Cost Benefit Analysis of Chlorinated Ethene Bioaugmentation in Groundwater

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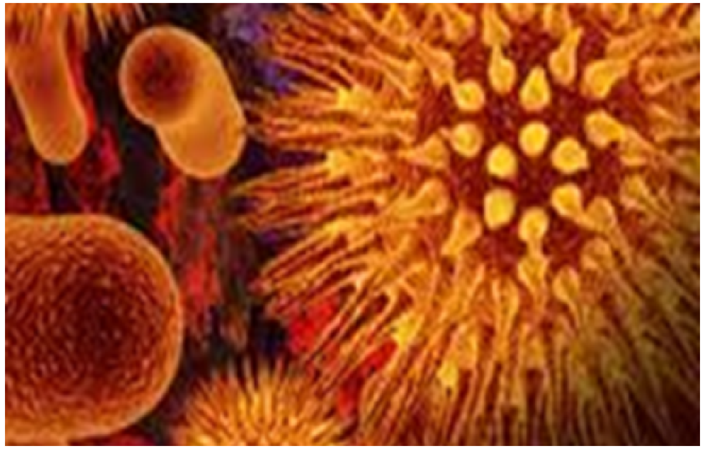

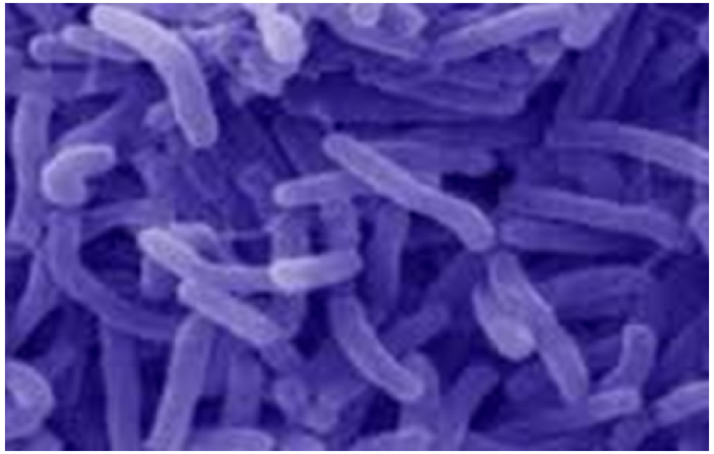

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Primary Cost Drivers Bioremediation Approaches

Project Cost Drivers	Key Information
Clean up Time Period	Is this regulatory driven or other factor, e.g., site development?
Clean up Contaminant Goals	Is MNA final goal or other factor, e.g., downgradient drinking water?
Microbial Testing/Bench/ISMs	Determine type of bioremediation approach is best and application rate for site
Injection Wells/Injection points or Permeable Reactive Barrier	Depth of contamination, geology, hydrogeology characteristics
Area Volume to be Treated	How well is plume defined?
How well is the bioaugmented culture distributed?	Stickiness of culture and hydrogeology
How often do you need to conduct additional bioaugmentation events?	Survival rate of bioaugmented culture

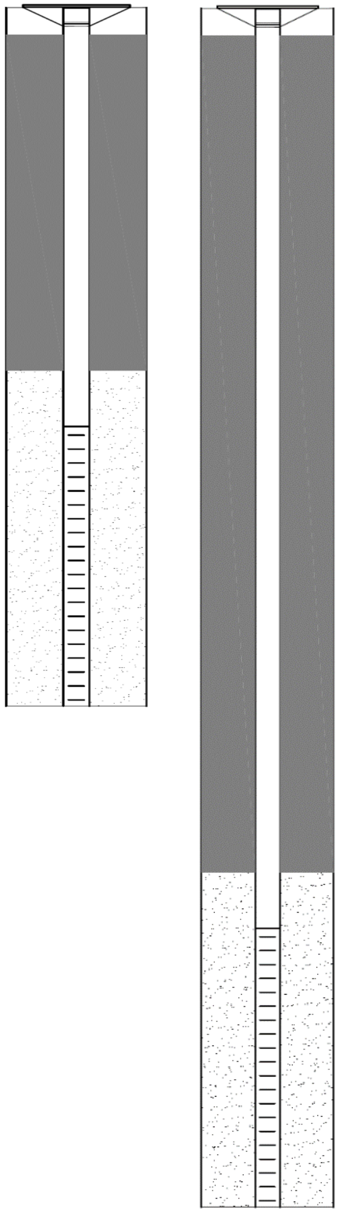
Cost Evaluation of Biostimulation versus Bioaugmentation

Example Cases	Details	Biostimulation	Additional Cost Bioaugmentation & % of NPV Total
		NPV of Total Cost	
Remediate Source Area (250 m^2 / 2,690 ft^2)	Install 15 injection wells spaced on 5 m (16.4 ft) centers, EVO carbon source (185 Kg (407 lb)) + ~2,400 gallons dilute/chase fluid; bioaugmentation >1.0 E+10 cells/L; biostimulation every 3 years; 5 years O&M; 10 years monitoring	$311K	$11K/3.4%
Site boundary-Shallow Barrier:	Reduce contaminant level (>90%); install 15 injection wells on 5 m; EVO carbon source (185 Kg); bioaugmentation >1.0 E+10 cells/L; biostimulation every 3 years; operate 30 years	$585K	$11K/1.8%
Site boundary-Deep Barrier:	Reduce contaminant level (>90%); install 15 paired injection wells on 5 m, one screened across upper 4.5 m (14.8 ft) and 2nd lower 4.5 m; EVO carbon source (280 Kg), bioaugmentation >1.0 E+10 cells/L; biostimulation every 3 years; operate 30 years	$952K	$18K/1.9%

Bioaugmentation for Groundwater Remediation, Stroo, Leeson and Ward, 2013

Site Background

- Located in Midwest United States
- Major Contaminants of Concern
  - 1,1,1-trichloroethane (1,1,1-TCA)
  - 1,1-dichloroethane (1,1-DCA)
  - 1,1-dichloroethene (1,1-DCE)
  - Tetrachloroethene (PCE)
  - Trichloroethene (TCE)
  - Cis-1,2-dichloroethene (cis-1,2-DCE)
- Upper aquifer divided into two zones:
  - Shallow (surface to 40 feet)
  - Deep (40 feet to approximately 60 feet)



