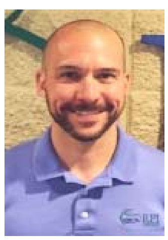
Combining Remedial Technologies and Implementation Methods to Address Chlorinated Solvent Impacts at Complex Sites



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SMART Remediation
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Combining Remedial Technologies and Implementation Methods to Address Chlorinated Solvent Impacts at Complex Sites

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In Situ Combined Remedy Strategies

- Planned combination of technologies and techniques to reach project objectives cost effectively and efficiently
  - Source: e.g. Thermal, CBI, ISCO, ISCR, surfactants + others
  - Plume: e.g. In situ bioremediation, CBI, ISCR + others
  - Application techniques: Excavation, mixing/trenching, injection (well/DPT), grid v. PRB
- Not all technologies are immediately compatible - need to consider this in planning phase
  - e.g. pH manipulation < in situ bioremediation
- Techs need to be sequenced properly
  - e.g. Injection < excavation/soil mixing

Keys to Success

- Characterization and contact…………….simple right?
- A solid CSM will guide the technology and implementation selection
  - Dense sample profiling of soil and groundwater in source zone
  - Solid understanding of geology and hydrogeology
  - Integrate applicable HRSC (e.g. MIP, HPT, UVOST) tools
  - Develop a surgical approach
- Distribution dictates success
  - Have a plan to verify distribution
  - Be realistic with distribution expectations

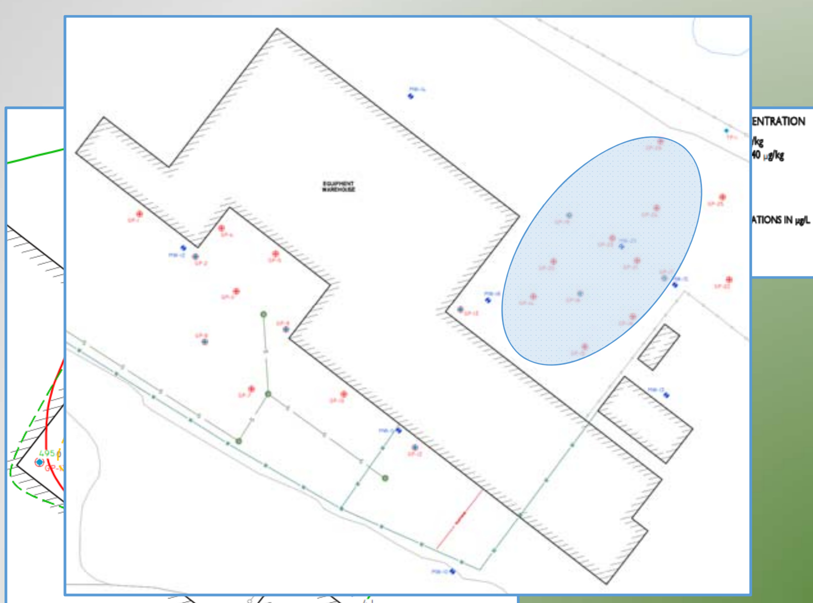
Site #1 - Background Information

- Historical Industrial Property that utilized chlorinated solvents for equipment maintenance from the 1950's to 1970's
- Contamination has been confirmed in both the unsaturated and saturated zones through high density characterization activities (depths of 2.5 - 14 m with depth to groundwater at 4.5 m)
- TCE concentrations have been detected in groundwater at a maximum concentration of **730 mg/L** and in soils at **5,350 mg/kg**

