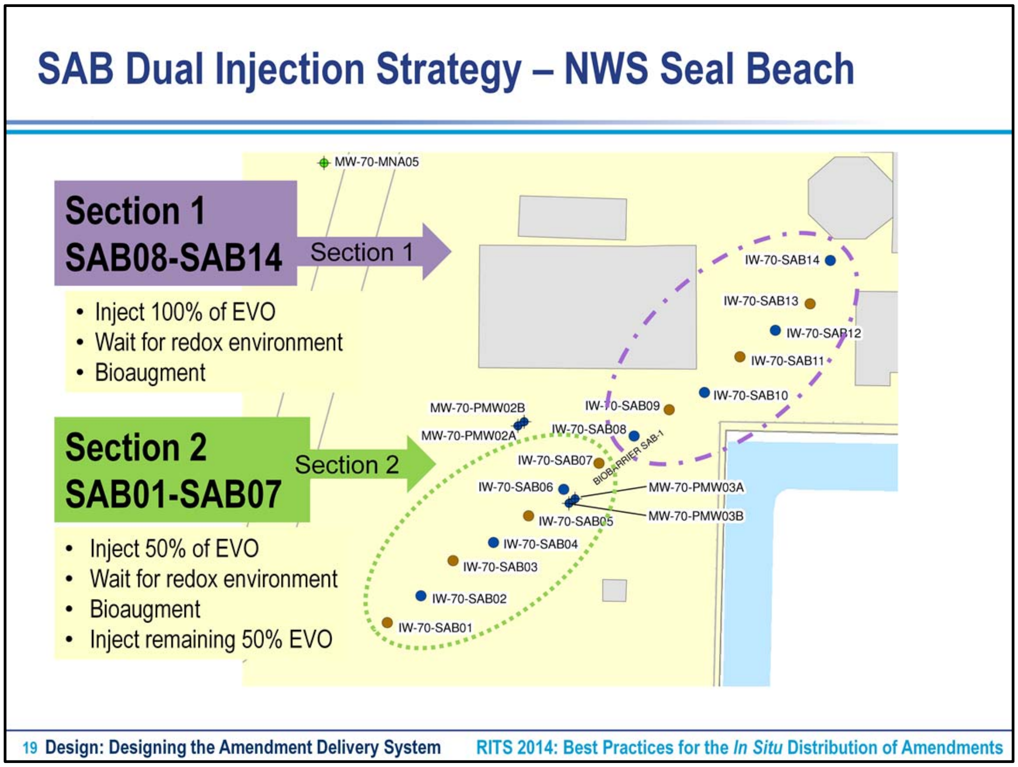


- Bench and pilot scale testing should be performed to reduce specific uncertainties, which could impact the design and implementation of the remedy
- Pilot tests are helpful to ensure proper application of the technology. Many times, the technology is implemented incorrectly (*e.g.* dosages are too high or too low, flowrates and pressures are too high, too little volume of amendment is introduced, etc.)
- It is very important to perform this additional testing at complex sites, such as those that contain DNAPL, have large dilute plumes, contain low permeability lenses from which matrix diffusion can occur, and/or contain fractured media.



4,000-foot-long dissolved phase plume.

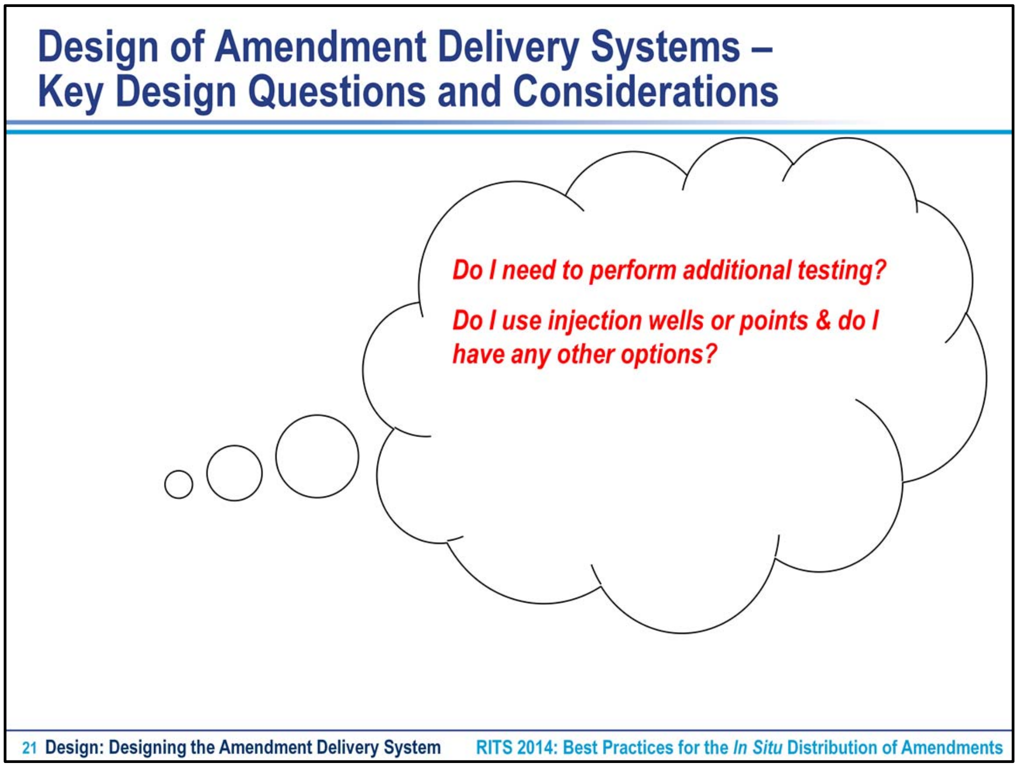


Evaluate two installation methods: ease of installation, time to achieve reducing conditions, distribution of EVO, survivability of culture

Section 1. Increase culture distribution through second EVO injection, but potential exposure to aerobic environment through second EVO injection
Section 2. Minimizes culture exposure to aerobic environment, but decrease culture distribution

Lessons Learned – NWS Seal Beach

- Easier to inject the first half of the EVO
  - Precipitates and/or biofouling significantly reduced flowrate of remaining EVO
- DO and ORP quickly reached conditions favorable for injection of bacteria using both methods
- Substantial decrease in pH observed
  - Sodium bicarbonate buffering required
  - Reformulated EVO to remove lactate
- Re-sequence installation of biobarriers
  - Begin with downgradient barriers to cut off plume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Methods of Introducing and Distributing Amendments

Delivery Method	Count	Percent
Injection Wells	53	35.8
Direct Push	35	23.6
Sparge Points (for introduction of gas)	24	16.2
Infiltration	17	11.5
Injectors (emplaced by direct push or through borings)	11	7.4
Recirculation	9	6.1
Fracturing (typically direct-push injection)	6	5.4
Mechanical Mixing	3	2.0
Horizontal Wells	2	1.4

Source: Is ISCO Right for Your Site?, RITS Fall 2010

Do I Use Direct Push Technology Points or Permanent Wells?

	Advantages	Disadvantages
Direct Push	• Low cost • Flexible • Easy to target discrete depths	• Remoblilization necessary • Depth limitation of ~100 feet • Smearing of formation material across screen • Compaction around rod tip can impact flow
Permanent Wells	• Lower overall cost when performing multiple injections • No depth limitation • Less potential for reduced flowrate	• High cost • May be difficult & costly to install additional wells during application • Fouling can be problematic • Difficult to target specific interval

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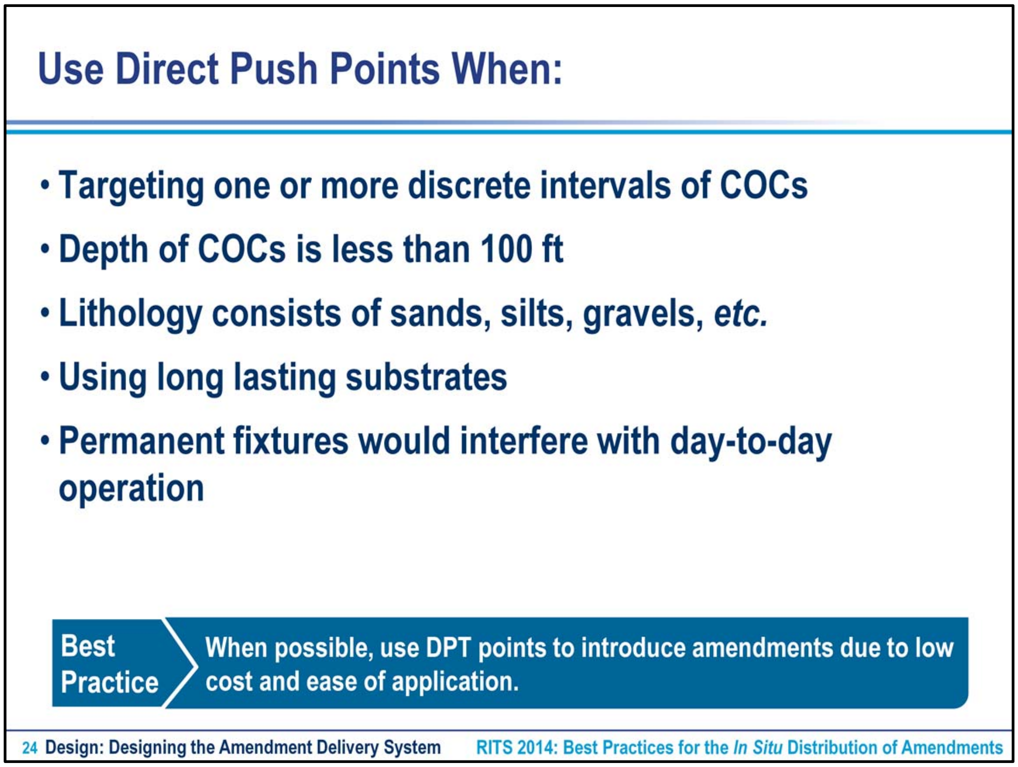
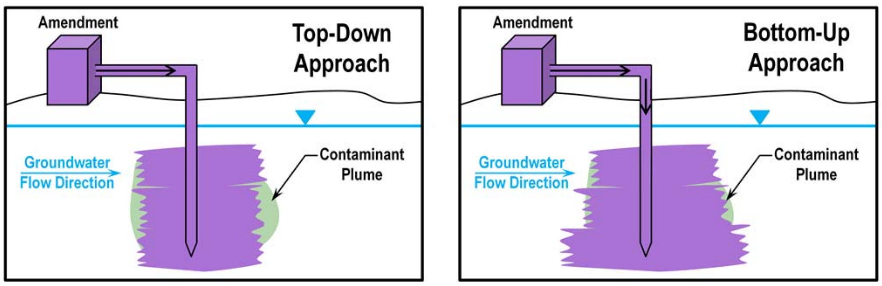
- Direct push wells are installed by pushing or hammering the drive rod into the ground. Flexible, injection locations can be easily changed or added during application



- Direct push points are not applicable when consolidated material is present. They can also be problematic in clays due to smearing of the clay across the screens.
- Achievable depth is dependent on lithology.
- Can be problematic in clays due to smearing of screens (and low permeability)

Top-Down/Bottom-Up Approaches for DPT Points



Best Practice When possible, use a top-down approach to facilitate uniform distribution of amendments.

When Wells must be Used…

- Design properly
  - Consider slot size
  - Use short screens or nested screens to target discrete intervals
  - Consider material compatibility
  - Install sufficient bentonite grout and concrete at surface
- Develop them
- Carefully evaluate using existing monitoring wells to inject fluids