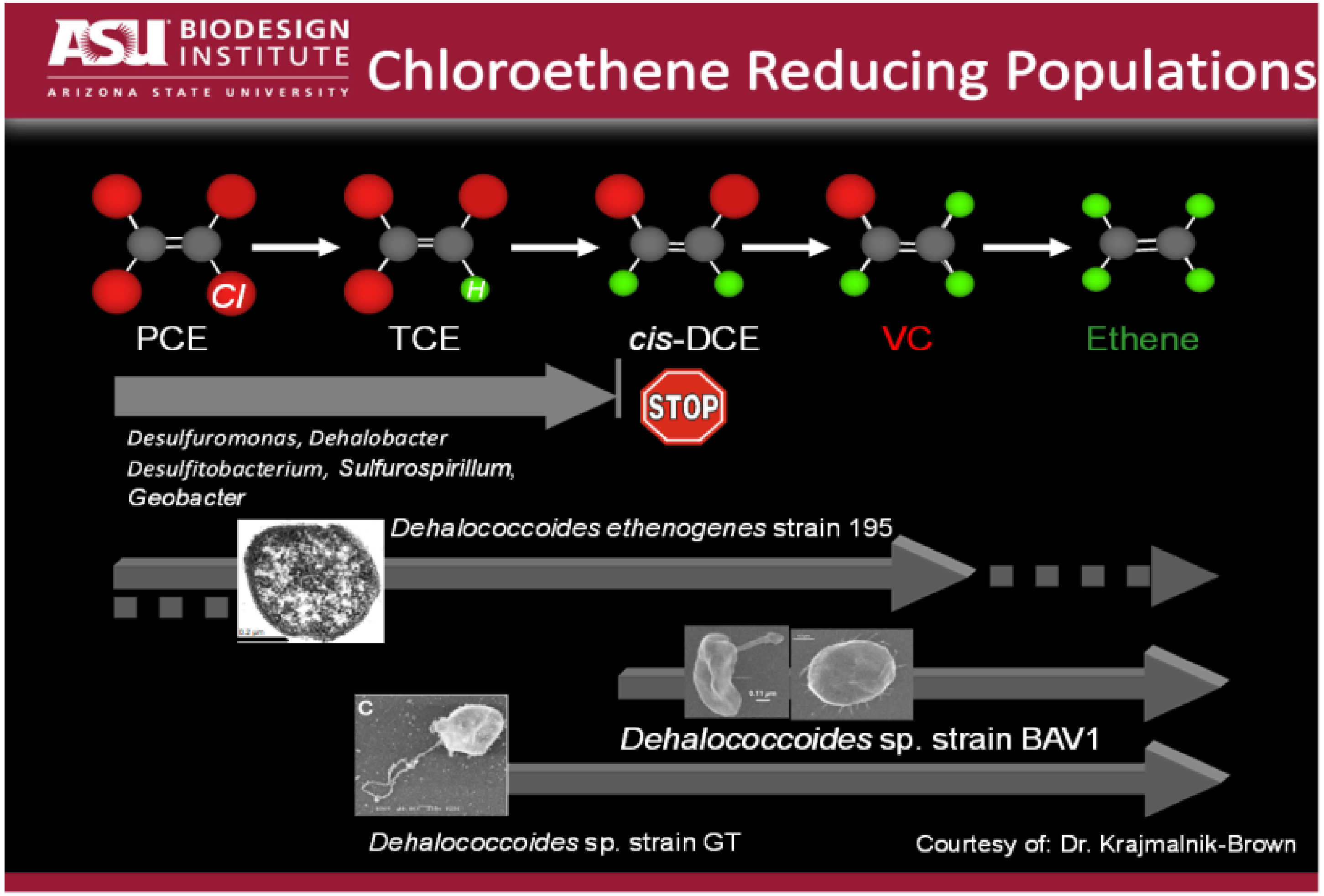
Historical CVOCs in Groundwater

Up Gradient

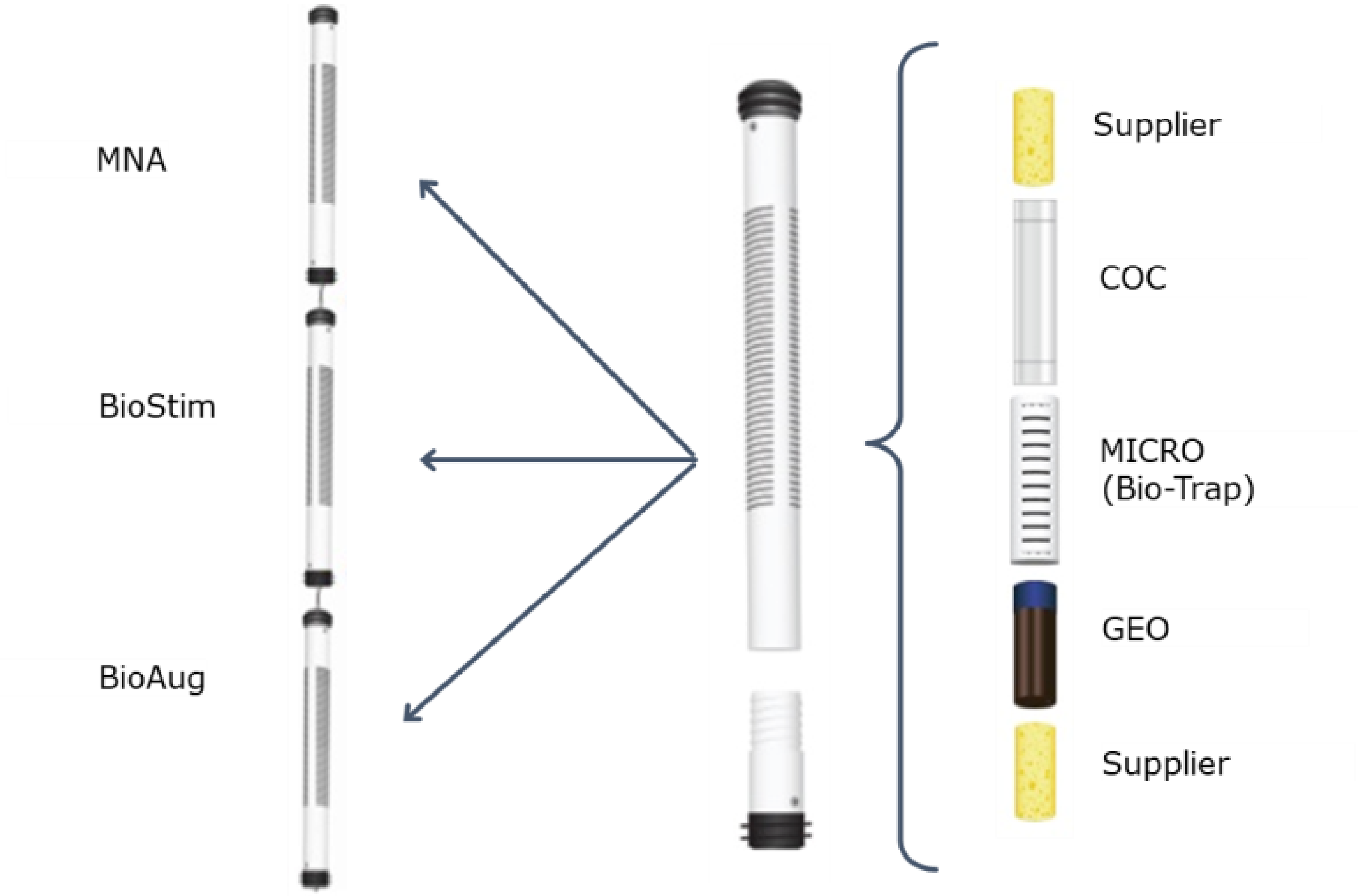
Down Gradient

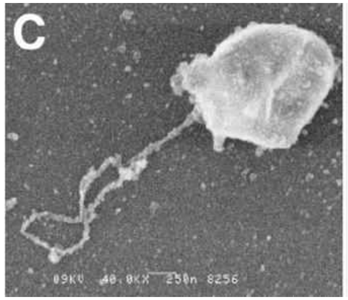
Historical CVOCs in Groundwater	PCE	TCE	cis-1,2-DCE	VC
	µg/L			
MW-56S (March 2019 to September 2020)	<5.0	**116 - 249**	<5.0 - 19.5	<2.0
MW-56D (March 2019 to September 2020)	<5.0	**1,130 - 293**	7.2 - 17.8	<2.0
MW-61S (March 2019 to September 2020)	<5.0 - **6.1**	**74.1 - 346**	8.3 - 10.6	<2.0
MW-61D (March 2019 to September 2020)	<25.0	**2,810 - 5,580**	<25.0	<10.0
MW-52S (September 2018 to March 2020)	<5.0	**85.2 - 283**	**204 - 400**	**147 - 451**