Project Time Line

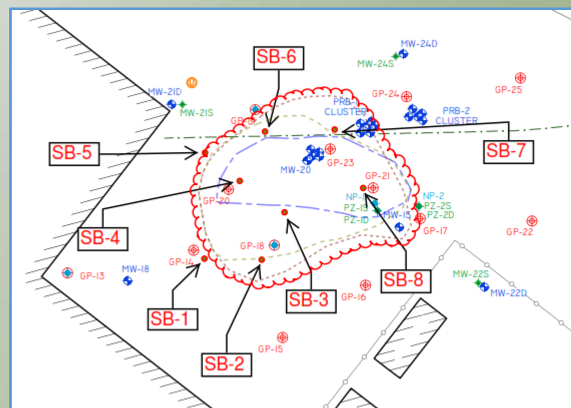
- October – December 2013
  - Remedial Design Characterization (RDC) + Hydraulic Profiling Tool (HPT)
- May 2014
  - Injection of BOS 100® PRB (CBI)
- October to December 2015
  - Soil Mixing of RemOx-L® (Sodium Permanganate)

Site Map



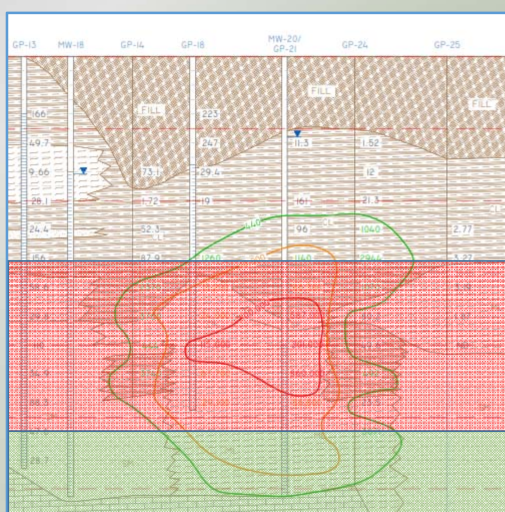
Remedial Design Characterization (RDC)

- Advancement of 26 soil borings
  - Collection of 186 soil samples
  - Soil samples collected approximately every 0.5 m vertically
  - Samples analyzed pro bono by RPI Quality Assurance Laboratory (Golden, CO)
- Installation of 31 micro wells
  - Collection of groundwater from discrete intervals based on soil and HPT data
- This information was used to bound the BOS 100® and RemOx-L® treatment areas and horizons



Cross Section

- Based on the RDC data
  - Remox-L® was selected for the shallower zone
    - Target soil concentration = 125 mg/kg TCE
    - Selected based on partitioning and mass flux that could be managed by PRB
  - BOS 100® PRB was selected for the deeper zone
    - Target groundwater concentration = 5ppb TCE (property boundary)



Approx. Soil Mixing Horizon (4-8 m)

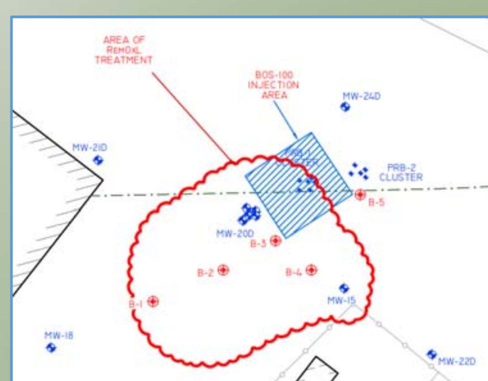
Approx. PRB Horizon (8 m to refusal, max = 14 m)

BOS 100® PRB Design

- Original design (pre-RDC)
  - TCE concentration of 350 mg/L (MW-20)
  - K = 1.65 10-5 cm/s (MW-20 slug test)
  - Iron demand (based on mass flux) = 20 lbs/year
  - Injection interval = 15-30 ft bgs
- Modified design (post-RDC)
  - Injection interval = 26-46 ft bgs
  - Mass in shallow zone (<26 ft) was significant and the system would be iron limited, leading to a shorter PRB life
  - Depth to bedrock was deeper than anticipated
  - 10 year PRB life predicted based on mass flux
  - Alternate options for shallow mass treatment would need to be considered