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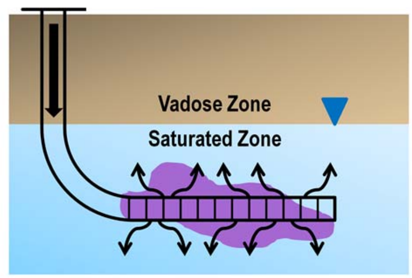
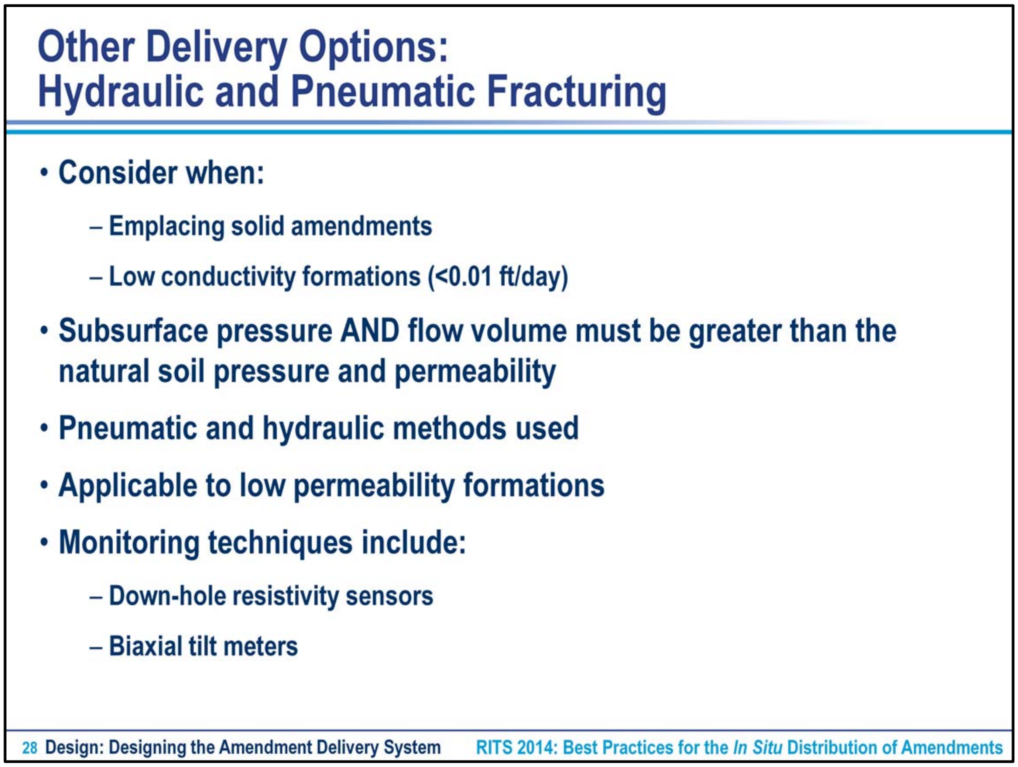
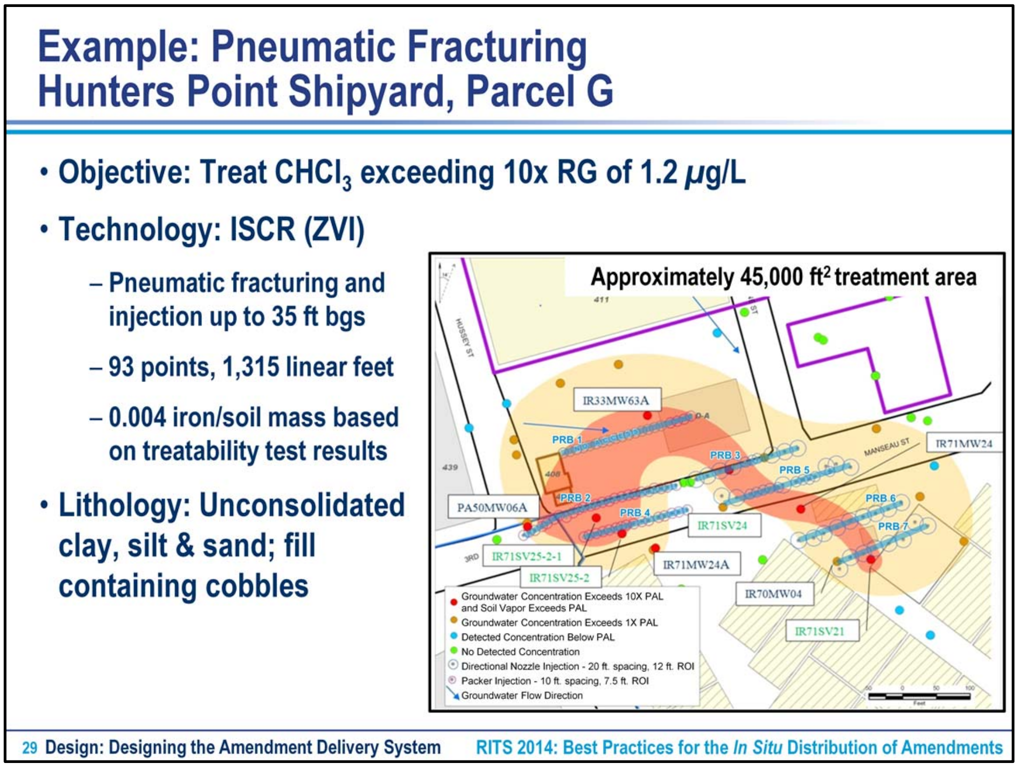
Other Delivery Options: Horizontal Wells

- Consider when:
  - Source area treatment and PRBs
  - Aboveground infrastructure
  - Thin plumes
- Substantial length of well casing may be required on each end of well screen
- A primary challenge is to ensure even distribution of amendments across screen
  - Wider slots at end, narrow at front
  - Proprietary casing/screen





- Pneumatic fracturing is used to form fractures with controlled bursts of high-pressure gas, while hydraulic fracturing is performed by injecting a biodegradable slurry comprised of a viscosifier (*e.g.*, guar gum) dissolved in water, which is polymerized using an agent (*i.e.*, borax) to create a viscous gel. An enzyme is added to the gel to break it down shortly after injection.
- Hydraulic fracturing creates horizontal fractures that are relatively thick (*i.e.*, a few inches); whereas pneumatic fracturing creates much smaller finger-like fractures. Fracturing can achieve radii of influence of 30 to 60 feet propagation in rock and 20 to 40 feet in silts/clays
- Although similar to the hydraulic fracturing used to enhance oil and gas recovery, this is on a much smaller scale at relatively shallow depths. The volume of fluids introduced into the aquifer is much less and so are the resulting pressures. Today’s technology allows vendors to maintain good control regarding where the fractures will be formed.
- LAI: Uses high-velocity nitrogen gas to disperse amendments into the treatment zone; potential increased radius of placement and enhanced distribution into the subsurface
- DPI: Amendments are injected into the subsurface using a positive displacement pump and steel injection rods with a retractable injection head



Unconsolidated clay, silt, & sand overlies Bay Mud or north-sloping bedrock

Hunters Point Parcel G: Remedial Technology Comparison

Factor	Vendor 1	Vendor 2	Comparison
Iron type	Blend of 60% cast iron with 40% with high-performance iron	Commercially available cast iron	• Both resulted in substantial reductions
Injection Fluid	Wet slurry	Dry slurry	• Both effective, dry may lead to larger ROI
Injection Technique	Multi-directional nozzle	Directional nozzle	• Both techniques effective • Directional nozzle is more sensitive to boring roughness
ROI Performance Monitoring	Visual observations; heave rods; pressures	Tilt meters	• Tilt meter monitoring highly recommended • Heave rods not effective

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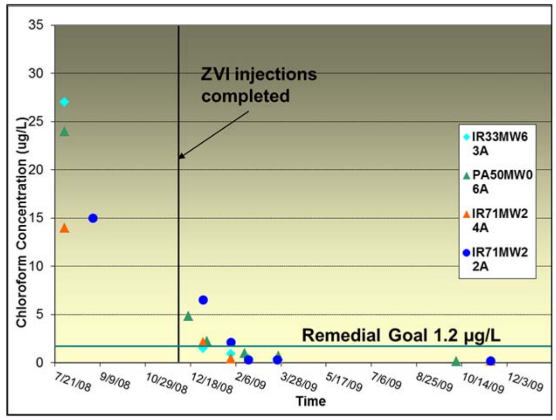
In addition to visual observations, heave rods, pressures, vendor two also used tiltmeters

Hunters Point Parcel G – Results & Lessons Learned

- **Biaxial tiltmeters to measure surface deformation facilitated determination of radius of influence**
- **$CHCl_3$ increased in one well, believed to be pushed**
- **Concentrations of some metals increased within the treatment zone**

Biaxial Tilt Meter



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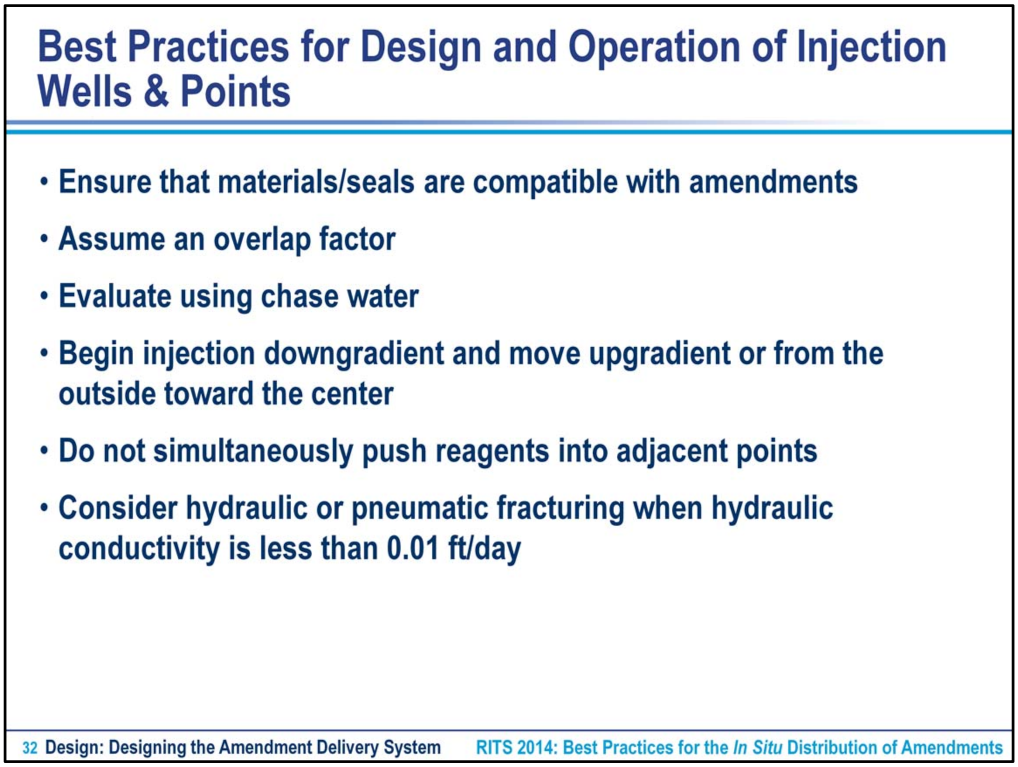
Flexibility in design and incorporating observations from tiltmeters allowed the injection well spacing to be increased from 10 to 20 ft.

Metals that increased during application included h as arsenic, manganese, and iron,



An overlap factor helps to minimize the possibility of “dead zones” between well/points

Chase water helps to push the amendments further into the formation, which improves distribution and also helps to prevent fouling

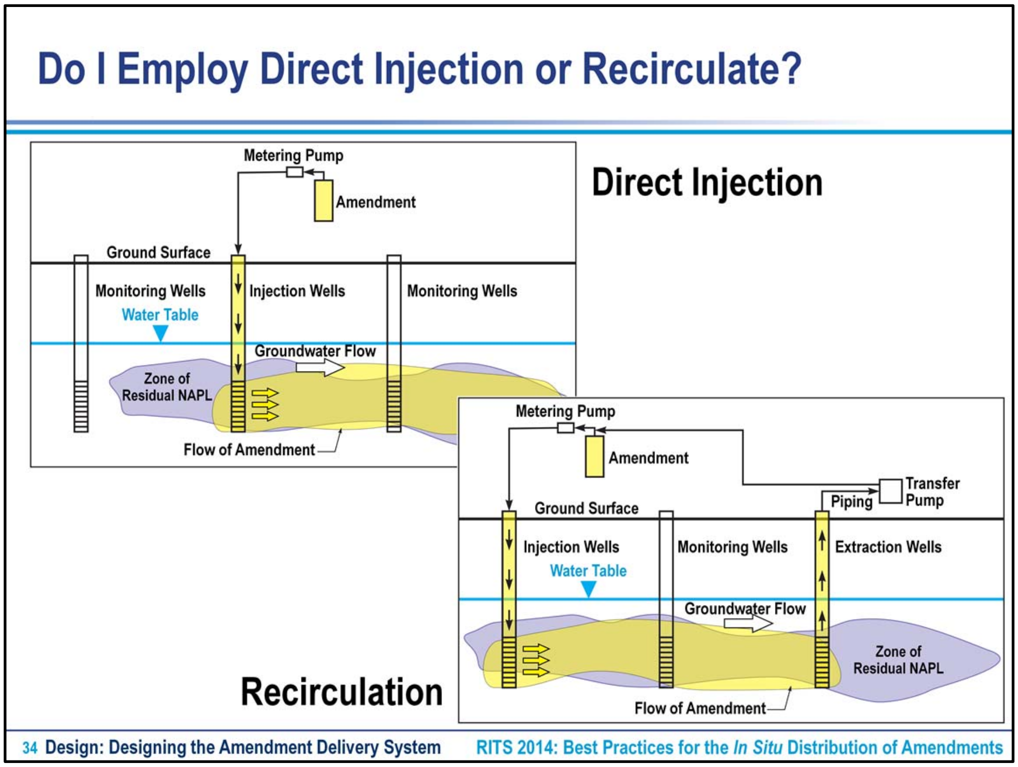
Simultaneously pushing reagents into adjacent points can result in flow distortions

Design of Amendment Delivery Systems – Key Design Questions and Considerations

Do I need to perform additional testing?

Do I use injection wells or points & do I have any other options?

Do I recirculate fluids?