CVOC Degradation

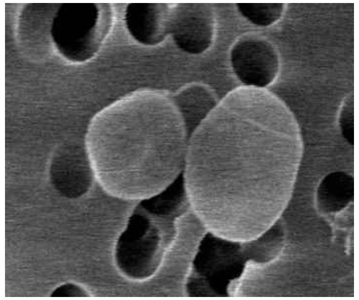


In Situ Microcosm Study





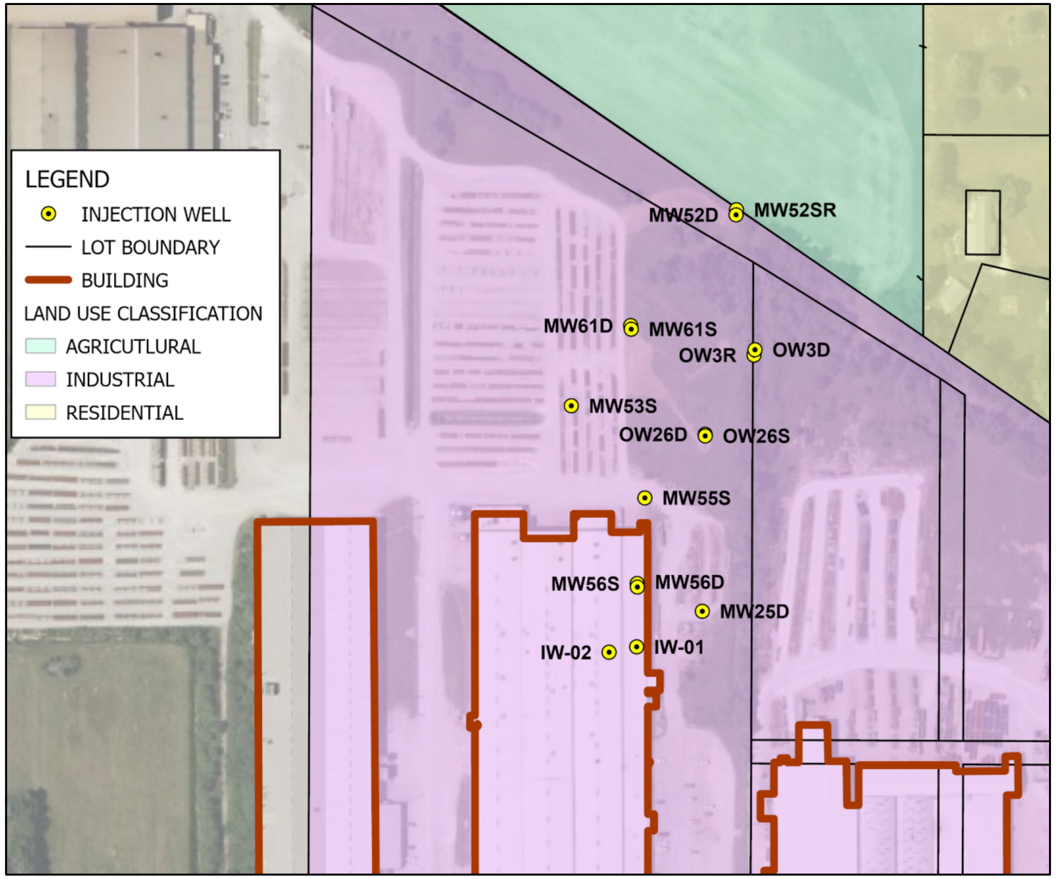
In Situ Microcosm Study



- Three carbon sources evaluated:
  - EOS PRO: enriched EVO; contains slow– and fast-release substrates
  - SRS-SD: small-droplet emulsified vegetable substrate; rapidly generates reducing conditions
  - Wilclear Plus: lactate as major quick release carbon substrate along with accelerant; provide a range of material to help promote the growth of the microbial populations
- Three microbial consortia evaluated:
  - KB-1®:naturally occurring, non-pathogenic microbial culture that contains *Dehalococcoides* (*DHC*)
  - SDC-9™ (BAC-9): includes anaerobic bacteria able to biodegrade CVOCs and perform fermentation processes. The culture contains *DHC* bacteria.
  - TCA-20™: includes anaerobic bacteria able to biodegrade chlorinated ethanes. The culture contains *DHC* bacteria too.

In Situ Microcosm Study Results

Pre-ISM Nutrient Information	IW-2	MW-61D	MW-52SR
Nutrient Information:	mg/L		
Nitrate as N	4.4	<0.10	<0.10
Total Organic Carbon	<32	1.1	3.4
Ammonia	0.6	<0.10	17.8
Nitrogen, Total Kjeldahl (TKN)	7.4	<0.50	20.2
Phosphorus	4.6	<0.05	1.2



In Situ Microcosm Study Results

Volatile Organic Compounds (VOCs)	MW-61D (µg/L)	IW-2 (µg/L)	MW-52SR (µg/L)
	Background Concentrations		
Tetrachloroethene (PCE)	<25	5.5	<5
Trichloroethene (TCE)	4,320	1,750	109-589
cis-1,2-Dichloroethenev(cis-1,2-DCE)	<25	64.7	238-615
Vinyl Chloride (VC)	<10	<2	444-767

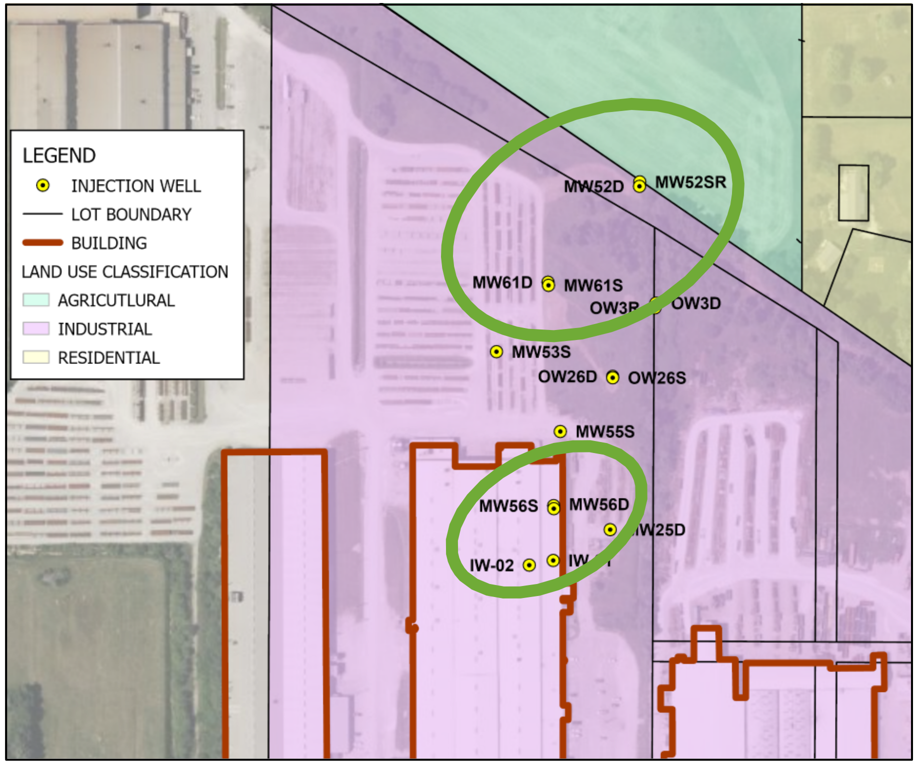
Volatile Organic Compounds (VOCs)	MW-61D			IW-2		MW-52SR	
	Bio Stim EOS-PRO	BioAug EOS-PRO, SDC-9 and TCA-20	BioAug EOS-PRO, KB-1 Plus	BioStim Wilclear Plus	BioAug Wilclear Plus, SDC-9 and TCA-20	BioStim SRS-SD	BioAug SRS-SD, SDC-9
	Percent Decrease or Increase in COC						
Tetrachloroethene (PCE)	36%	-96%*	53%	NA	45%	ND	ND
Trichloroethene (TCE)	-27%	-99%	-47%	-85%	-5%	-90%	-20%
cis-1,2-Dichloroethene (cis-1,2-DCE)	14,664%	9,488%	5,288%	29%	475%	-45%	-41%
Vinyl Chloride (VC)	-25%	1355%	-30%	65%	6750%	-74%	-68%
Ethene (µg/L)	<0.4	13.2	<0.4	27.3	277	8.2	30.6