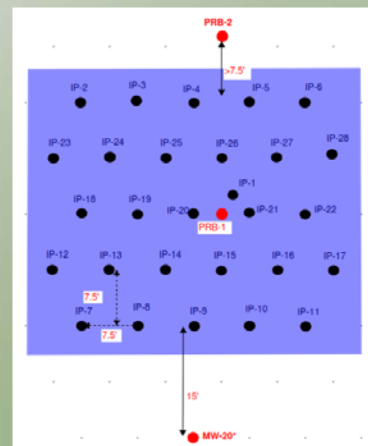
BOS 100® PRB Design

- 1,900 kg of BOS 100® were applied in a 12 m x 12 m area from a depth of 8 -14 m bgs
- 28 DPT injection points on 2.3 m centers (with alternating elevations at each injection point)
- Monitoring points PRB-1 and PRB-2 were utilized to evaluate the effectiveness of the pilot test from May 2014 to September 2015
- Note PRB wells were destroyed during soil mixing operations



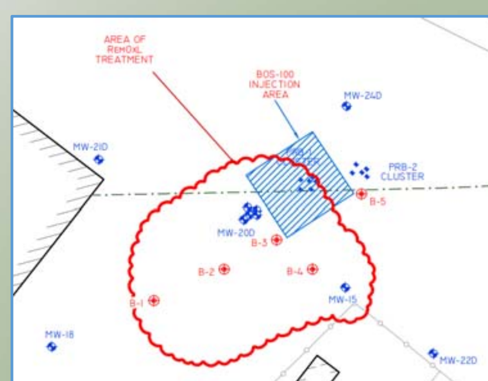
BOS 100® PRB Installation

- Top down progression
- Multiple injection tips utilized (to provide different injection tip exit velocities)
- Fracture pressure = 200-300 psi (avg)
- Propagation pressure = 50-100 psi (avg)



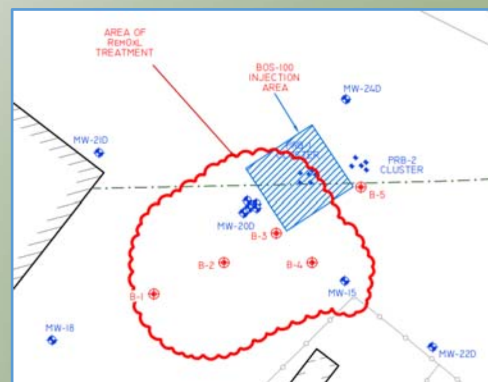
RemOx-L® Soil Blending

- 24,500 kg of RemOx-L® was selected for treatment of 2,160 m^3 of soil
- 5,350 m^3 of overburden to access the 4 - 8 m treatment zone
- 43 grid blocks (4 m x 4 m x 3 m) were treated in place