Direct injection – Reagents are injected directly into the subsurface within a specified volume of water from an external source, displacing groundwater corresponding to the volume of reagent injected

Recirculation also may be performed using groundwater recirculation wells

Recirculation vs. Direct Injection

	Advantages	Disadvantages
Direct Injection	• Less expensive than recirculation • Fast application • Less equipment	• May cause COC displacement • May require external water source • Limited radius of influence
Recirculation	• Good hydraulic control • Larger radius of influence • Facilitates mixing • Minimizes surfacing • Allows for cross-gradient distribution	• Equipment intensive • Channeling can be problematic • More expensive

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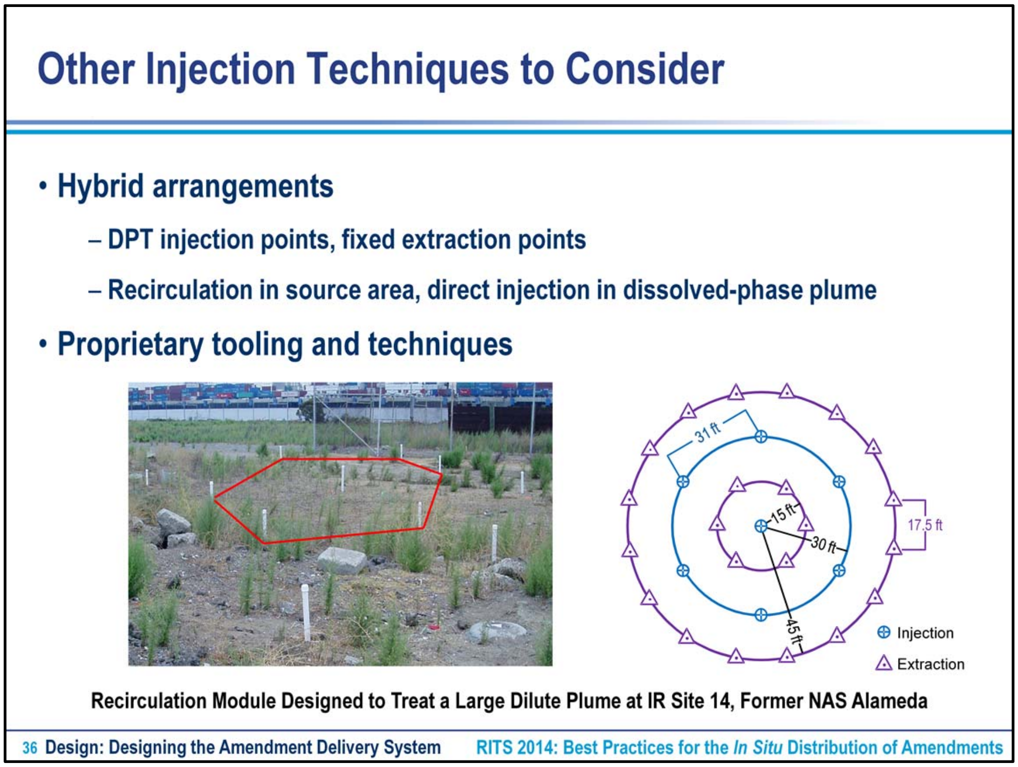
Recirculation – Groundwater is extracted from one or more extraction wells, amended with the reagents and then reinjected into a different series of injection wells

Pull-Push – A set volume of groundwater is extracted, amended with reagents above ground and then reinjected into the subsurface through the same well and well screen from which it was extracted

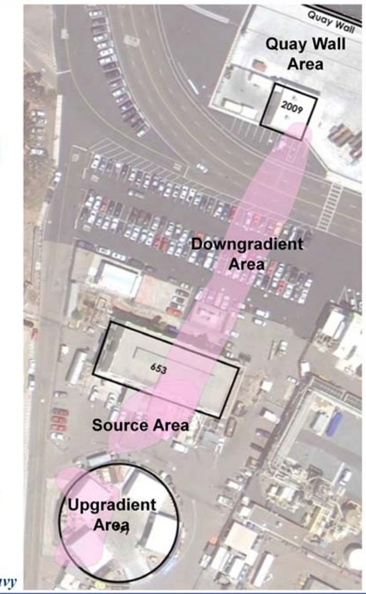
Hydraulic conductivities should be greater than 10^{-4} cm/s to ensure adequate circulation of water



Proprietary tooling and techniques consist of a large group of specialized tooling and patented applications

Example: Recirculation – NAS North Island OU 24

- **Groundwater contaminants:** TCE, *c*DCE, VC
- **Technology:** *In situ* bioremediation
- **Lithology:** fill, primarily dredged sediment consisting of silty sands
- **Treatments:**
  - **Active Recirculation**
    - Upgradient Area (5-10 ft bgs)
    - Source Area (4-19 ft bgs)
  - **Biobarriers**
    - Downgradient & Quay Wall Areas (19-37 ft bgs)

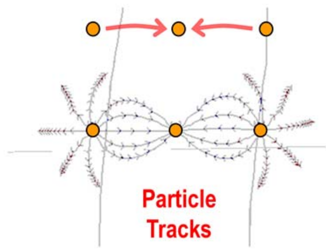


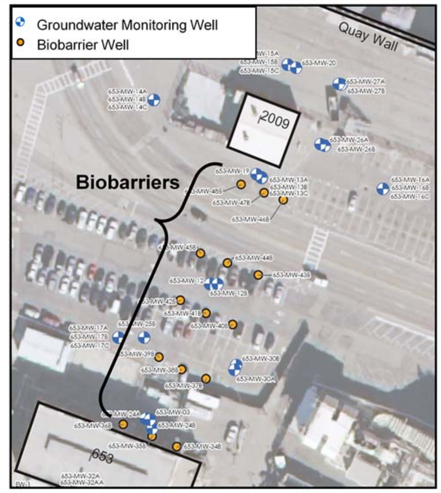
Courtesy U.S. Navy

Towards the end of Source Area treatment, high concentrations were discovered upgradient and the active recirculation system was re-designed to treat that area.

NAS North Island OU 24: Downgradient Biobarriers

- **Biobarriers originally installed by batch recirculation within each 3-well biobarrier**





Courtesy U.S. Navy

- **Challenge: low groundwater flow rates between biobarriers & preferential pathways**
  - **Designed for 2-year groundwater travel time between biobarriers**
  - **Performance observed in some monitoring wells was too slow**

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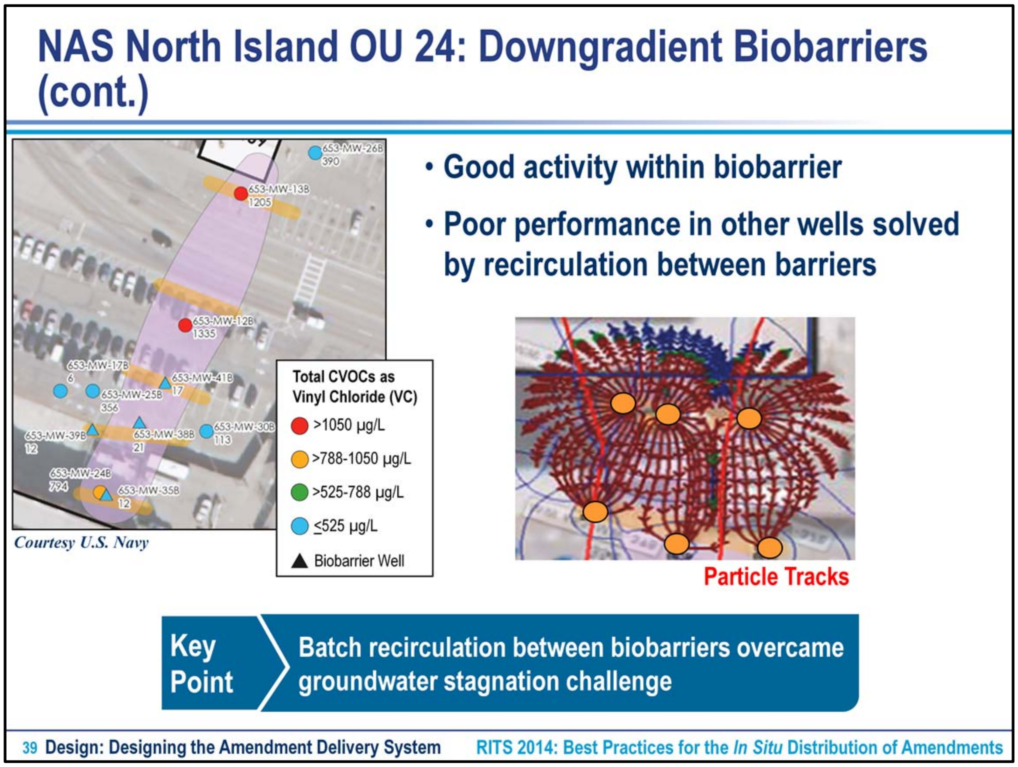
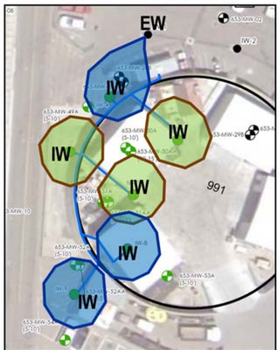
- Barriers were installed by extracting from the middle well, and injecting into the outside wells
- The aquifer was amended with emulsified vegetable oil and a reductive dechlorinating culture



- Activity within biobarrier was confirmed by demonstrating high *DHC-vcrA* populations; elevated organic carbon (e-donor); reduced sulfate; decreasing total chlorinated ethenes
- Used both soluble e-donor (lactate) and long-lasting electron donor
- Established larger treatment area than original biobarrier concept

NAS North Island OU 24: Active Recirculation



Estimated distribution of e-donor after 1 month of recirculation

Stage 1 Stage 2

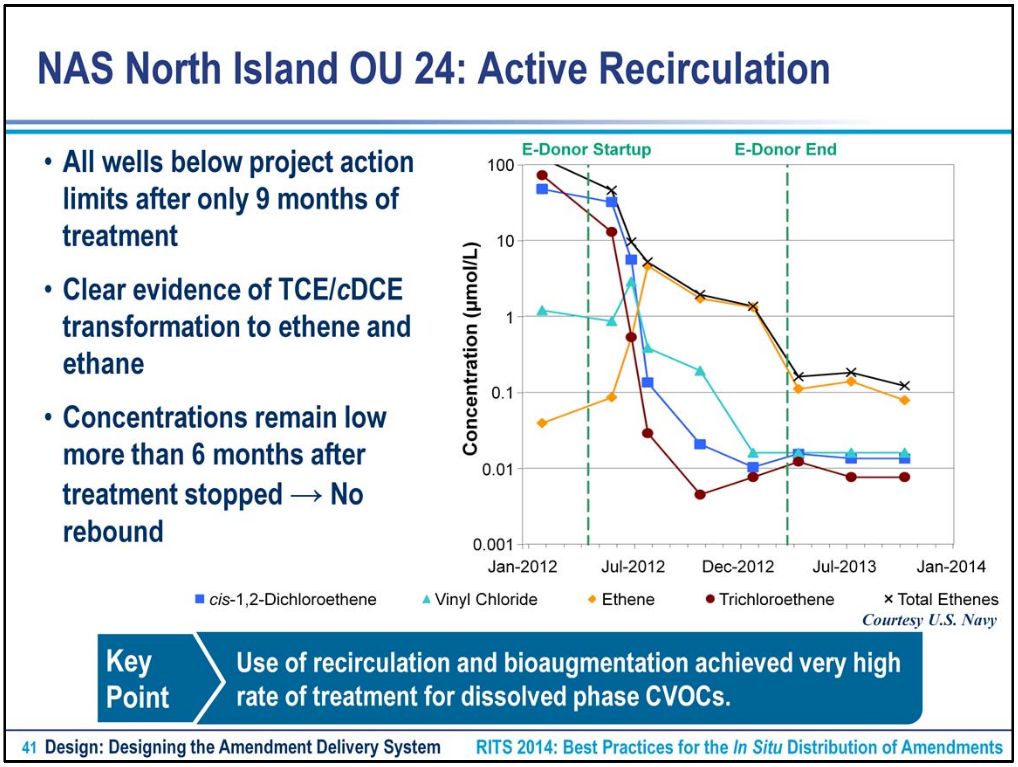
EW = Extraction well

IW = Injection well

- **Continuous recirculation system**
- **Weekly electron-donor dosing**
  - **Benzoate and ethanol, enough to reduce sulfate & CVOCs**
- **One time bioaugmentation with dechlorinating culture**
- **Biofouling control for injection wells**
  - **Aqueous chlorine dioxide (ClO_2)**
- **Recirculation pattern was optimized over time to target areas where total CVOCs > project action limit**

Courtesy U.S. Navy

- Extract from 1-2 wells, inject into 3 wells at a time
- ~1.4 gpm combined rate
- Designed to cover target treatment area within ~1 month and minimize vertical spreading beyond target treatment zone



- From highest concentration of over 7,000 µg/L total CVOCs to non-detect in many wells

Design of Amendment Delivery Systems - Key Design Questions and Considerations

Do I need to perform additional testing?

Do I use injection wells or points & do I have any other options?

Do I recirculate fluids?

How close do I space my wells/points and how much mass & volume do I inject?

How Close do I Space my Injection Wells/Points?

