Remediating Bedrock:

What Once Was Impossible Is Now Routine.
Three Case Studies

RemTech – Banff, AB.

October 13, 2022

Kevin E. French, P.Eng.

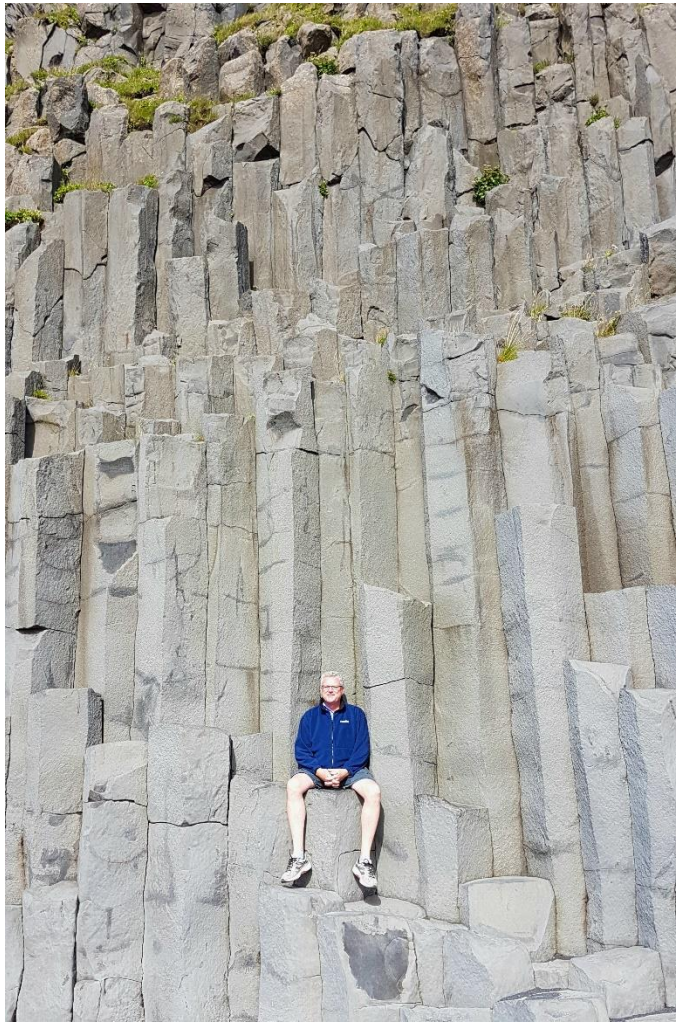
Presentation Overview

- Bedrock Remediation Difficulties
  - Why is it so difficult?
- Three Case Studies
  - Bedrock and PHCs (including LNAPL)
  - Bedrock and Heavy Metals (Hex Chrome)
  - Bedrock and Chlorinated Solvents (TCE)
- Take Aways / Lessons Learned
- Questions

Introduction – Presenter

Kevin French, P.Eng

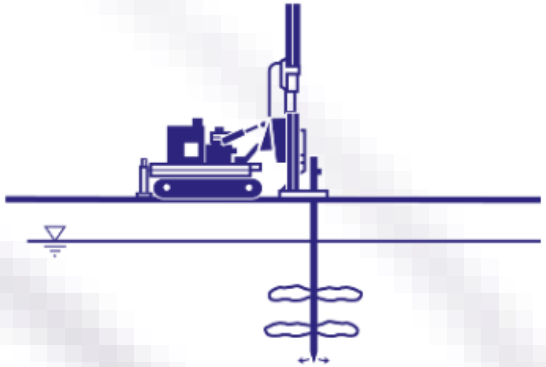
- Vice President, Vertex Environmental Inc.
- B.A.Sc., Civil/Env. Eng., U. Waterloo
- Environmental engineering
  - Consulting starting 1988
  - Remediation contracting since 2012



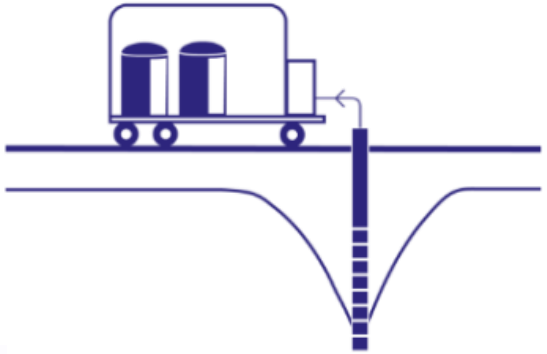
Vertex Environmental Inc.