In Situ Microcosm Study Results

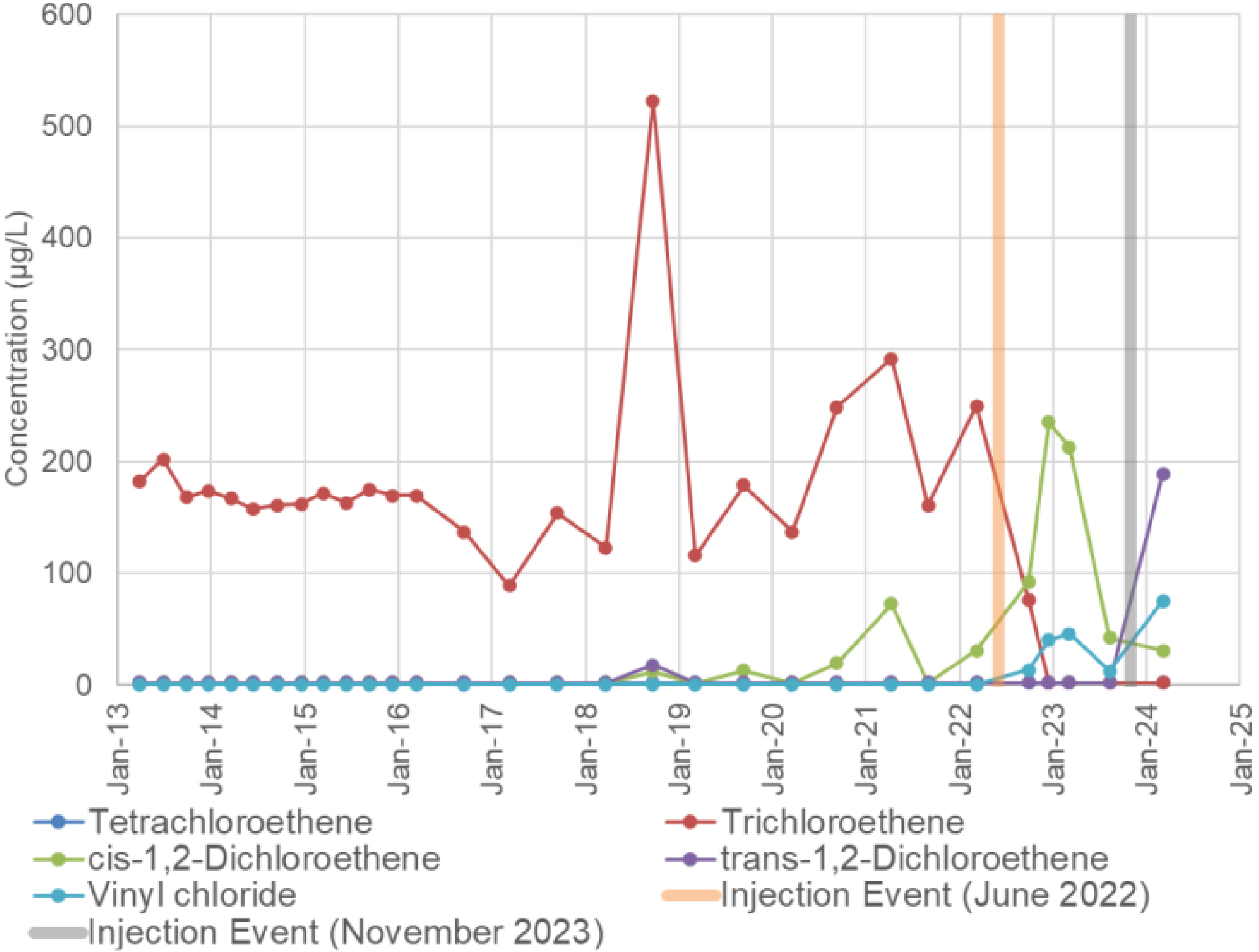
	MW-61D			IW-2		MW-52SR	
	Bio Stim EOS-PRO	BioAug EOS-PRO, SDC-9 and TCA-20	BioAug EOS-PRO, KB-1 Plus	BioStim Wilclear Plus	BioAug Wilclear Plus, SDC-9 and TCA-20	BioStim SRS-SD	BioAug SRS-SD, SDC-9
Volatile Fatty Acids (mg/L)							
Lactic Acid	1.6	0.43(J)	NA	<5.0	<5.0	16	13
Acetic Acid	9.8	76	NA	3.0 (J)	170	130	11
Propionic Acid	0.62	<0.5	NA	<5.0	100	<0.5	<0.5
Butyric Acid	<0.5	<0.5	NA	<5.0	21	<0.5	<0.5
Microbial Parameters (cells/bead)							
Dehalococcoides	6.88E+02	1.84E+06	9.29E+05	2.96E+04	1.28E+07	1.20E+04	1.26E+07
tceA Reductase	2.07E+01 J	1.48E+05	1.47E+04	1.23E+03	7.89E+05	5.91E+02	8.65E+05
BAV1 Vinyl Chloride Reductase	<2.5E+01	<2.5E+01	4.41E+02	<2.5E+01	<2.5E+01	<2.5E+01	<2.5E+01
Vinyl Chloride Reductase	5.91E+01	1.92E+05	5.08E+04	2.02E+03	9.01E+05	8.98E+02	1.01E+06

In Situ Bioremediation Pilot Test

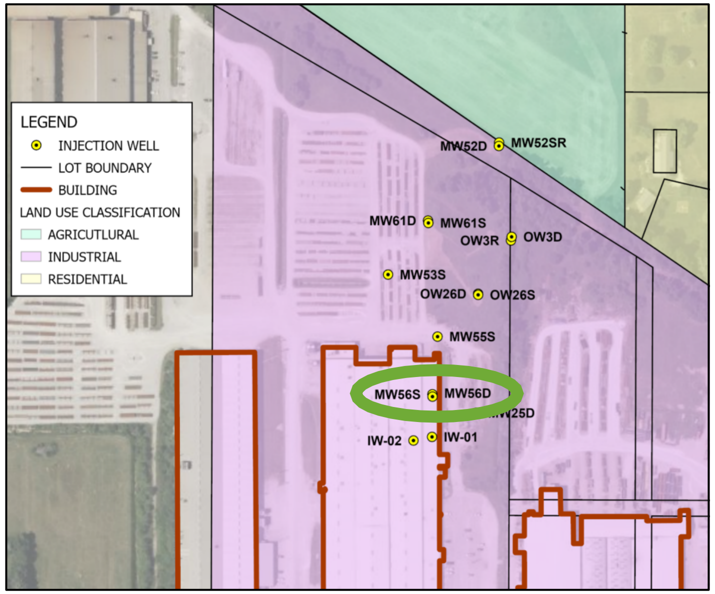
- Start *In Situ* Bioremediation pilot test in June 2022
- Carbon substrate EOS Pro and EOS QR
- Chase water amended with ascorbate to reduce DO to <0.5 mg/L and ORP to <-100 mV.
- After carbon substrates and chase water, BAC-9 (e.g. SDC9) was injected into the following wells:
  - MW-52SR, MW-61S, MW-52D, MW-61D
  - MW-56S
  - MW-56D
  - IW-02



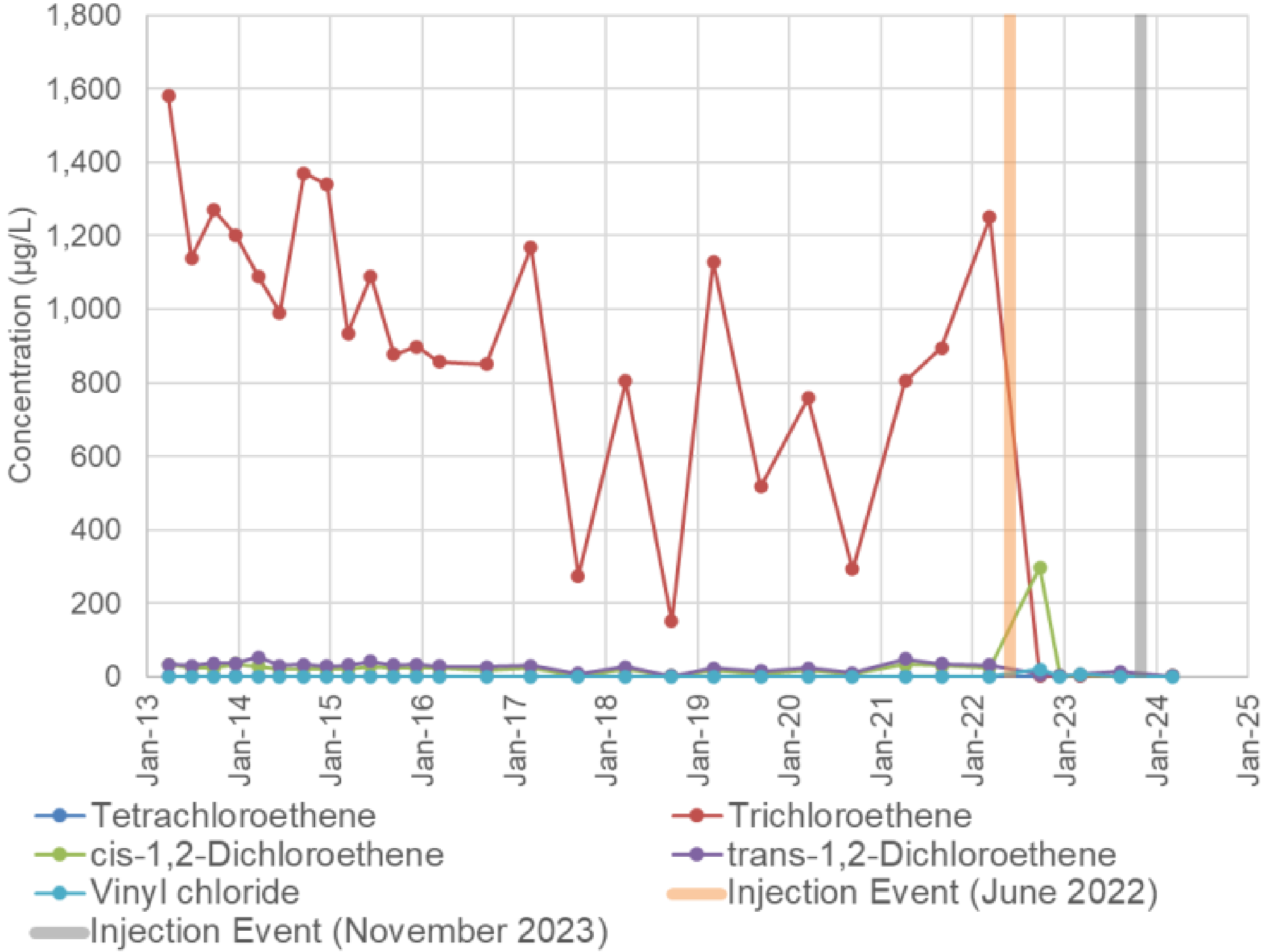
In Situ Bioremediation Pilot Test Results – MW-56S