- For direct injection, ROI may be calculated based on displacement of pore water:

$$ROI = \sqrt{\frac{V}{\pi * L * n}}$$

V = volume of contaminated media
L = Vertical interval of contamination
n = aquifer porosity

- Flow modeling
  - Reactive transport modeling
- Vendor models and spreadsheets
- Perform a pilot test

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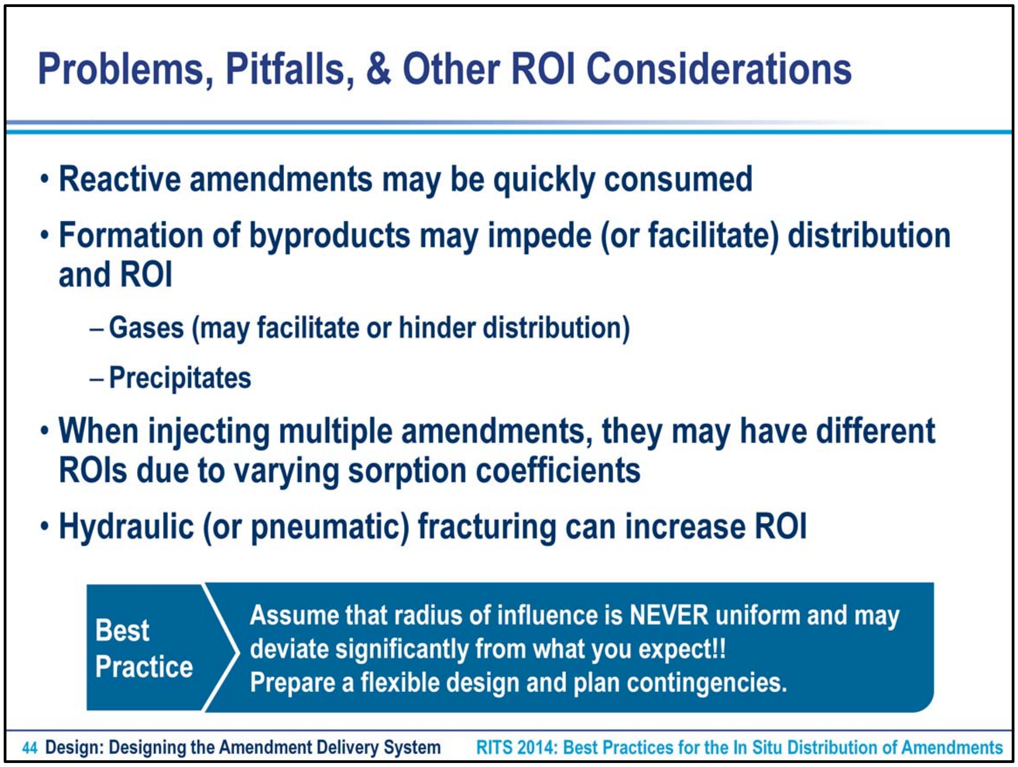

Expand treatment area beyond perimeter of source area

What Volume and Mass of Reagents Do I inject?

- Determine target treatment volume (TTV)
- Determine mass of COCs and non-target demand compounds in TTV
- Consider physical and chemical properties of amendments and site specific properties of the aquifer

***In Situ* Chemical Oxidation using Sodium Persulfate**

Site	Injection Method	Activation Mechanism	Dosing (g/L)	% Pore volume (estimated)
North Island	Recirculation	None	45	42
ABL	Direct Injection	Iron	297	40
MCBQ	Direct Injection	Steam and Iron	200	100
NAS Alameda	Recirculation	Iron	14	39
Washington Yard	Direct Injection	Sodium Hydroxide	100	60

Bench-scale test results to determine oxidant dose

Site specific factors that influence number of pore volumes that should be injected include delivery method, type of oxidant, concentration of oxidant injected, oxidant dispersion, concerns with displacement, etc.

Radius of influence can range from as little as about 1 m in tight clays to about 10 meters in permeable soils

The practitioner must then consider many site- and application-specific factors such as aquifer properties like total organic carbon (TOC), hydraulic conductivity, anisotropy; chemical and physical properties of the amendments including viscosity, density, solubility, sorption coefficients, etc.; reaction kinetics and thermodynamics of the system; and the practitioner’s experience applying amendments at other sites

Target treatment volume is based on the treatment area, the saturated zone thickness, and the porosity of the aquifer material

Site specific properties include density viscosity, solubility, sorption coefficients, reaction rates

Radius of Influence and Dosing Design Tools

- **Enhanced bioremediation**
  - Substrate Estimating Tool for Enhanced Anaerobic Bioremediation of Chlorinated Solvents (Parsons/ESTCP)
  - Source Area and DNAPL Design Worksheet (EOS Remediation)
  - Emulsified Oil Design Tool (North Carolina State/ESTCP)
  - Design tool for estimation of buffer requirement for enhanced reductive dechlorination (Robinson *et al.*)
- ***In situ* chemical oxidation**
  - Permanganate Design tool (ESTCP)
  - CDISCO (ESTCP)
  - Chemical Oxidation Reactive Transport in 3-D (CORT3D)

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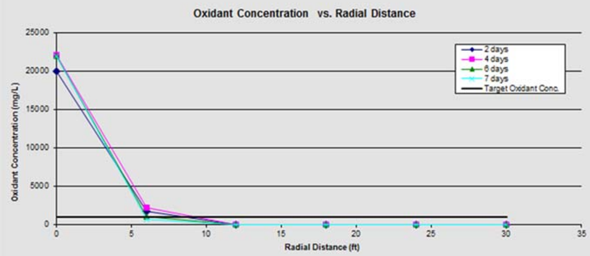
Spreadsheet-driven design tools readily available

Example CDISCO

Model Output



INSTRUCTIONS

Go Back to Site Data Input

Go to Cost, Direct Push

Reset the Output

Selected	Run Number	Injection Duration (day)	Aquifer Thickness (ft)	Thickness of Mobile Zone (ft)	NOD Fraction Instantaneous (-)	Total NOD (g KMnO4/kg)	Slow NOD Rate (L / mmol - d)	Injection Oxidant Conc (mg/L)	Injection Rate (gal/Day)	ROI (ft)	Minimum Oxidant Conc to Calc ROI (mg/L)	Target Number of Days to Calc ROI (days)	Injection Duration / Well or Point (day)	Injection ROI Overlap	Additional Inj Events Planned
	1	3	22.1	2.75	0.2	3.48	0.01	30,000	1,500	17.62	1,000	4	3	1.5	1
	2	3	22.1	11	0.2	3.48	0.01	30,000	1,500	10.53	1,000	4	3	1.5	1
	3	3	22.1	11	0.2	3.48	0.01	30,000	3,000	11.83	1,000	4	3	1.5	1
	4	3	22.1	11	0.2	3.48	0.01	30,000	1,500	10.53	1,000	4	3	1.5	1
	5	3	22.1	11	0.2	3.48	0.01	30,000	1,500	11.27	500	4	3	1.5	1

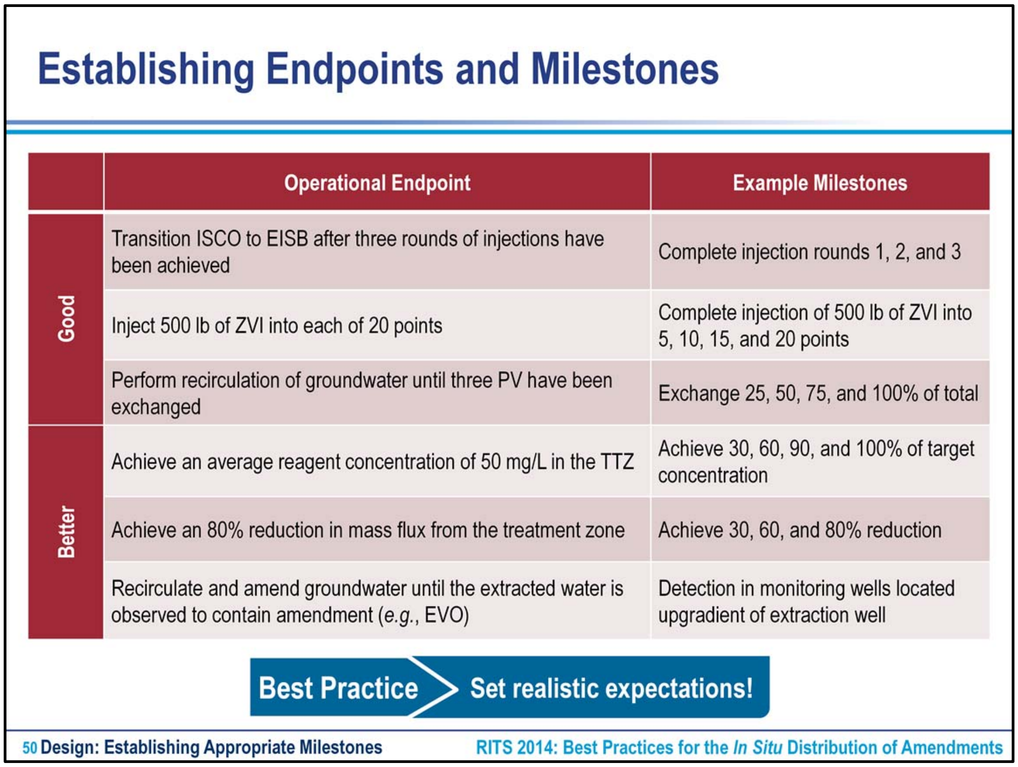
Courtesy ESTCP

Impacts of Overdosing

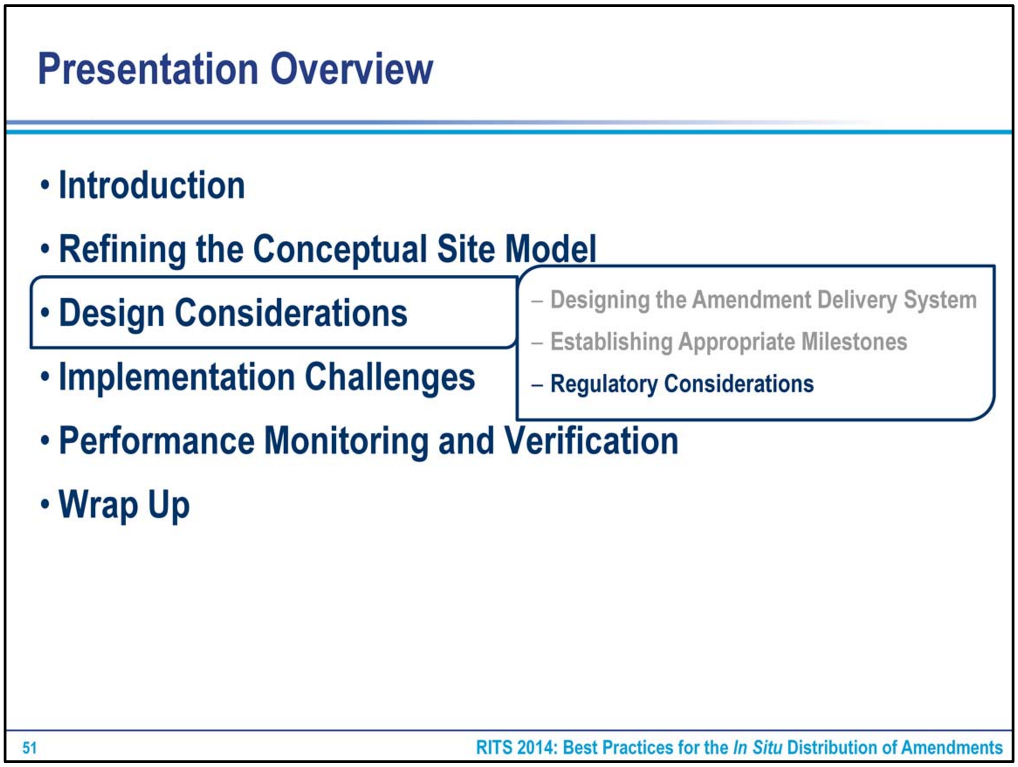
- Health & Safety
- Well/formation fouling
- Adverse groundwater chemistry changes
- Formation of adverse byproducts
- Impacts to distribution

Presentation Overview

- Introduction
- Refining the Conceptual Site Model
- Design Considerations
  - Designing the Amendment Delivery System
  - **Establishing Appropriate Milestones**
  - Regulatory Considerations
- Implementation Challenges
- Performance Monitoring & Verification
- Wrap Up



Many times, remedial actions are perceived to fail because of unrealistic expectation and a lack of appropriate endpoints and milestones to gauge remedial progress. Of particular importance is to establish criteria to demonstrate that amendments have been distributed sufficiently in the aquifer. This endpoint should be realistic and achievable, and should specify when to discontinue an application.