- Founded in 2003
- Specialized Environmental Remediation Contracting (in-situ, ex-situ, treatment systems, vapour intrusion mitigation)
- High Resolution Site Characterization (HRSC) and Remedial Design Characterization (RDC)

Vertex Environmental Inc.

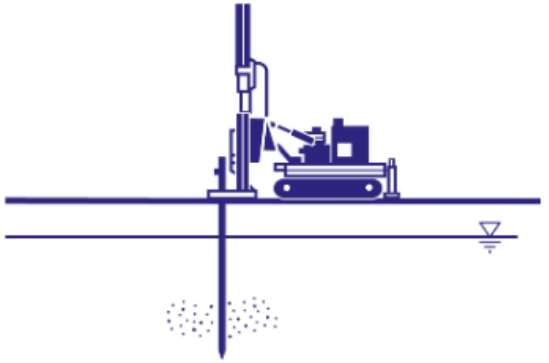


In-Situ Remediation

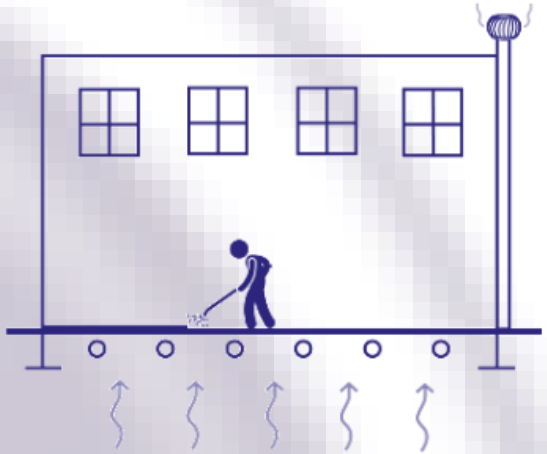


Dewatering & WTS