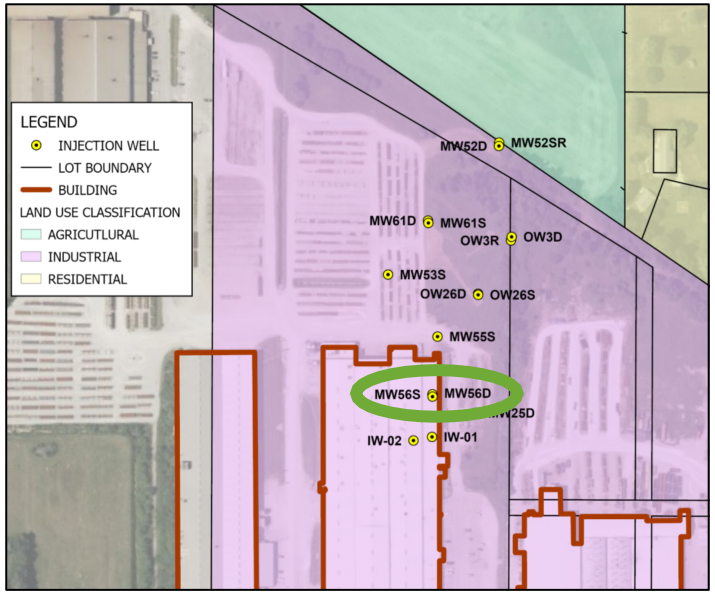
	TCE	Cis-1,2-DCE	VC
	µg/L		
April 2021	292	72.9	<2
August 2023	<5	42.5	12.7



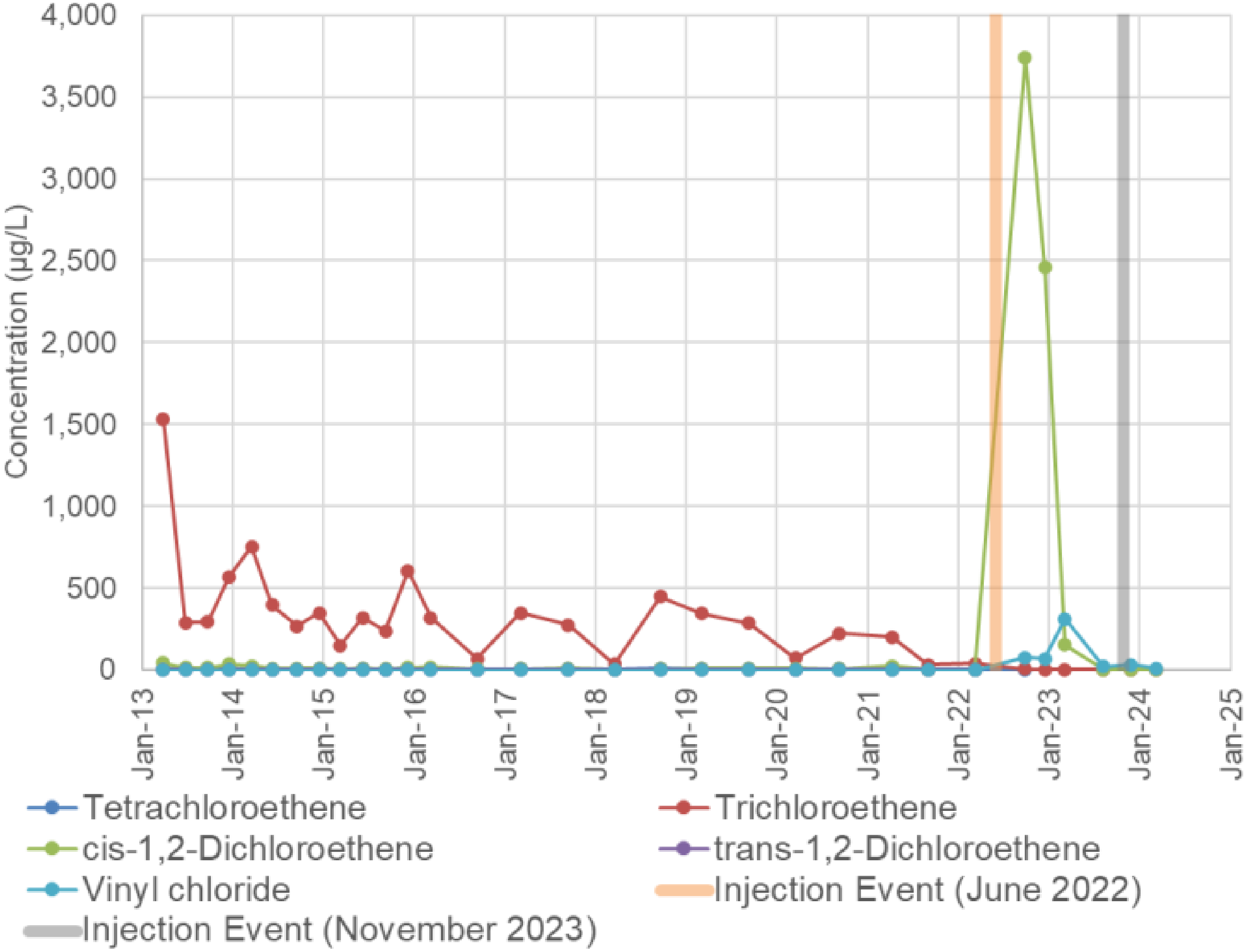
In Situ Bioremediation Pilot Test Results – MW-56D



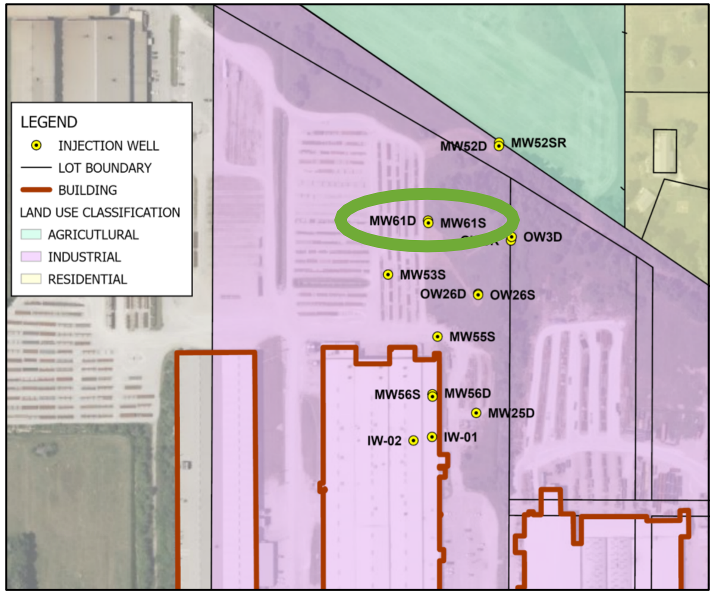
	TCE	Cis-1,2-DCE	VC
	µg/L		
April 2021	804	33.1	<2
August 2023	<5	<5	<2