Presentation Overview
• Introduction
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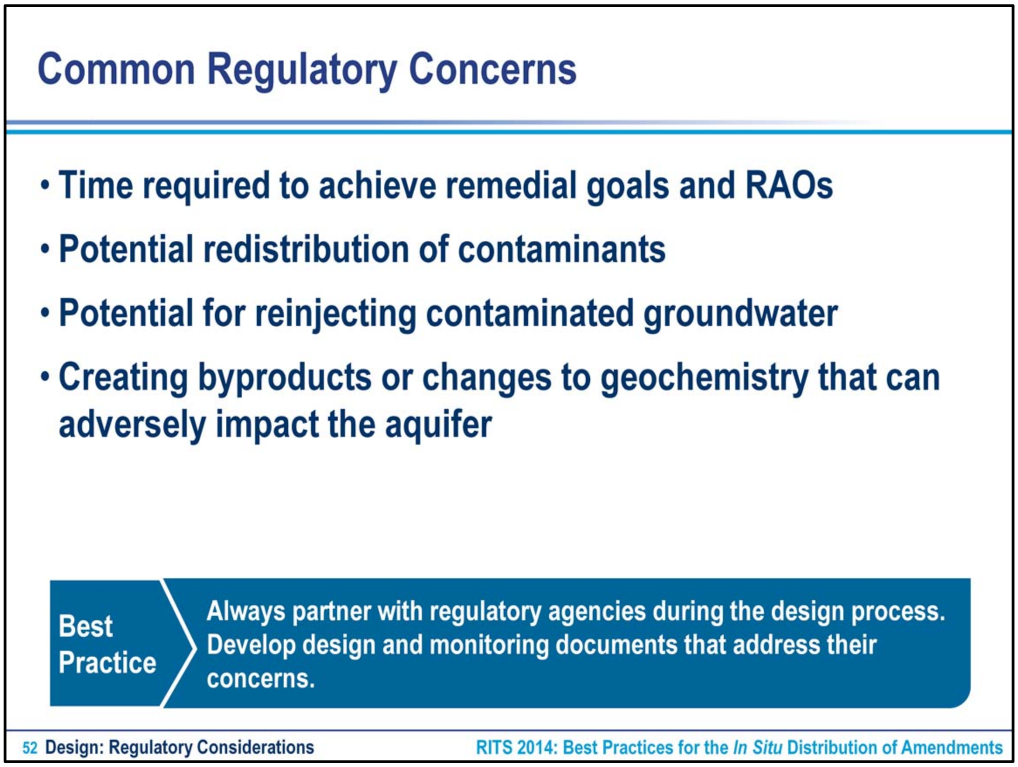
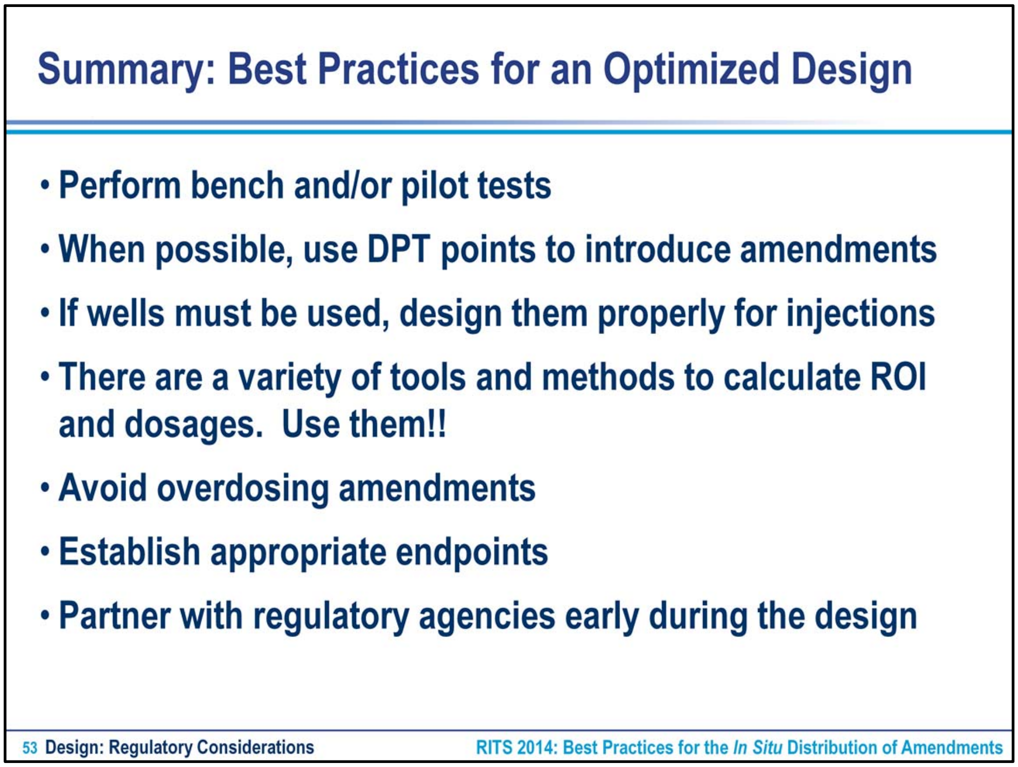


Application of remedies that rely on the introduction of amendments have been document to perform byproducts such as manganese dioxide precipitates, which can clog the aquifer; introduction and/or mobilization of metals; formation of trihalomethanes, and other potential byproducts



- When using DPT points, use a top-down approach to achieve better distribution of amendments

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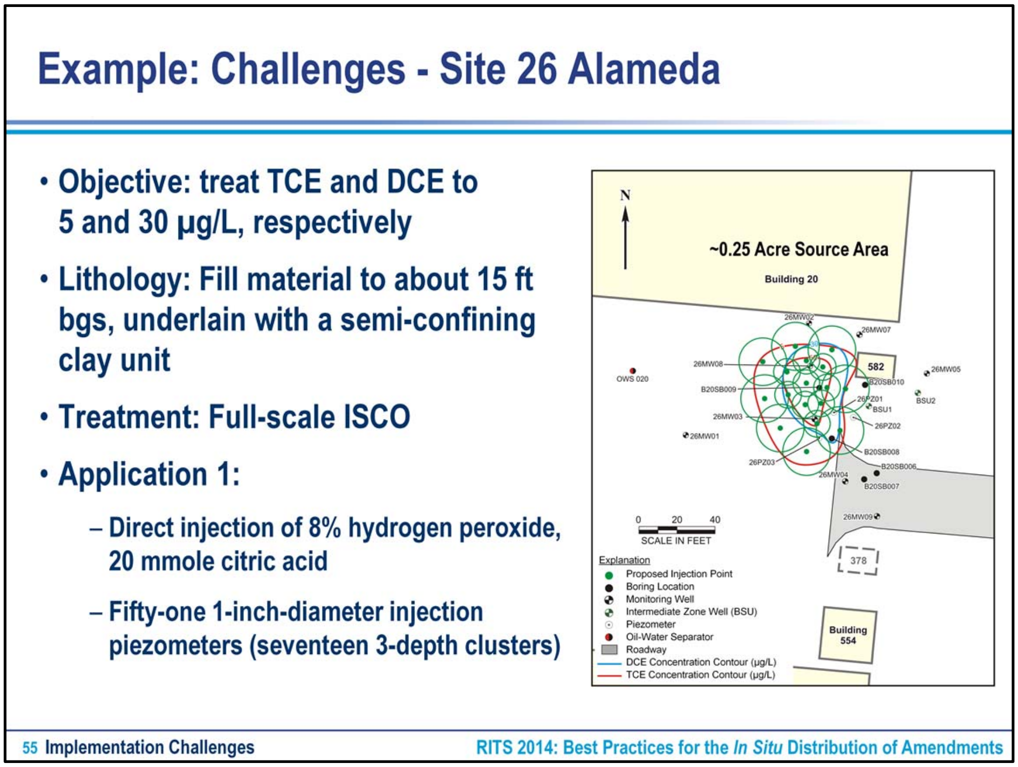

Direct injection piezometers (1-inch-diameter) were screened 3 to 7 ft, 7 to 11 ft, and 11 to 15

Application Challenges

Extensive Gas Generation

- Likely pushed COCs from treatment area
- High pressures generated causing piezometers to fail

Surfacing of Groundwater

- Amendments transported to non-target locations
- Required temporary shutdown of system
- Detected (previously unknown) LNAPL

Dissolution of Metals

- Elevated concentrations within and possibly downgradient of treatment area

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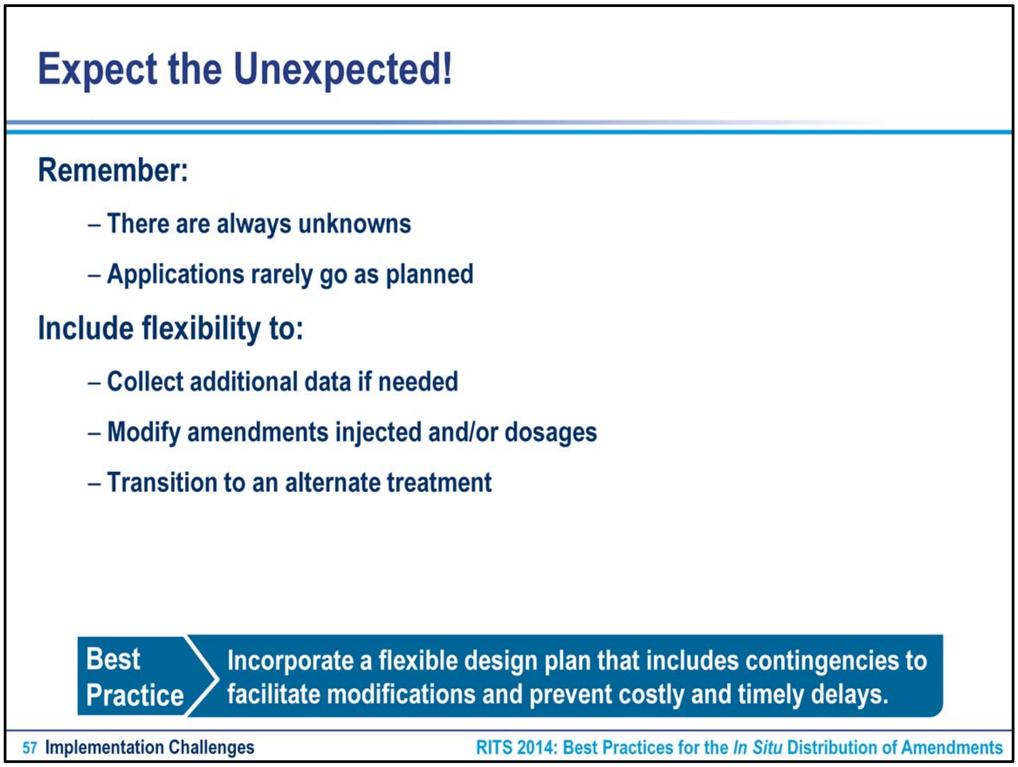

Adequate monitoring must be employed and flexibility maintained in the field so that deviations from the plan can be easily identified and strategies and approaches adapted to optimize application of the remedy. Incorporate a flexible design plan to allow design modifications and operating adjustments during the remedial action operation phase, without the need for high cost construction efforts. As an example, if multiple injection events are required and there is a concern for preferential pathways to develop during application, an appropriate design approach would be to introduce amendments through DPT points as opposed to permanent wells since the points can be relocated easily for each injection event.

Health & Safety Considerations & Challenges

Reagent hazards (well considered)

- Corrosive, reactive particulates
- Inhalation, absorption, *etc.*
- Material compatibility

Application hazards (well considered)

- Surfacing of amendments
- Well/point blowout
- High subsurface temperatures
- Vapor intrusion

Post-application hazards (less considered)

- Vapor intrusion
- Exceedance of secondary GW standards
- Production of VC (EISB)
- mobilization of metals

Best Practice Incorporate health and safety monitoring both during AND after injections are completed.

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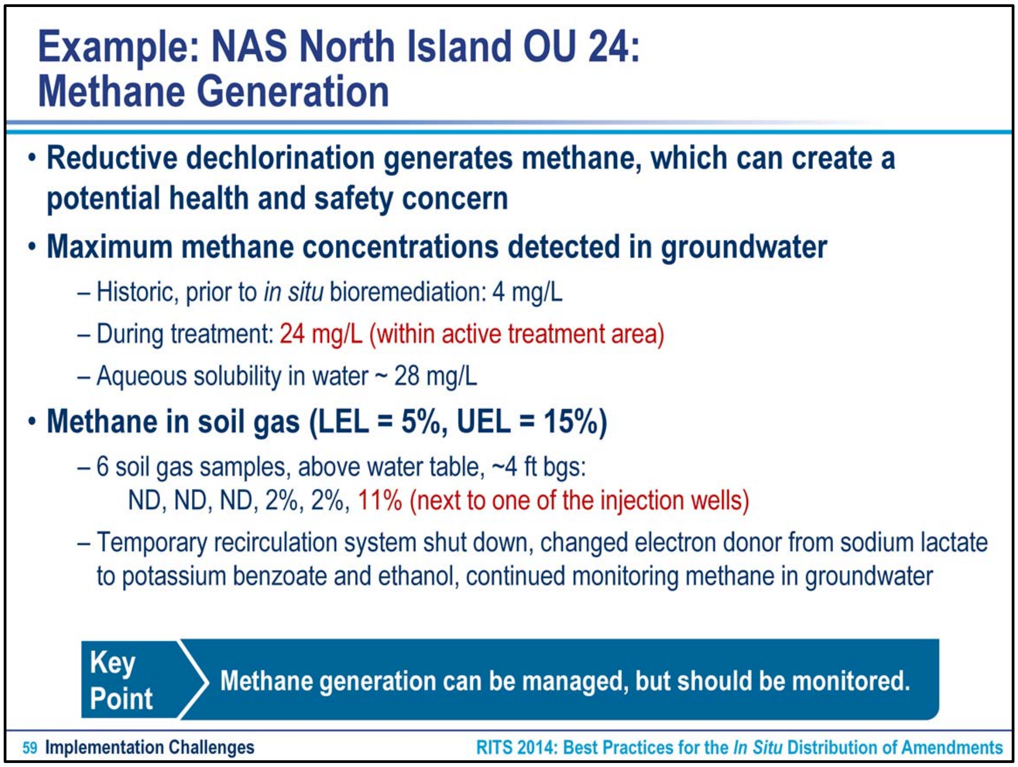
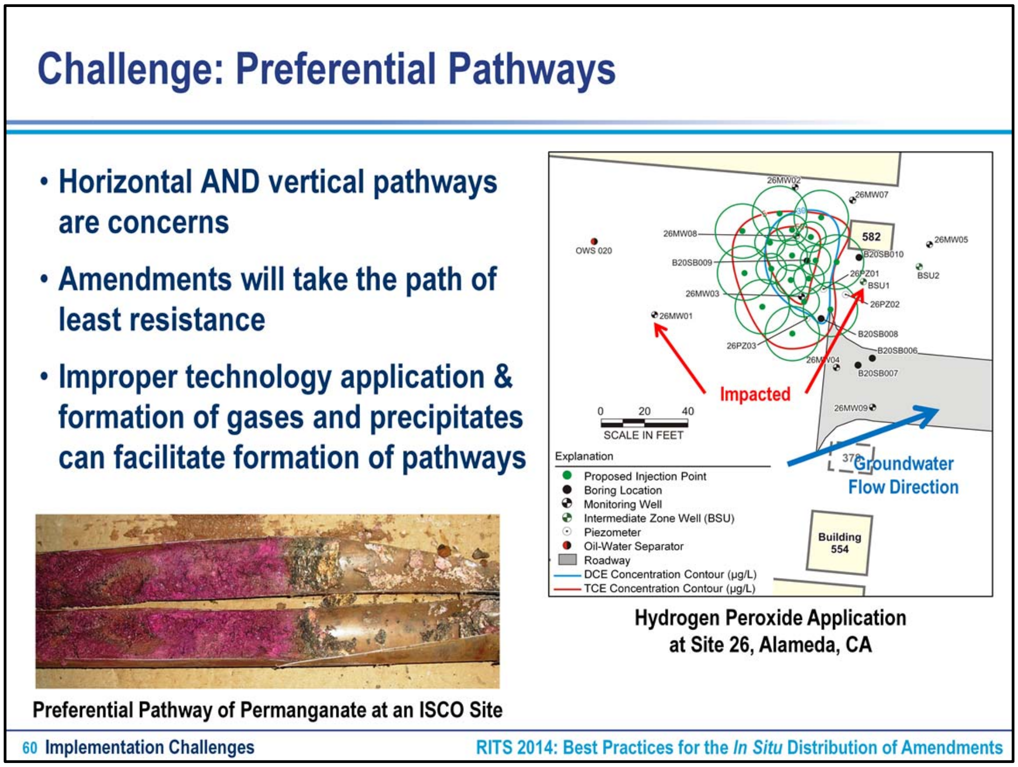
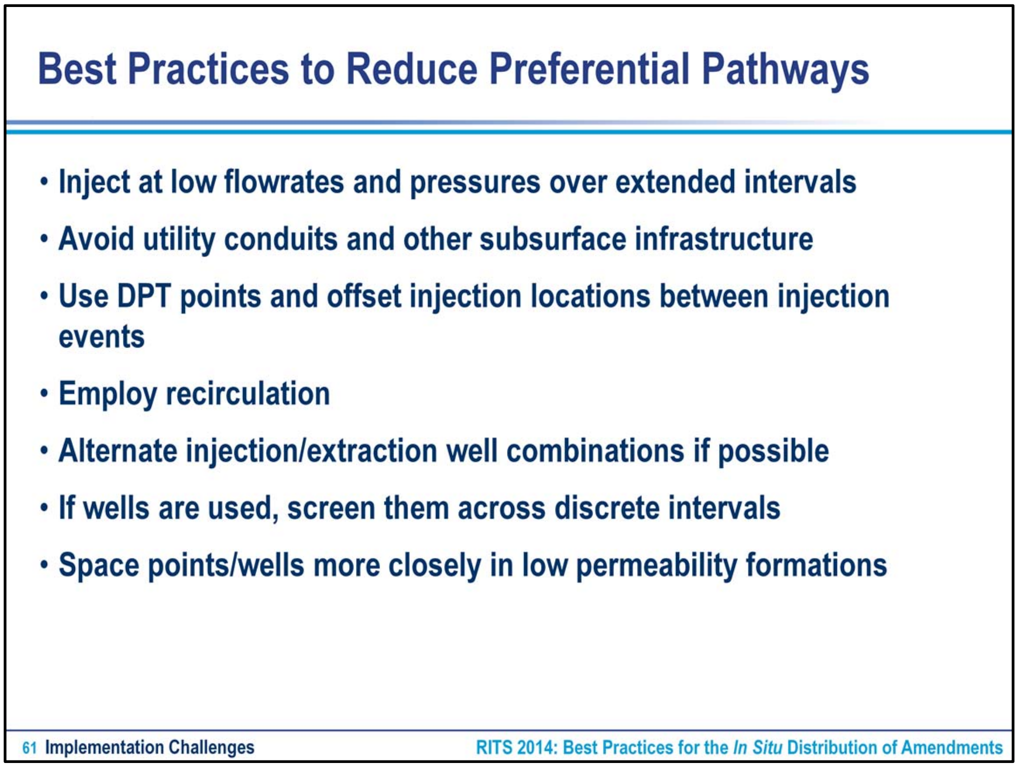