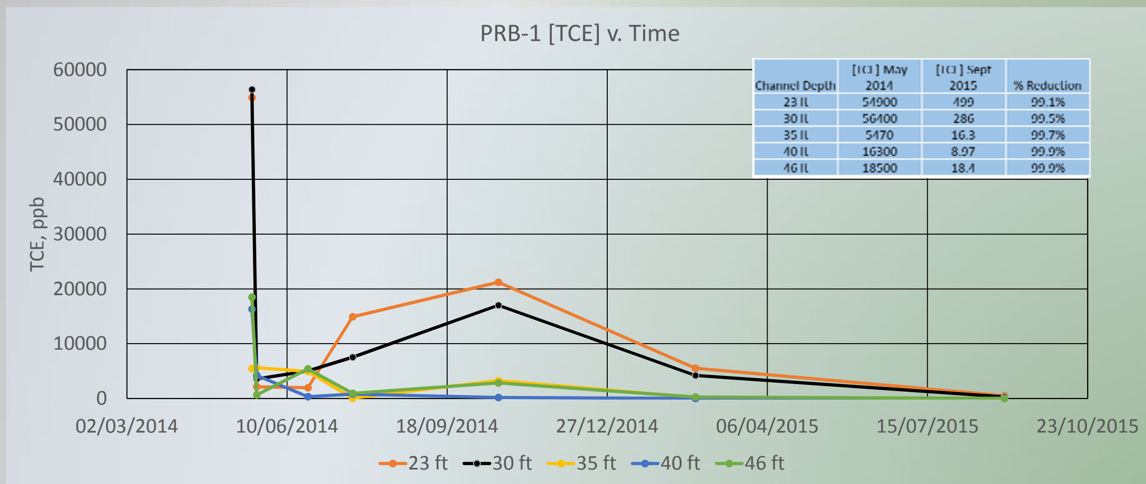
RemOx-L® Soil Blending

- Performance sampling was conducted in real time (24 hr TAT at RPI lab)
  - 31 of 43 blocks were below the 125 ppm target after one pass
  - After treatment the average concentration was 92 ppm which is a 92% reduction from initial average concentration of 1,126 ppm
- Post Treatment Monitoring
  - Reinstallation of groundwater monitoring well in treatment area (MW-20)
  - Confirmation sampling of soil utilizing DPT. Samples were collected at 0.5 m vertical intervals at 4 locations across the treatment area.



RemOx-L® Soil Blending

BOS 100® PRB Results



Channel Depth	[TCE] May 2014	[TCE] Sept 2015	% Reduction
23 ft	54900	499	99.1%
30 ft	56400	286	99.5%
35 ft	5470	16.3	99.7%
40 ft	16300	8.97	99.9%
46 ft	18500	18.4	99.9%

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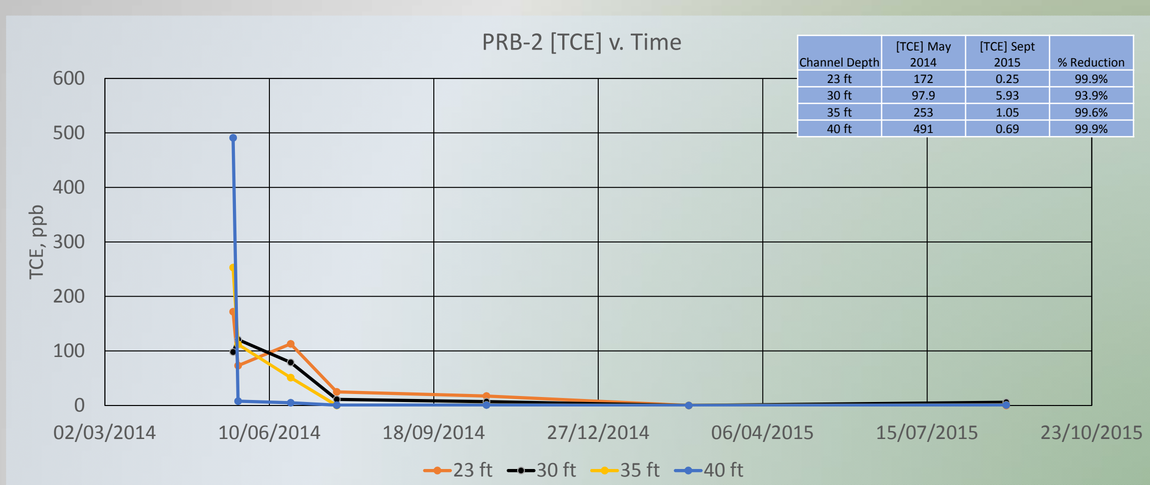
BOS 100® PRB Results



Channel Depth	[TCE] May 2014	[TCE] Sept 2015	% Reduction
23 ft	172	0.25	99.9%
30 ft	97.9	5.93	93.9%
35 ft	253	1.05	99.6%
40 ft	491	0.69	99.9%