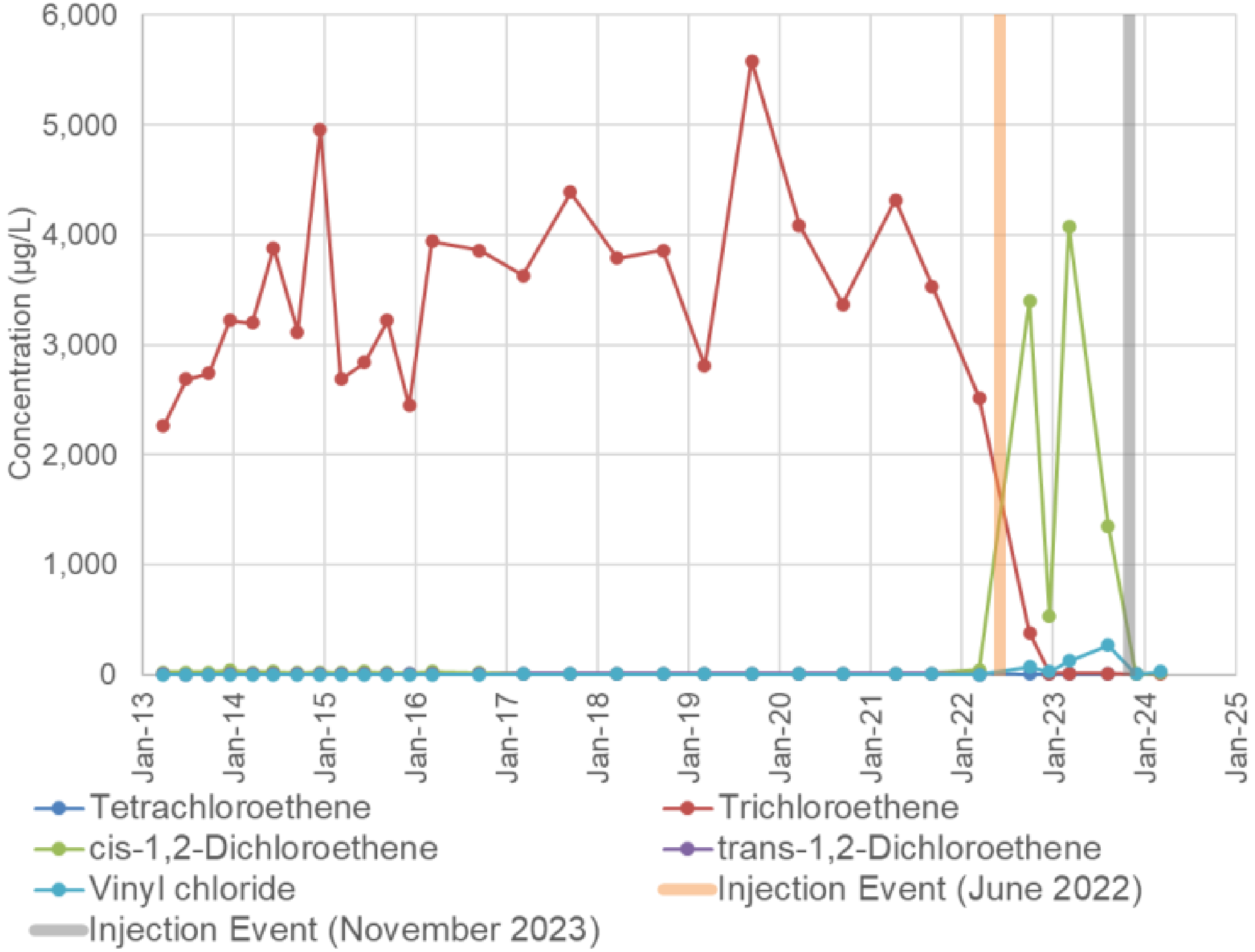
In Situ Bioremediation Pilot Test Results – MW-61S



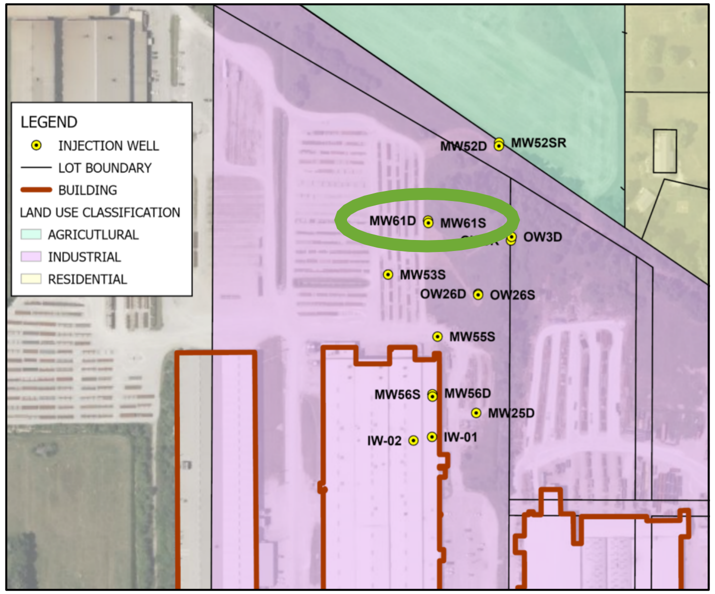
	TCE	Cis-1,2-DCE	VC
	µg/L		
April 2021	202	25.1	<2
August 2023	<5	<5	22.0



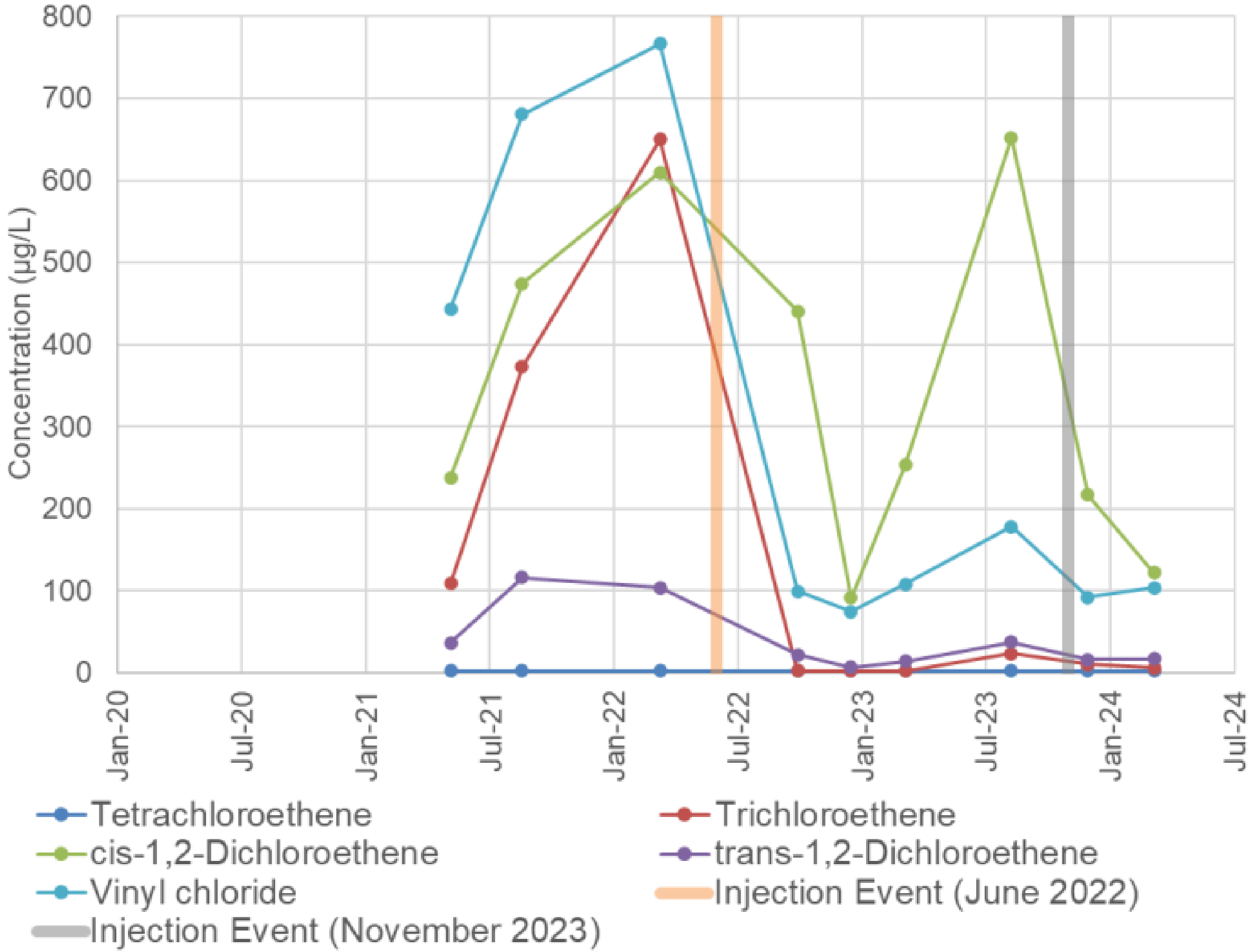
In Situ Bioremediation Pilot Test Results – MW-61D