Methane not detected during breathing space monitoring in treatment system trailer, above wellheads, or in buildings.



- Preferential pathways always occur to some extent even in “homogeneous” media
- The soil core shown in this slide depicts how the potassium permanganate flowed through the sandy material. Very little entered the clay lens. This illustrates the difficulty to treat sites that have interbedded low permeability lenses, from which matrix diffusion of COCs can occur over extended periods of time



- Gravity flow if possible to help minimize formation of preferential pathways

Challenge: Well Fouling

- Biofouling, inorganic precipitate fouling and gas fouling
  - All may occur simultaneously
  - Biofouling is especially problematic at EISB sites
  - Gas fouling is a concern at ISCO sites
- Fouling is most problematic in injection wells and immediate vicinity
- Indicators include:
  - An increase in injection pressure and/or decrease in flowrate
  - Black precipitate or gelatinous substance in well or water

Fouling in a Deep Recovery Well

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Fouling is less problematic with injection points since typically they are not left in place for an extend time.

Biofouling can be particularly problematic at sites where EISB is employed. The enhanced growth of naturally-occurring microorganisms due to the introduction of biostimulants and any bioaugmented often leads to fouling. Changes in temperature, dissolved solids, and pH also impact this process. The enhanced microbial activity results in the formation of a biogel that can plug the well screen, the filter pack and the aquifer in the immediate vicinity of the injection well.

Best Practices to Prevent & Mitigate Well Fouling

- Design the well with adequate slot size and use a large filter pack
- Periodically inspect with a down-hole camera
- Operate the injection system using short pulses of amendments followed by clean water
- Add levels of amendments that would inhibit microbial growth or conversely, consider dosing lower concentrations for longer time
- Perform periodic brushing/surging of wells
- Perform hot water injection
- Consider adding peroxide, biocides, and enzymes as applicable

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Design operation of system to utilize short pulses of amendments to break up growth followed by clean water to push amendments away from the well into the aquifer
Add levels of amendments that would inhibit microbial growth around injection wells, but would dilute to levels in the formation that would not be inhibitory
Perform periodic brushing or surging

Challenge: Daylighting of Fluids

- Daylighting occurs when injection flowrate exceeds acceptance flowrate of aquifer
- Common causes include:
  - Low hydraulic conductivity and permeability
  - Application of reagents that generate a substantial volume of gas
    Shallow depth to groundwater
  - High injection flowrates
  - Preferential pathways are present (or formed), which connect the area of mounding to the surface

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Best Practices to Prevent & Mitigate Daylighting

- Assess and be aware of all subsurface utility corridors and structures
- Reduce injection flowrate to maintain a pressure less than 60% of the maximum calculated pressure
- Monitor pressure in each point/well
- Perform pulsed injection to allow mounding of water to dissipate
- Install and operate vapor recovery
- Use a recirculation system

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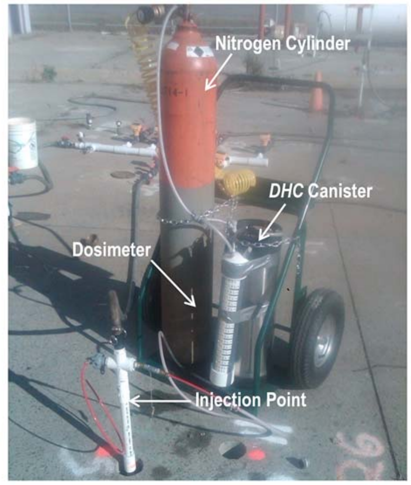
It may be necessary to reduce or eliminate injections in areas near subsurface utility corridors or possibly install a barrier to prohibit reagents and groundwater from entering

High pressures may indicate increased risk of daylighting

Activators may not travel same distance or persist for same length of time as oxidant

EISB Technology-Specific Challenges

- Wide range of substrates available
- Insufficient dosing may result in incomplete dechlorination, excessive loading may result in uncontrolled fermentation reactions
- pH and REDOX conditions are altered (at least temporarily)
- Microbes are very sensitive to aquifer conditions
- Fouling of well and formation is a major issue



Bioaugmentation with Dehalococcoides

Bugs do not tolerate oxygen

ISCR Technology-Specific Challenges

- Amendments are generally applied in solid phase, although other materials are being researched
- Emplacement by direct injection
- Hydraulic or pneumatic fracturing may be required
- Settling can be an issue when injecting solids as slurry
- Redox conditions can change dramatically

Fractured Formation

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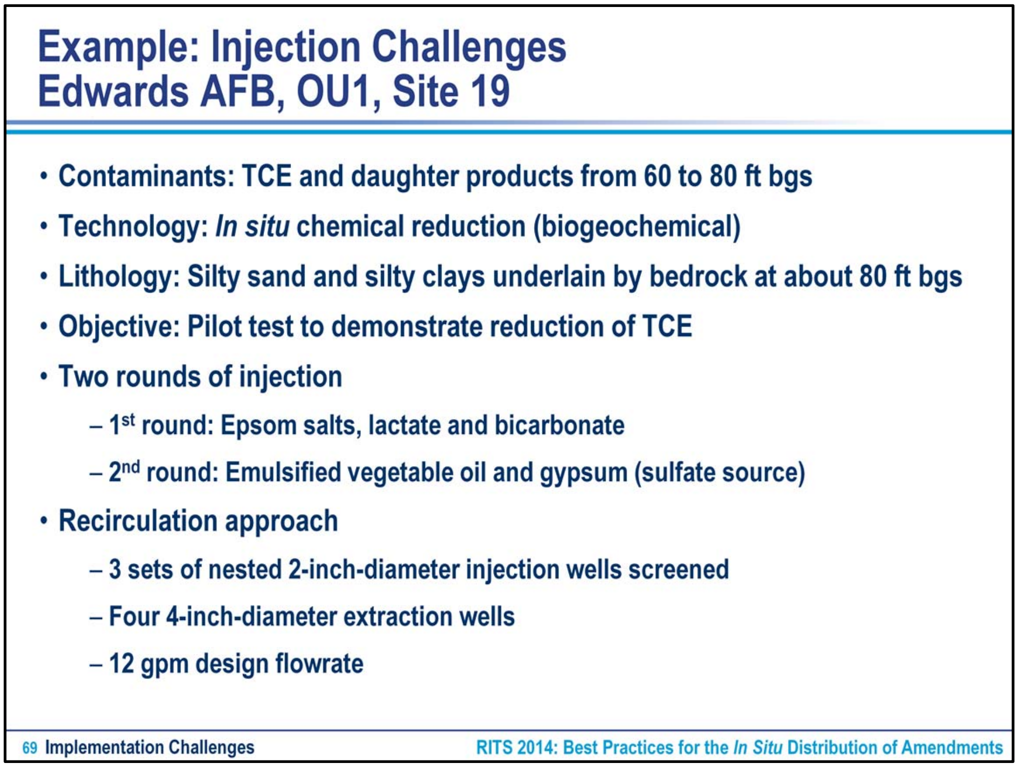
Liquid atomization injection is a technique that uses a combination liquid-gas stream to inject ZVI into the subsurface

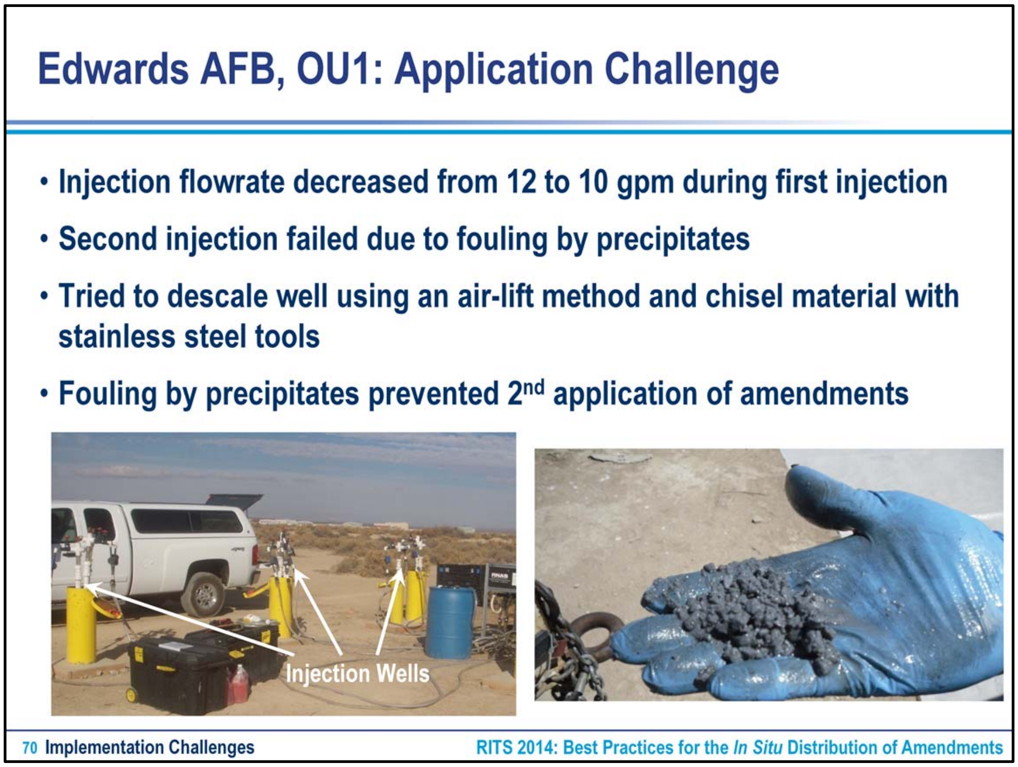
Pressure pulse technology (PPT) uses regular pulses of pressure, while injecting the ZVI slurry to force the slurry forward through the subsurface

Jetting technology uses very high pressure to inject the ZVI slurry through the subsurface.

Bimetallic systems are being researched. The iron is coated with a second metal such as nickel or platinum. The secondary metal is facilitates the transfer of electrons from the iron.