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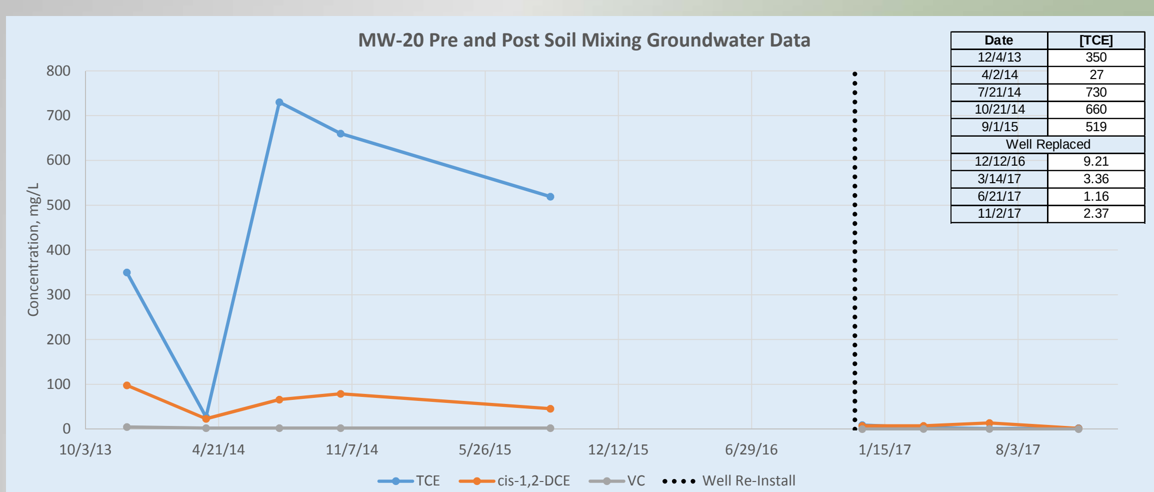
RemOx-L Soil Blending Results

- Post injection average concentration is based on samples collected from 5.5 - 10 m bgs
- Of the 20 samples collected only 1 sample was above the 125 mg/kg goal at a concentration of 133 mg/kg.

	Baseline (September 2015)	Post Application (December 2016)	% Reduction
Groundwater	519 mg/L	9.21 mg/L	98.2%
Soil	1,126 mg/kg (avg)	SB-1 - 16.75 mg/kg	98.5%
		SB-2 - 56.45 mg/kg	95.0%
		SB-3 - 12.08 mg/kg	99.0%
		SB-4 - 56.42 mg/kg	95.0%

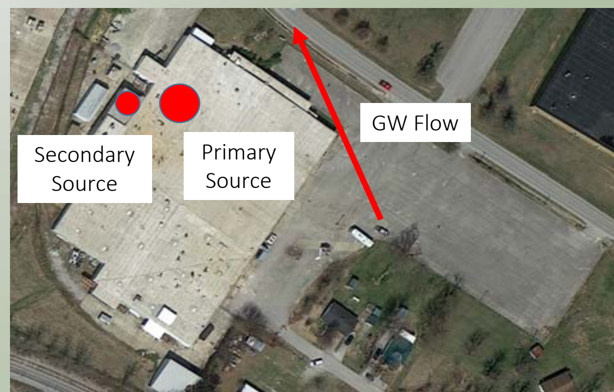
RemOx-L Soil Blending Results



Date	[TCE]
12/4/13	350
4/2/14	27
7/21/14	730
10/21/14	660
9/1/15	519
Well Replaced	
12/12/16	9.21
3/14/17	3.36
6/21/17	1.16
11/2/17	2.37

Site #2 – Background Information

- Shallow groundwater in unconsolidated soil (silty clay) and weathered bedrock (weathered shale)
- Depth to water varies from 0.6 - 1.5 m bgs, weathered bedrock varied from 1.5 - 5.5 m bgs
- The site was broken down into the following treatment areas:
  - Primary Source (>50 mg/L TCE)
  - Secondary Source (10-50 mg/L TCE)
  - Dilute Plume (<10 mg/L TCE)