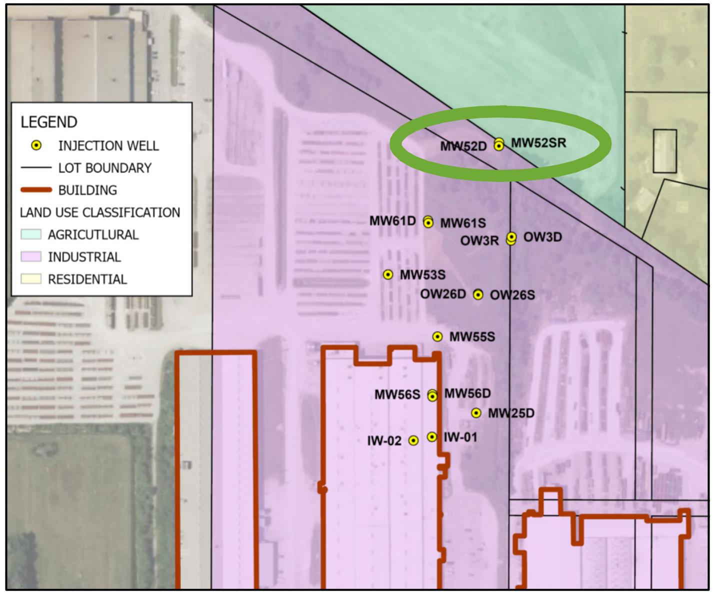
	TCE	Cis-1,2-DCE	VC
	µg/L		
April 2021	4,320	<25	<10
August 2023	<25	1,350	268



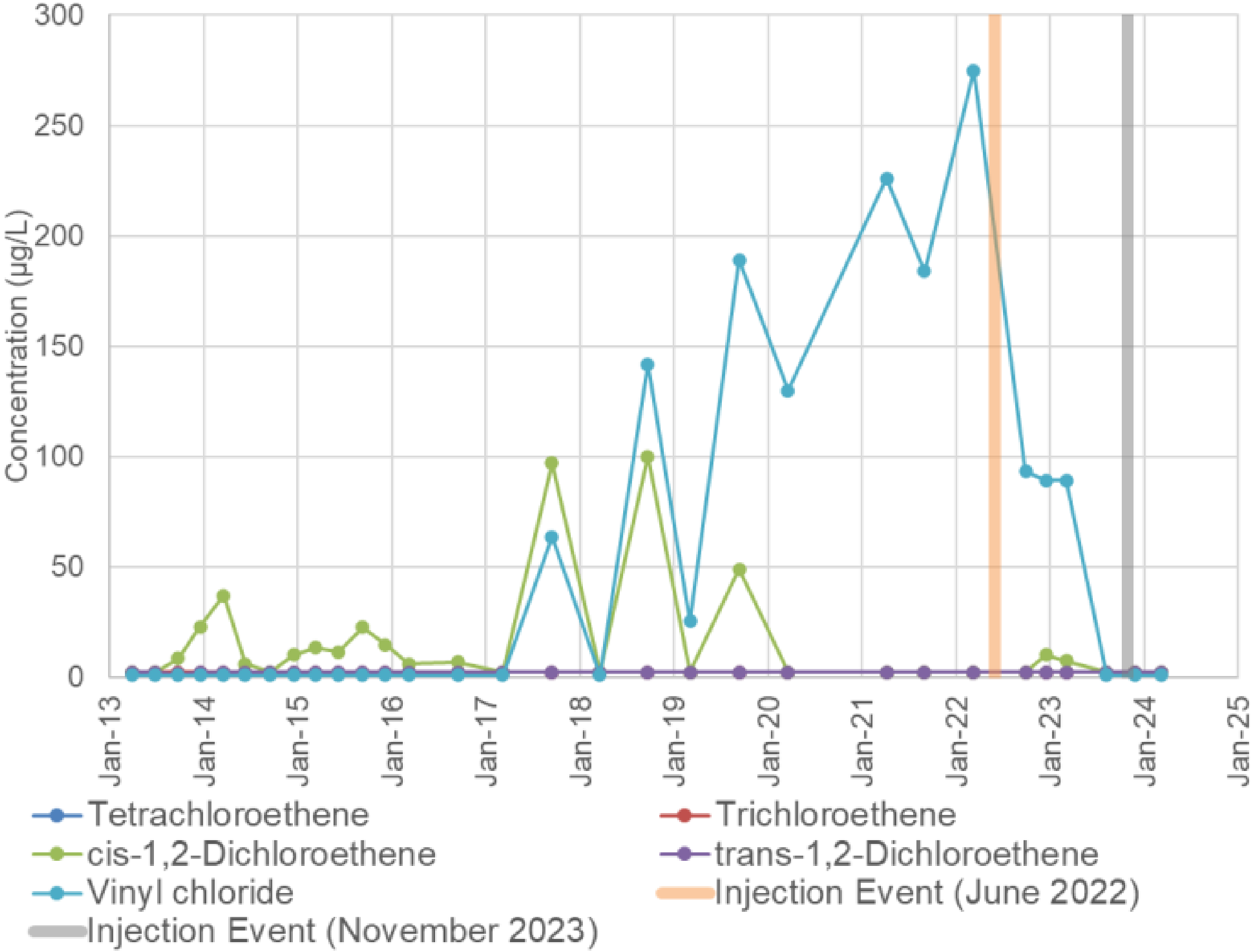
In Situ Bioremediation Pilot Test Results – MW-52SR



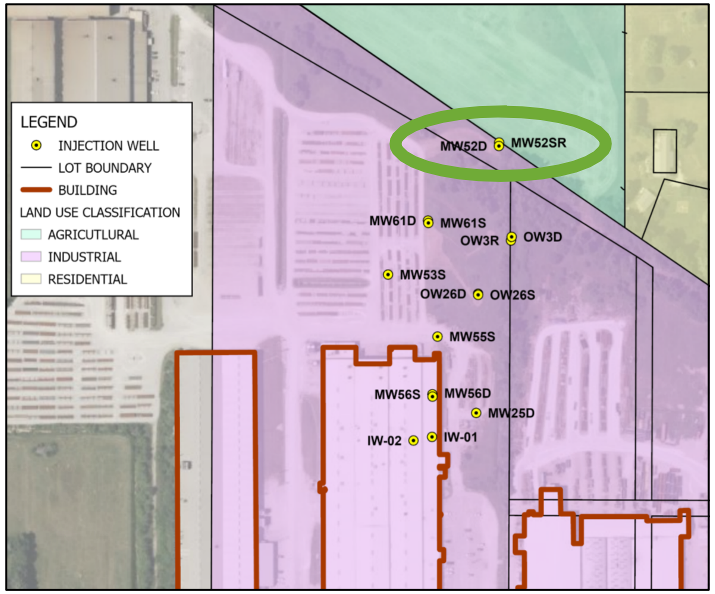
	TCE	Cis-1,2-DCE	VC
	µg/L		
2021	109-373	238-474	44-681
August 2023	23.2	652	178



In Situ Bioremediation Pilot Test Results – MW-52D



	TCE	Cis-1,2-DCE	VC
	µg/L		
April 2021	<5	<5	226
August 2023	<5	<5	<2



In Situ Bioremediation Pilot Test Results

Pilot Test Results	IW-02		MW-56D		MW-56S		MW-61D		MW-52D		MW-52SR	
	Dec 2022	Aug 2023	Dec 2022	Aug 2023	Dec 2022	Aug 2023	Dec 2022	Aug 2023	Dec 2022	Aug 2023	Dec 2022	Aug 2023
Total Organic Carbon (mg/L)	281	38.9	93.0	<4.0	784	99.7	299	480	93.0	11.5	178	192
Nitrogen, Total Kjeldahl (TKN) (mg/L)	0.61	1.3	2.1	1.5	7.2	5.1	3.4	1.1	3.2	7.6	8.2	18.1
Ammonia (mg/L)	3.0	<0.10	<0.10	0.26	2.4	<0.10	0.21	0.14	0.77	1.8	6.9	15.1
Phosphorus (mg/L)	0.27	0.51	1.4	2.2	3.0	2.5	0.59	0.26	0.80	1.0	0.39	0.62
Dissolved Oxygen (mg/L)	0.10	0.22	2.56	4.3	0.54	0.52	0.02	0.06	0.03	0.01	0.02	0.04
ORP (mV)	-197	-29.7	-170	72.3	-183	26.6	-233	-13	-256	-111.4	-354	-220.6