Ex-Situ Remediation



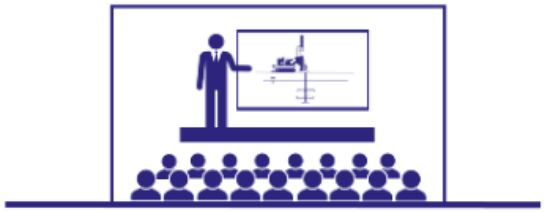
HRSC & RDC



Vapour Intrusion

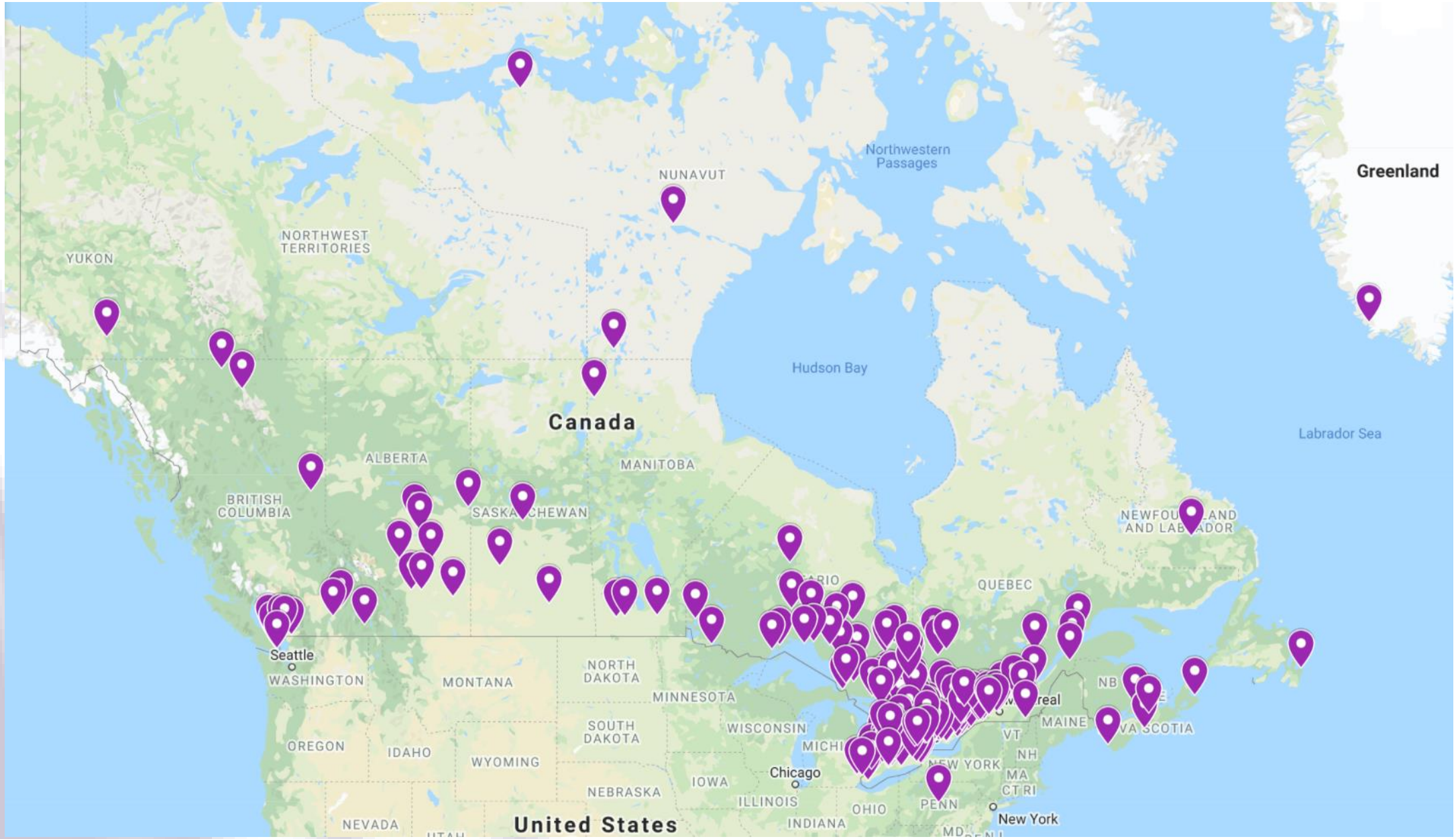
Bench-Scale Testing

Remedial Design



Outreach

Vertex Environmental Inc.



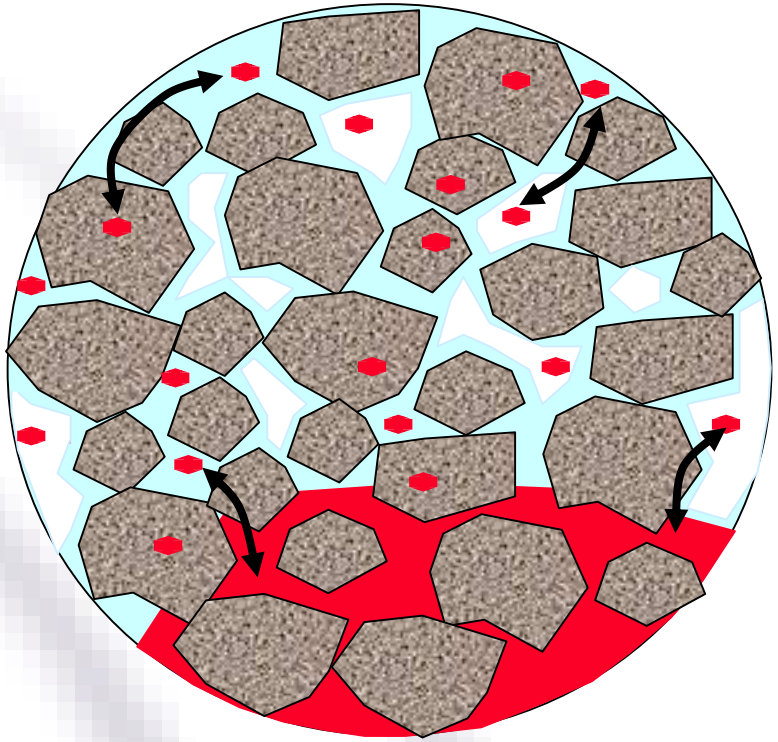
Bedrock Remediation Difficulties

Bedrock Remediation Difficulties

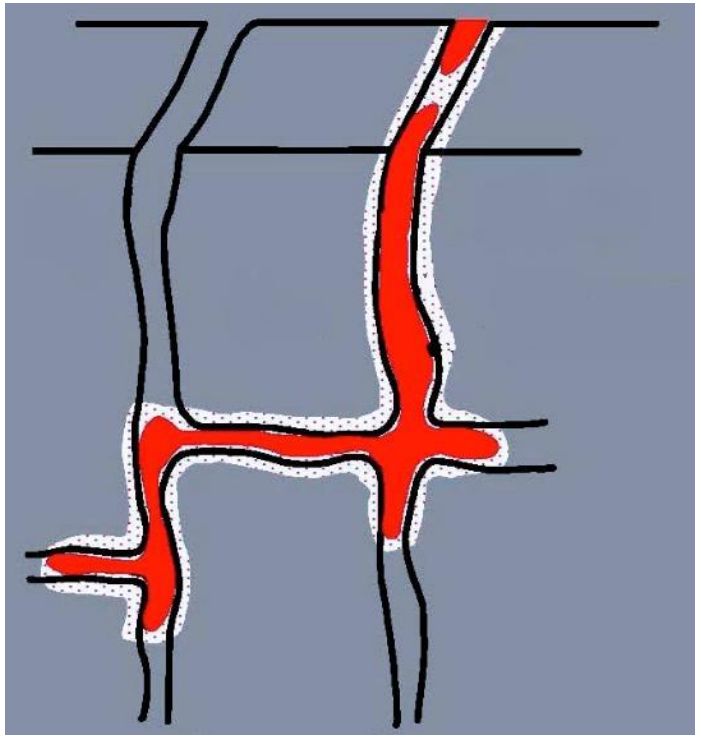
Why So Challenging?