Project Timeline

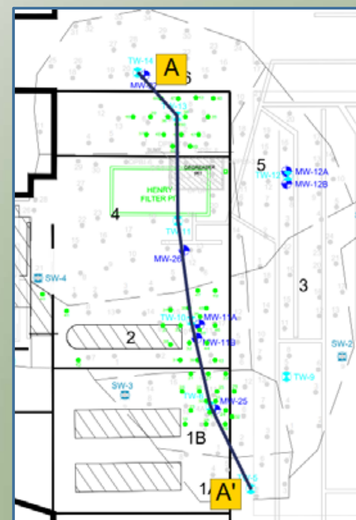
- Project timeline
  - 2010 BOS 100 Pilot Test
  - Spring 2012 Full Scale Remedial Design Characterization (RDC)
    - Soil profiled every 0.6 m to refusal (20 borings, 128 soil samples*)
    - Eight locations converted to temporary wells (TWs)
  - Fall 2012 1st Full Scale Injection Event (BOS 100 and EVO)
  - Winter 2013/2014 2nd Full Scale Event (BOS 100, EVO, $NaHCO_3$, and DHC)

*Analyzed at RPI laboratory (Golden, CO)

Remedial Design Characterization (RDC)

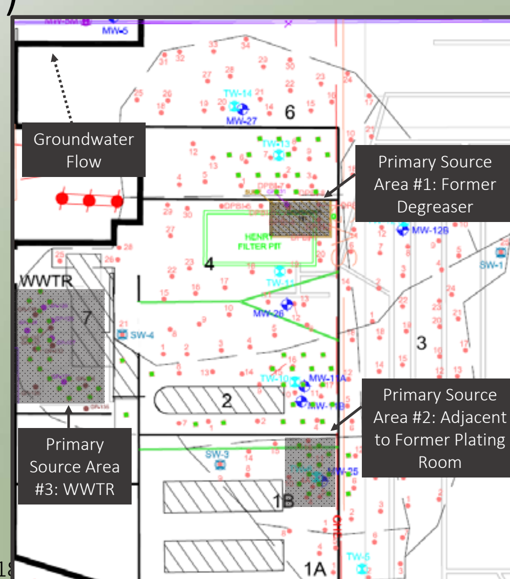
Depth below grade (ft)	A (North) TW-14	TW-13	TW-11	TW-10	TW-6	A' (South) TW-5
0	51	87	63	69	2,862	414
1						
2	106	85	58			841
3						
4	159	2,430	841	612	1,247	3,710
5						
6	1,570	7,195	183	3,068	887	3,277
7						
8	2,220	16	1,560	1,180	1,789	1,973
9					5,433	
10	4,191	60	29	18	50	37
11				245		
12	3,160	191	80	Refusal	Refusal	16
13						Refusal
14	2,515	42	116			
15		455				
16	Refusal	Refusal	245			
17			Refusal			

Notes:
Values are summation of PCE, TCE, cis-1,2 DCE and VC in ug/kg
Data generated by RPI Laboratory (Golden, CO)



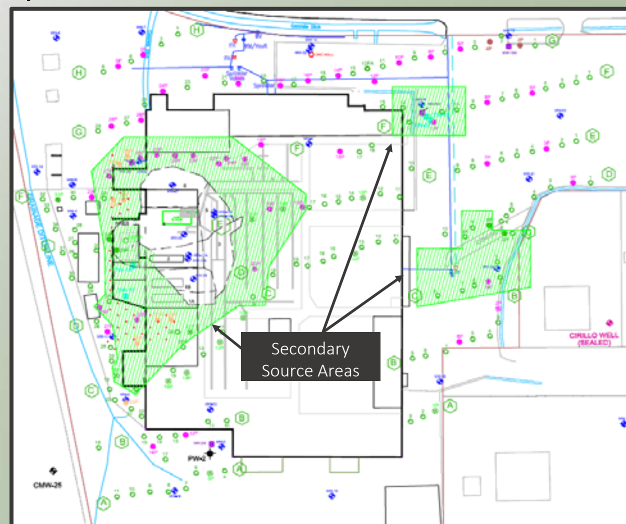
Injection Event #1 (BOS 100)

- BOS 100 applied in source area
  - 2nd injection planned for areas 1B and 2 based on baseline concentrations and access issues
- 157 total injection locations (~1 m ROI), goal to penetrate 0.5 - 1 m into weathered shale at each location (small diameter augers used to tie into weathered shale)
- Sentinel wells (SW) used to ensure EVO and BOS 100 didn't interact