In Situ Bioremediation Pilot Test

Pilot Test Results	IW-02		MW-56D		MW-56S		MW-61D		MW-52D		MW-52SR	
	Dec 2022	Aug 2023	Dec 2022	Aug 2023	Dec 2022	Aug 2023	Dec 2022	Aug 2023	Dec 2022	Aug 2023	Dec 2022	Aug 2023
Methane (µg/L)	40,400	48,100	36,900	22,200	22,900	50,600	8,630	90,300	79,400	85,600	58,800	71,500
Ethane (µg/L)	<50.0	<100	<20.0	<100	12.4	<100	14.5	<100	<50.0	<100	<50.0	<100
Ethene (µg/L)	<50.0	<100	<20.0	<100	25.8	<100	13.3	<100	<50.0	<100	<50.0	<100
Sulfate (mg/L)	<10.0	<10.0	<10.0	43.3	<10.0	<10.0	<10.0	<10.0	<10.0	17.5	<10.0	23.4
Nitrate (mg/L)	<0.10	<0.10	<1.0	0.54	<2.0	<0.10	<1.0	<0.10	<2.0	<0.10	<0.10	<1.0

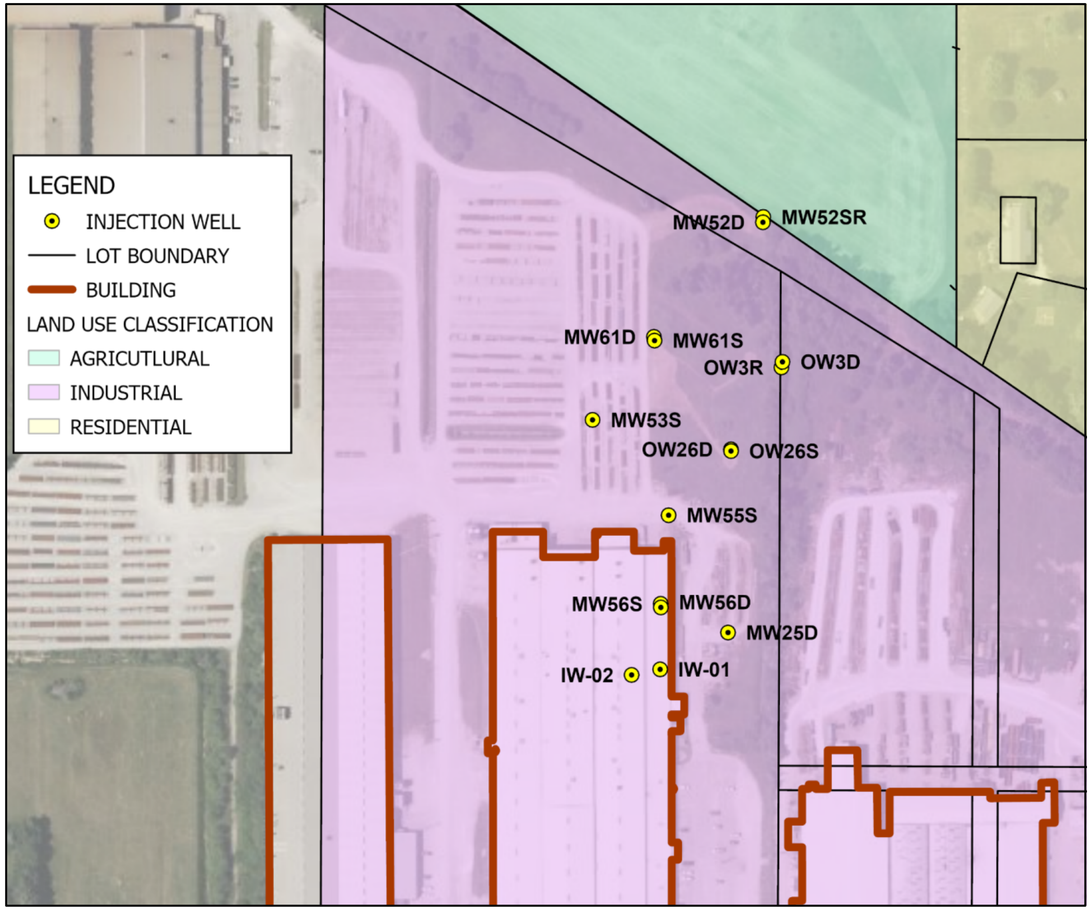
In Situ Bioremediation Pilot Test Results – *Dehalococcoides*

Microbial Parameters	IW-02		MW-56D		MW-56S		MW-61D		MW-52D		MW-52SR	
	Dec 2022	Aug 2023	Dec 2022	Aug 2023	Dec 2022	Aug 2023	Dec 2022	Aug 2023	Dec 2022	Aug 2023	Dec 2022	Aug 2023
	Cells/mL											
Dehalococcoides	3.96E+5	1.2E+4	2.30E+5	1.12E+5	1.01E+5	1.34E+5	6.84E+3	4.39E+4	2.36E+3	4.01E+4	6.32E+2	4.89E+4
tceA Reductase	1.65E+5	--	7.10E+4	--	4.34E+4	--	2.27E+3	--	1.42E+3	--	2.43E+2	--
BAV1 Vinyl Chloride Reductase	5.E-01	--	1.1E+0	--	6.3E+0	--	3.8E+0	--	1.11E+2	--	1.0E+0	--
Vinyl Chloride Reductase	7.58E+4	--	2.95E+4	--	2.34E+4	--	4.04E+1	--	1.03E+3	--	1.89E+2	--

Bioaugmentation Design Considerations

- Native Concentration of Key Microbes
- Results of Bench-Scale or ISM Study
- Concentration of Amended Microbes
- Geochemical and Nutrient Requirements (e.g., Vitamin B12)
- Target Bioaugmented concentration in GW ~ 1.0E+07 cells/liter;
  - Bioaugmentation culture typically contains 1.0E+11 cells/L
- Distribution of injected culture depends on:
  - Distance between injection points
  - How culture is injected – amount of anaerobic chase water
  - Transport properties or stickiness of microbe
  - Hydrogeology and geochemistry of groundwater

Full-Scale ISB Design



Full-Scale ISB Design

Well ID	Screen Depth Interval (ft bgs)	Radius of Influence (feet)	Screen Length (feet)	Effective Thickness (%)	EOS Pro dose (gallons)	EOS QR dose (gallons)	BAC-9 dose (Liters)	Scavenger (lbs)
Area 1- MW-61D	37-47	15	10	25%	0	0	5	0.1
Area 2 - MW-52SR	19.5-29.5	15	10	40%	0	0	5	0.1
Area 3 - OW-3R	22-32	15	10	40%	118	15	5	2
Area 3 - OW-3D	40-50	15	10	25%	74	10	5	1
Area 4 - OW-26S	29-39	15	10	40%	118	15	5	2
Area 4 - OW-26D	44-54	15	10	25%	74	10	5	1
Area 5 - MW-53S	22-32	15	10	40%	118	15	5	2
Area 6 - MW-55S	25-35	15	10	40%	118	15	5	2
Area 7 - IW-01	15.0-45.0	7	30	35%	68	9	3	1
Potential MW-25D		15	10	25%	74	10	5	1
				Total	**762**	**99**	**48**	**12**

Cost Analysis

- For this project, the bioaugmentation cost is anticipated to be about 3-4% of total project.
- Utilizing several on site monitoring wells as part of the injection program.
- Monitoring program was developed to focus on key parameters, which kept costs down.
- Bioaugmentation for Groundwater Remediation, Stroo, Leeson and Ward, 2013: additional cost for bioaugmentation 2% to 3.5%

Conclusions

- Based on results from ISM moved forward with pilot test
- Post implementation, TOC and DO observed at levels to support reductive dechlorination
- Results indicate reductive dechlorination is proceeding in all of the wells, where enhanced *in situ* bioremediation was applied
  - Significant decreases in TCE were observed
  - Cis-1,2-DCE decreased
  - VC concentrations decreased in MW-52SR, MW-52D, MW-61D and MW-56D.
  - Final product of reductive dechlorination, ethene, is observed in several wells
- Full-Scale design implementation in progress
- Bioaugmentation is cost effective
  - 3-4% of total project cost

Questions?

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