Injection wells were screened 77 to 82, 69 to 74 , and 61 to 66 ft bgs



During first set of in injections, flowrate decreased from 12 to 10 gpm with an concomitant increase in injection pressure. First injection was successfully completed; however there were problems with second injection.

Tried to use wells second time and had failure. Tried to rehab the 2-inch-diamter wells, air lift technique, so hard and so much precipitate. Barely just chipping it away with a stainless steel bailer. Used a mini-sonic rig. DPT had never been used. TCE on aquitard around 82 ft bgs. Went down to depth. Dropped 5 ft stainless steel screen, Moyno pump. Second around included: epsom salts, ferrous iron, Newman Zone. Each mixed in a tank and injected. Much less time consuming. 3.5 to 4 days to mobilize, setup, mix, and inject. Well injection took 8 or 9 days with well operation. With the points, water was removed from extraction wells amendments added and then reinjected. Recirculation volume was 25,000 gallons recirculated. 10 to 12 gpm total (for 9 points). Started dropping below 10 toward the end. Direct injection was always kept at 6 to 7 gpm. Still injected into 9 intervals with direct injection.

Gypsum precipitated inside well 0.7 ft at bottom of well

Tried mechanical rehabilitation, discovered hardness

Bio project did not want to inject acid

Edwards AFB, OU1: Lessons Learned and Solutions

- Advanced 9 DPT points using a mini sonic rig
  - Easier to apply design dosing to each interval
  - Maintained 10 to 12 gpm flow
  - Fouling was not an issue with DPT
- All mixing performed aboveground
- Dry amendments very difficult to mix and introduce into formation

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Application of dry amendments was messy and difficult to achieve complete dissolution, which likely contributed to well fouling

Used mini sonic rig to perform direct push. No recirculation performed. Extracted groundwater, but did not actively recirculate

Presentation Overview

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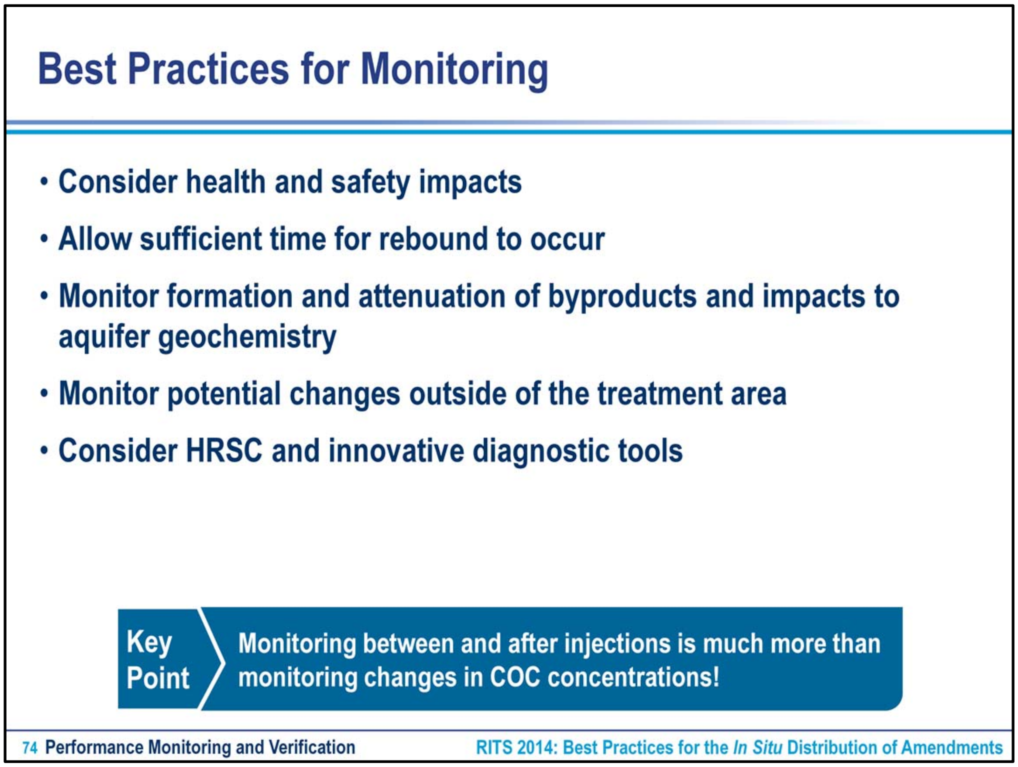
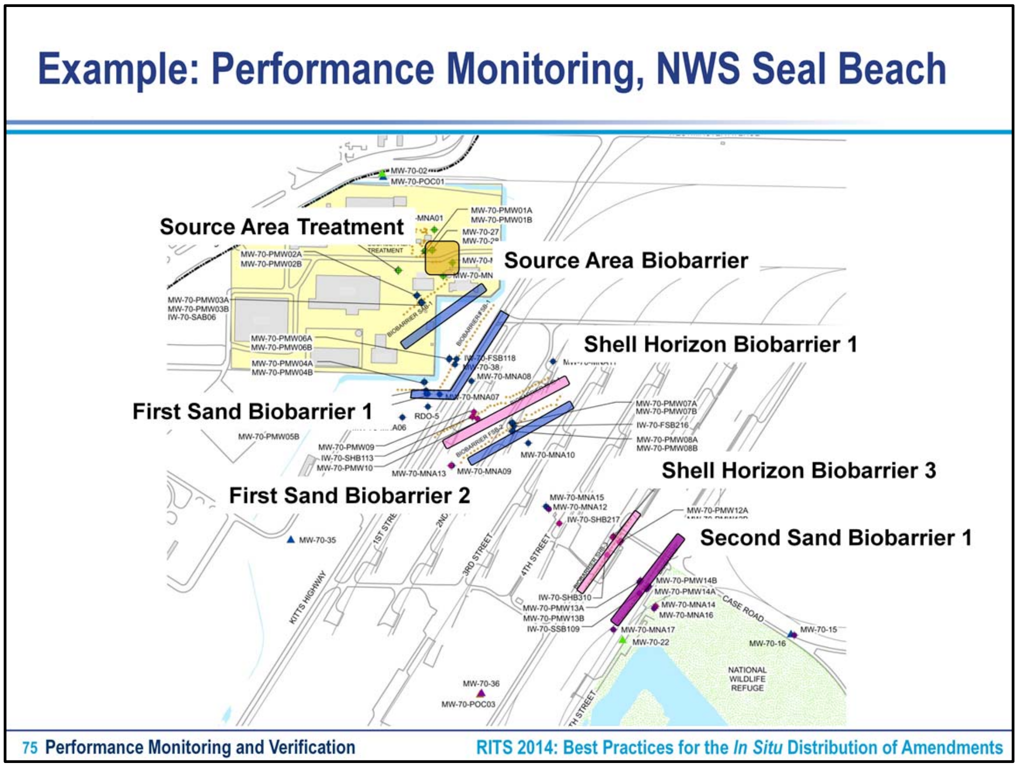
Performance Monitoring

- Provides framework for evaluating remedial action
- Evaluates progress of remedy
- Provides contingency triggers in the event that milestones are not being achieved
- Provides specific criteria that define the end point of the technology that is being applied



Mass flux measurements
High resolution characterization
Compound-specific isotope analysis
Sensors
Geophysics



•The SAB, SSB1, and SHB3 were installed in 2009. Activities discussed in 2009 PMR

NWS Seal Beach: What is Monitored and Why

- 2 upgradient and 2 downgradient wells at each barrier
- Point of compliance wells for each barrier/lithologic unit
- Monitored natural attenuation wells downgradient & side gradient of each barrier

Measurement	Objective
Groundwater Elevations	Ensure barriers are not impacting groundwater flow direction
VOCs & DHGs	Evaluate remedy performance
Geochemistry	Determine conditions are present for DHC survival
TOC and VFAs	Determine distribution of EVO & need for reinjection
qPCR (DHC and vcrA)	Track growth and distribution of DHC
Dissolved Metals	Demonstrate localized or minimized impact
Vapor samples for CH_4 & H_2S	Vapor intrusion, assess gas production from degradation

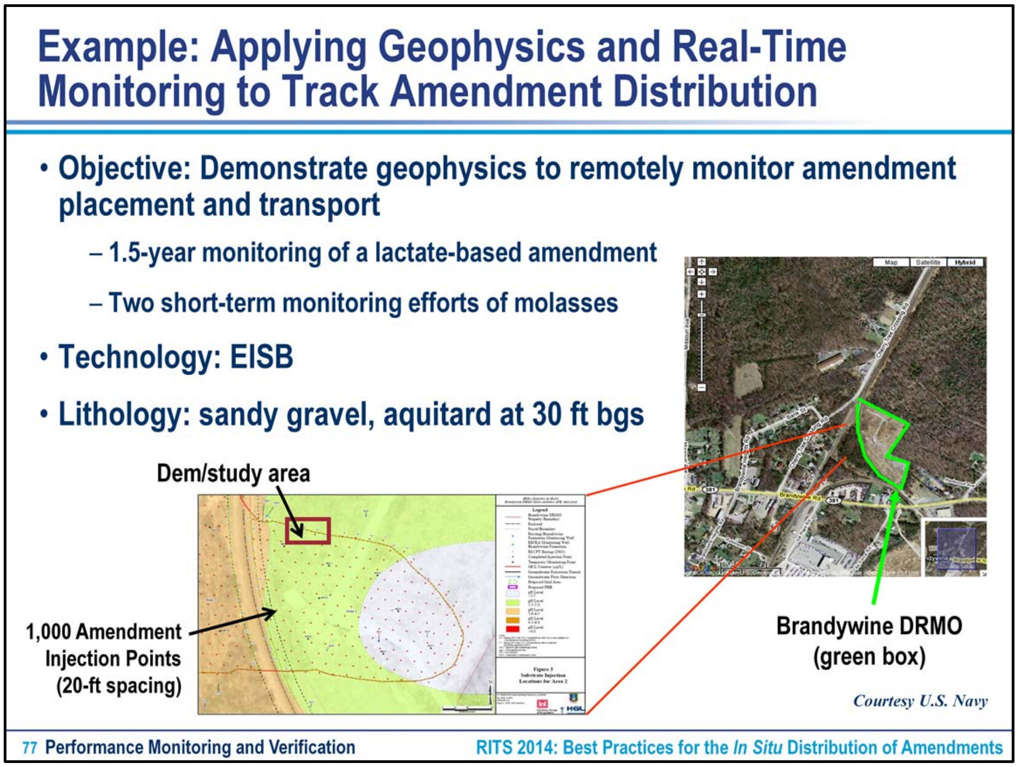
Data are used to answer the three primary questions:

Are the biobarriers performing as designed?

Are the barriers impacting groundwater flow direction?

Is there an adverse impact to secondary groundwater quality?

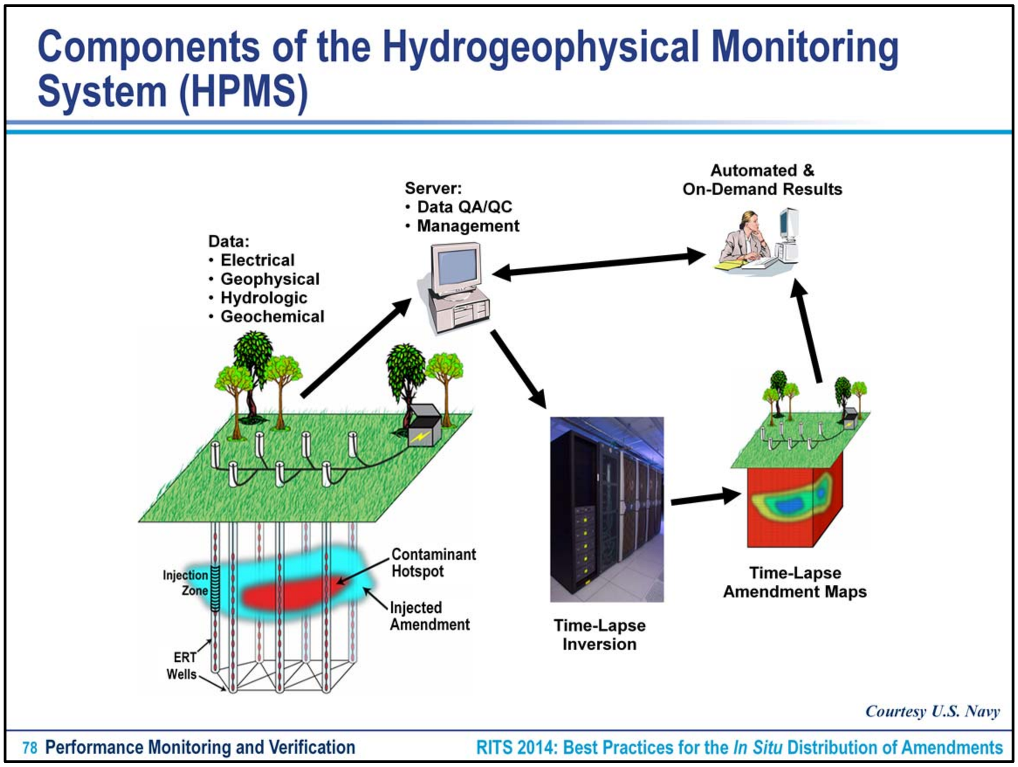
Geochemistry parameters include dissolved oxygen, oxidation reduction potential, pH, nitrate, sulfate, and ferrous iron



Unconsolidated clay, silt, & sand overlies Bay Mud or north-sloping bedrock.