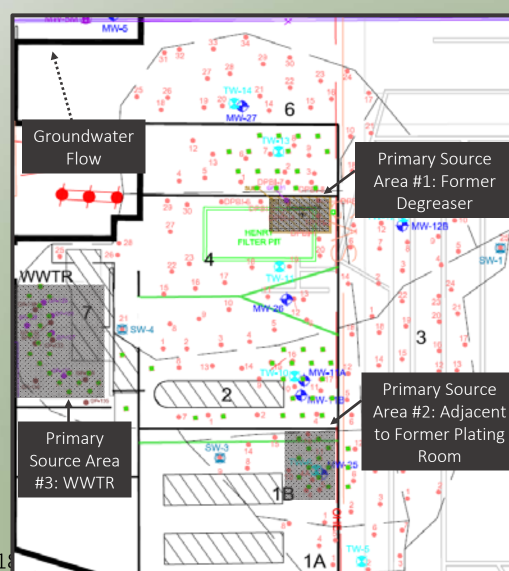
Injection Event #1 (EVO)

- EVO applied in Secondary Source (hatched) and Plume areas
- 182 total injection locations (~50% converted to IWs)
- Sand proppant injected with EVO



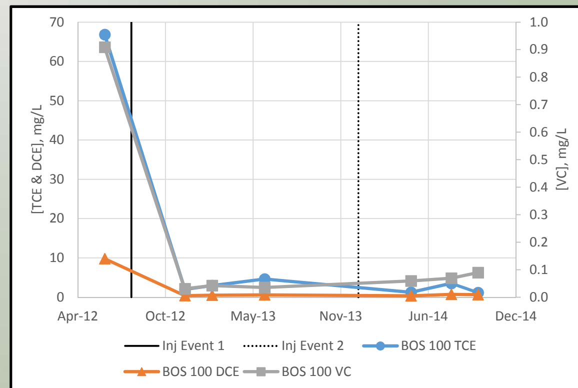
Injection Event #2 - Adjustments

- Additional source discovered during the 2012 injection event (up to 500 mg/kg TCE under slab)
  - 7th injection area added (areas 1B and 2 reinjected as planned, area 6 unplanned)
- $NaHCO_3$ added to additional EVO to help buffer pH
- DHC added in pilot test area



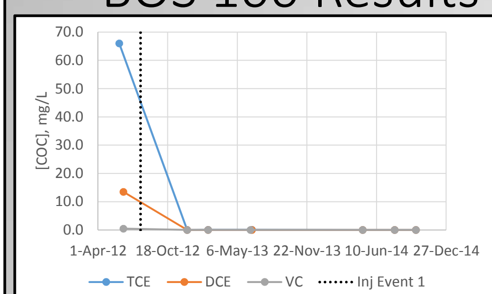
Results

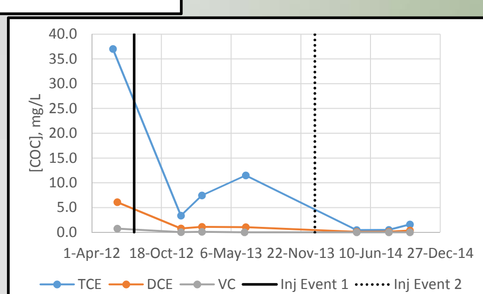
- CVOCs in the Primary Source Area reduced on average 90.2 to 98.3%
- Daughter product concentrations did not increase with decreasing TCE concentration.
- Abiotic degradation was confirmed via dissolved gas concentration