Contamination resides in upper 30 feet

Dem/Val effort monitored two of the injections at edge of March/April 2008 treatment area



Amendments have different electrical properties than native pore fluids
Injections of large amounts of amendment will change the subsurface bulk conductivity. Electrical resistivity is a direct measurement of the conductivity of the subsurface. The conductivity changes as an amendment having different electrical properties than the native pore fluids propagates through the aquifer. In addition, conductivity changes as fermentation reactions occur. Hence, it is possible to track the distribution and consumption of the amendment.

HPMS: Advantages and Disadvantages

Advantages	Disadvantages
• Provides near real-time volumetric, temporally dense information on amendment behavior • Lower recurring costs	• Limited applicability in complex environments • High capital cost for resistivity wells • Spatial resolution • Must have a sufficient contrast of electrical properties between amendment and initial bulk conductivity

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Advantages:

Volumetric, temporally dense information on amendment behavior: The primary advantage of the technology is the ability to provide volumetric, temporally dense, information on amendment behavior to the site operator in near real time. Essentially, operators are able to link amendment injection histories to resulting amendment distributions. Alternative technologies rely on direct measurements in soil and groundwater. Because of the associated analysis time and cost, these methods do not provide a viable alternative to obtain similar information.

Lower recurring costs than direct sampling method: This method has substantially lower recurring cost than direct sampling methods.

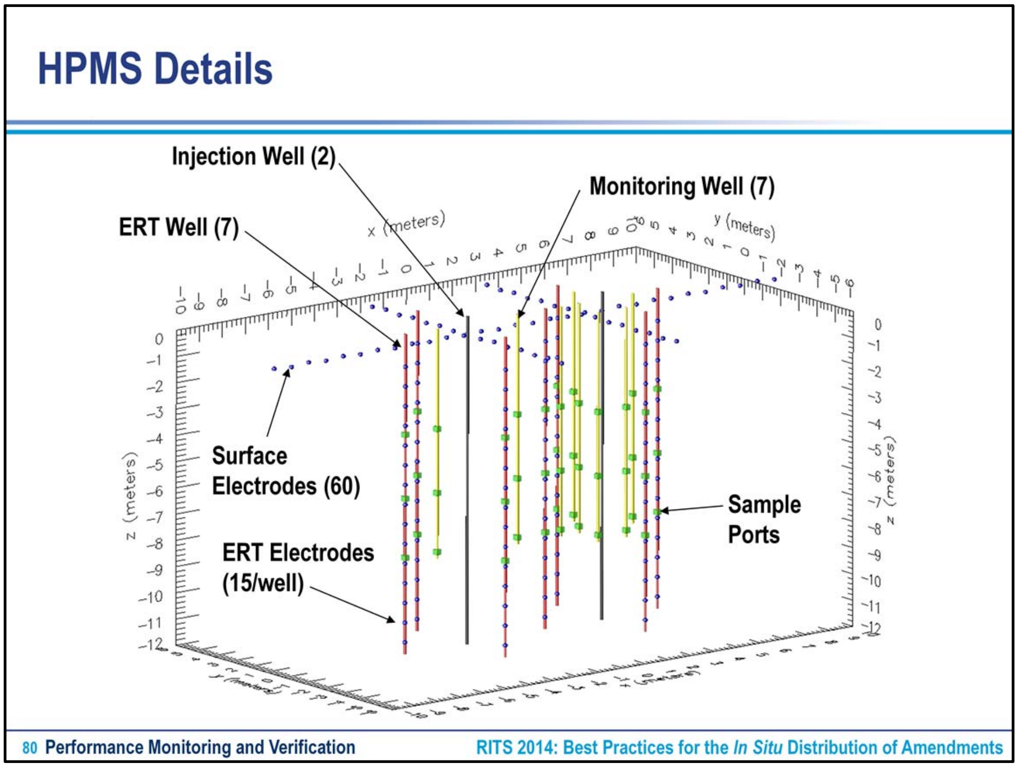
Disadvantages:

Applicability in complex environments: This approach is challenging to implement in extremely complex geologic and highly heterogeneous lithology. For instance, even though this method can, in principle, be used in bedrock aquifers, there is an important limitation in that the geophysical signal is a function of changes to pore-fluids; hence it varies with porosity. If the changing pore fluid occupies only a small fraction of the bulk (*e.g.*, 2% porosity), the signal will be relatively weak.

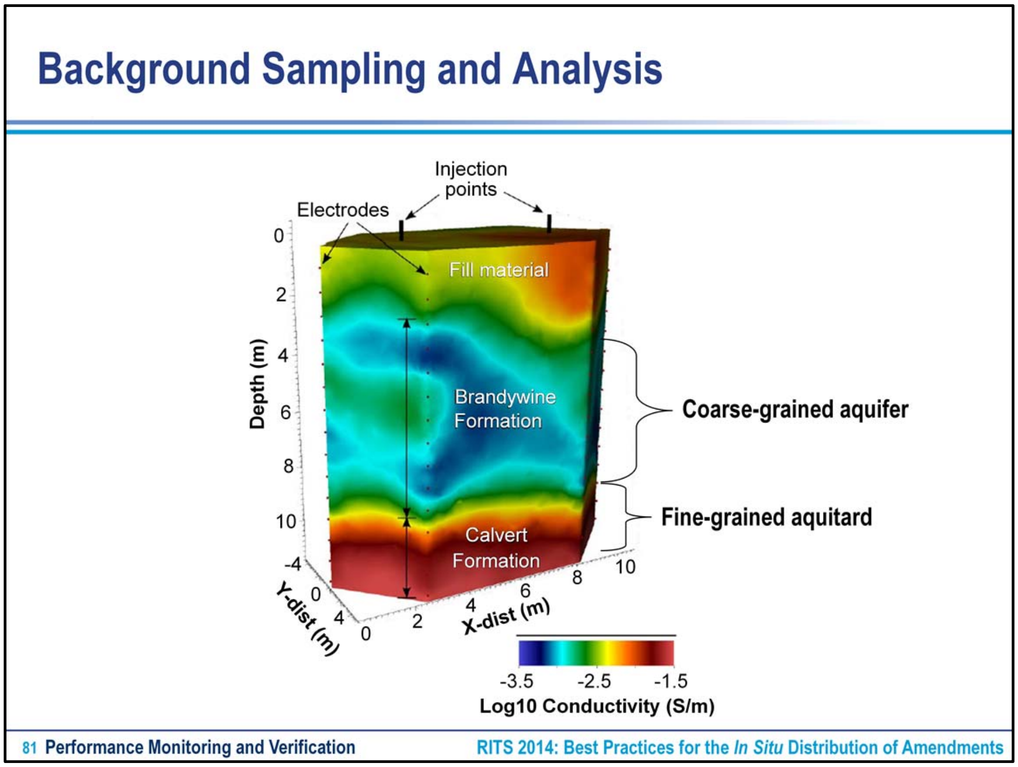
Well installation cost: For extensive but shallow sites, or for fractured rock sites installation costs of borehole electrodes will be substantial and may make this technology non-cost competitive unless cheap ways to install vertical resistivity strings are developed.

Spatial resolution: The resolution degrades with the horizontal distance between wells relative to the vertical distance over which the imaging is performed.

Need for a sufficient contrast in electrical properties between amendment and initial bulk conductivity: The approach requires a sufficient contrast in electrical properties between the amendment and the ambient groundwater. Thus, for cases where such a contrast does not exist a modification to the amendment would need to be made to create the necessary contrast



- A general rule of thumb is that the horizontal offset between two ERT electrode strings should not exceed the vertical length of each electrode string (measured as the distance between the top and the bottom electrode), and ideally should be 1/2 or less the vertical length of an electrode string.



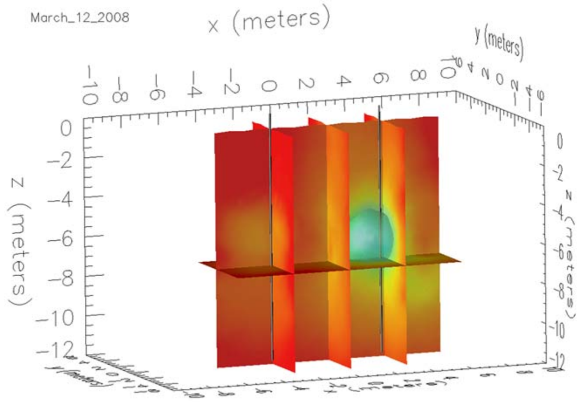
This image is in agreement with the known geology. It indicates 2-3 meters of fill material above the less conductive Brandywine Formation, extending to a depth of about 10 meters, below which the more conductive Calvert Formation is present. The Calvert Formation acts as an aquitard limiting the downward migration of contaminants. The target zone for treatment thus extends from land surface to the top of the Calvert Formation.

Electrical Conductivity Logs and Electromagnetic Logs – used as a second line of evidence to confirm results of electrical resistivity measurements. EC logs were collected only in those wells that were to be fitted with ERT electrodes. EM logs were collected in the 4 ground penetrating radar wells. The EC and EM results were found to be consistent with the ERT results

Crosshole Radar - Radar results are qualitatively consistent with the EC and background ERT results, showing higher amplitude signal (and thus lower attenuation and lower electrical conductivity) in the Brandywine Formation than in the overlying fill or underlying Calvert Formation.

Chemical sampling - Provided insight into site geochemical conditions, the electrical conductivity of native groundwater, and background, pre-treatment contaminant levels

Time-Lapse ERT Imaging



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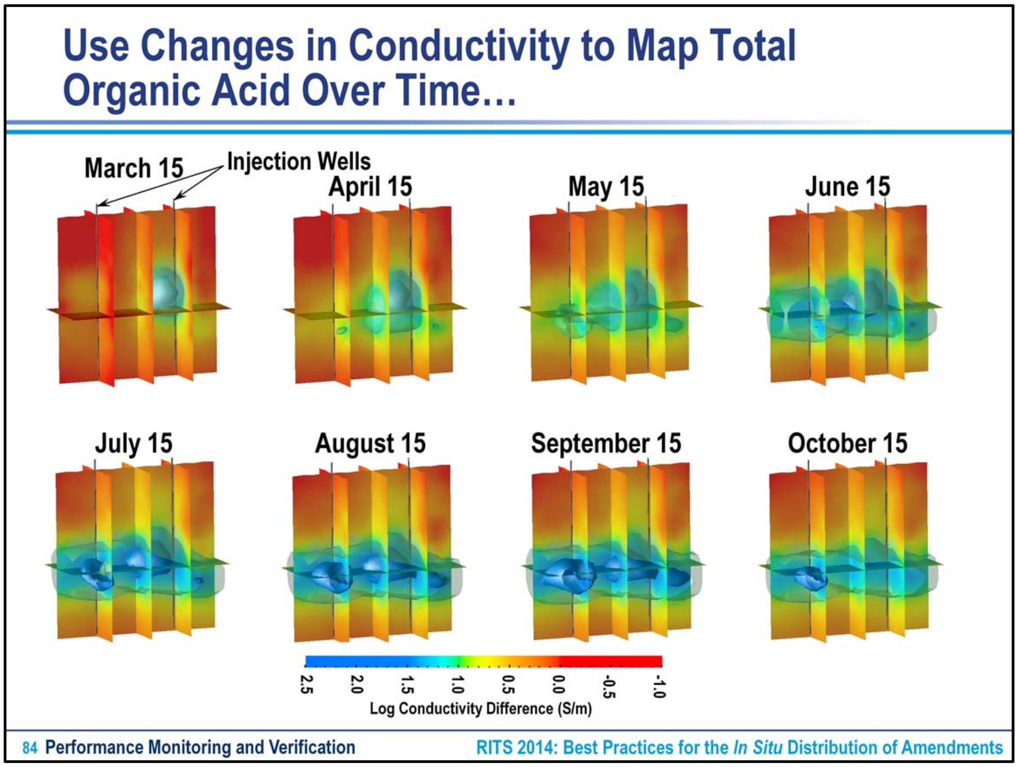
RITS 2014: Best Practices for the *In Situ* Distribution of Amendments

How would a RPM use this data?

- Look at whether specific areas in the surface are being hit by the amendment → decide on additional amendment
- Get quantitative maps of total organic acid spatiotemporal distribution → evaluate efficacy of remedial effort
- Reduce and focus confirmatory sampling efforts


Use Changes in Conductivity to Map Total Organic Acid Over Time…
March 15
Injection Wells
April 15
May 15
June 15
July 15
August 15
September 15
October 15
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
Log Conductivity Difference (S/m)
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RITS 2014: Best Practices for the In Situ Distribution of Amendments

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- Extent of mass of contaminants rarely is completely understood (especially vertically)
- Incomplete knowledge of lithology and site heterogeneities
- Insufficient scale of characterization

Best Practices and Take-Away Messages: Site Characterization & Design

- Optimize the CSM for the remedy
- Use a flexible/adaptable approach and plan for contingencies
- Establish appropriate endpoints and milestones
- Consider health and safety during AND AFTER injections
- Partner with regulatory agencies during the design process

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Best Practices and Take-Away Messages: Implementation

- Perform a pilot test to identify site specific challenges
- Be prepared to implement contingencies to address site-specific challenges
- Minimize preferential pathways
- Plan for and take actions to mitigate fouling, especially at EISB sites
- Plan for and take actions to mitigate fouling, which is especially problematic at ISCO site

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Best Practices and Take-Away Messages: Monitoring

- Follow "Monitoring and Management Approach" guidance
- Monitor during and after each injection event
  - Monitoring between and after injections is much more than monitoring changes in COC concentrations!
  - Allow sufficient time
  - Consider HRSC and innovative diagnostic tools

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