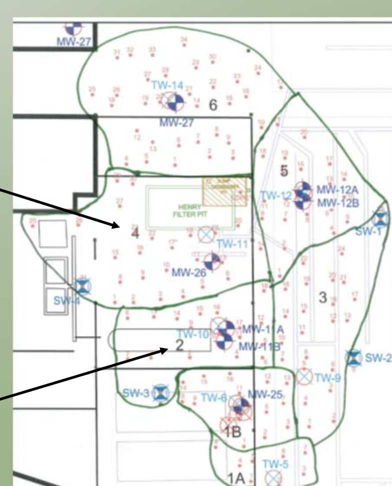


COC (mg/L)	Jun-12	Oct-14	% Red
TCE	66.828	1.157	98.3%
DCE	9.787	0.618	93.7%
VC	0.909	0.089	90.2%

BOS 100 Results

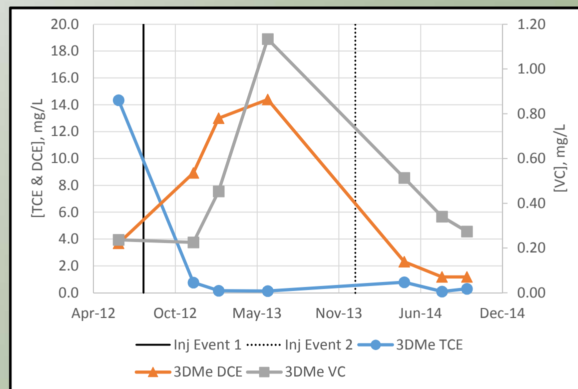






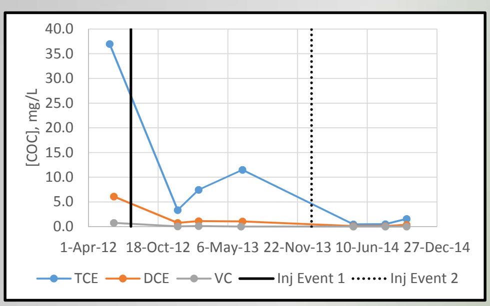
EVO Results

- The EVO exhibited classic anaerobic reductive dechlorination trends with DCE and VC generation concurrent with rapid TCE degradation.
- Overall average reductions for the three compounds ranged from -15.8 to 97.9%.
- The pH modification was successful in increasing the degradation rates for DCE and VC.

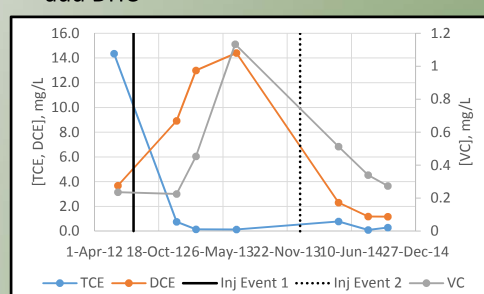


BOS 100 vs. EVO

- Minimal daughter generation
- No need for pH manipulation or DHC addition
- 2nd application necessary due to iron demand



- Longer treatment timeframe
- Possibility of generating high concentrations of daughter products
- 2nd application necessary to adjust pH and add DHC



Data Summary

Treatment Area	Reagent	COC	Jun-12	Oct-14	% Red
Primary Source Area	BOS 100®	TCE	66.828	1.157	98.3%
		DCE	9.787	0.618	93.7%
		VC	0.909	0.089	90.2%
Secondary Source Area	EVO + $NaHCO_3$	TCE	14.350	0.295	97.9%
		DCE	3.685	1.175	68.1%
		VC	0.237	0.274	-15.8%
Dilute Plume	EVO + $NaHCO_3$	TCE	0.569	0.002	99.7%
		DCE	0.742	0.014	98.1%
		VC	0.057	0.023	59.0%
Dilute Plume + DHC	EVO + $NaHCO_3$ + DHC	TCE	0.500	0.001	99.9%
		DCE	2.000	0.006	99.7%
		VC	0.031	0.010	68.1%
Note: All concentrations in mg/L					

Summary

- Multiple application techniques and technologies were successfully integrated to optimize budgets and remediation timeframes
- High density soil and groundwater sampling were integral to design optimization, remedy selection, and client expectation management
- Reagent distribution was verified throughout each project for each product

Thank you.

Please contact me with questions:

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