- Fracture Network
  - Can be complex
  - Thus contaminant distribution also complex
- Secondary Porosity
  - Contamination diffuses into rock, difficult to get out
- Hard to Access / Expensive to Access
  - Easy for contaminant to enter fractures
  - Costly to access with remedial infrastructure (drilling)
- Groundwater Flow Velocity
  - Fast compared to porous media = shorter contact time
- Plume Length
  - Thin but long fractures = large plume

Bedrock Remediation Difficulties

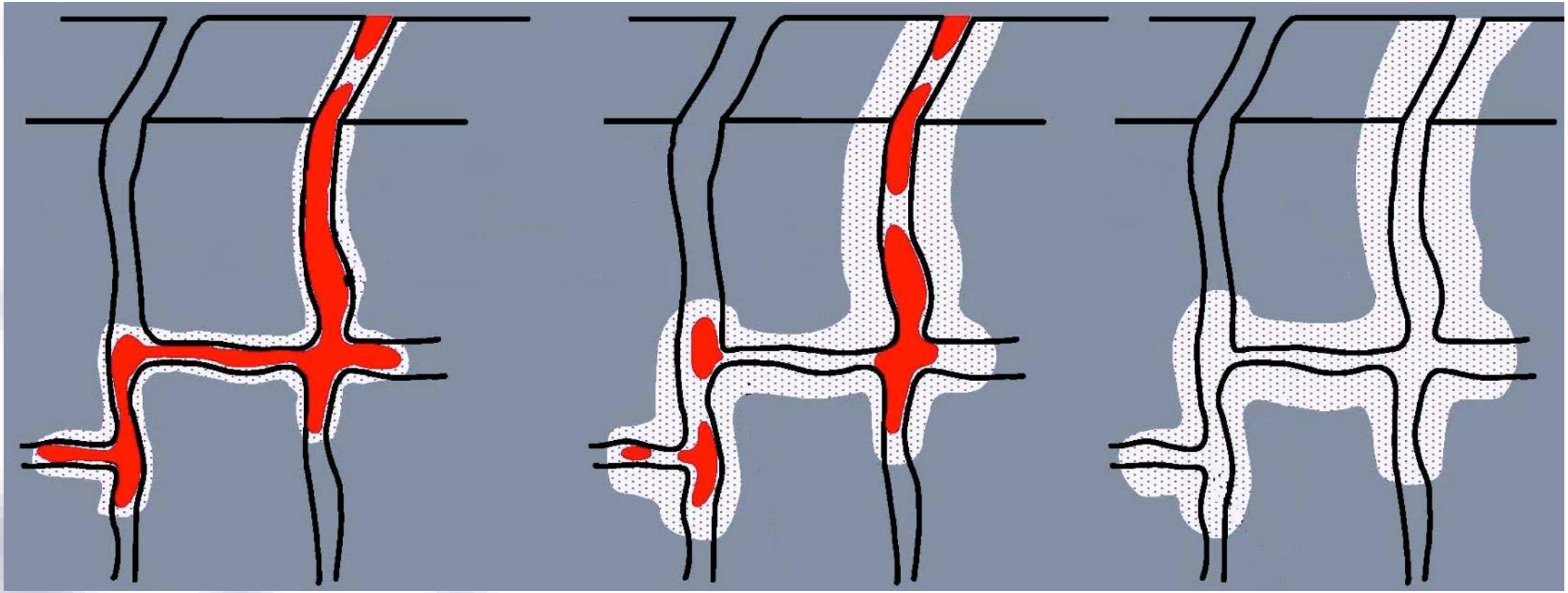


Porous Media
Porosity = 30%



Fractured Rock
Porosity = 1 to 10%

Bedrock Remediation Difficulties



Early Time | Intermediate Time | Late Time

Diffusion into the Rock Matrix

Back Diffusion – a Problem for Remediation

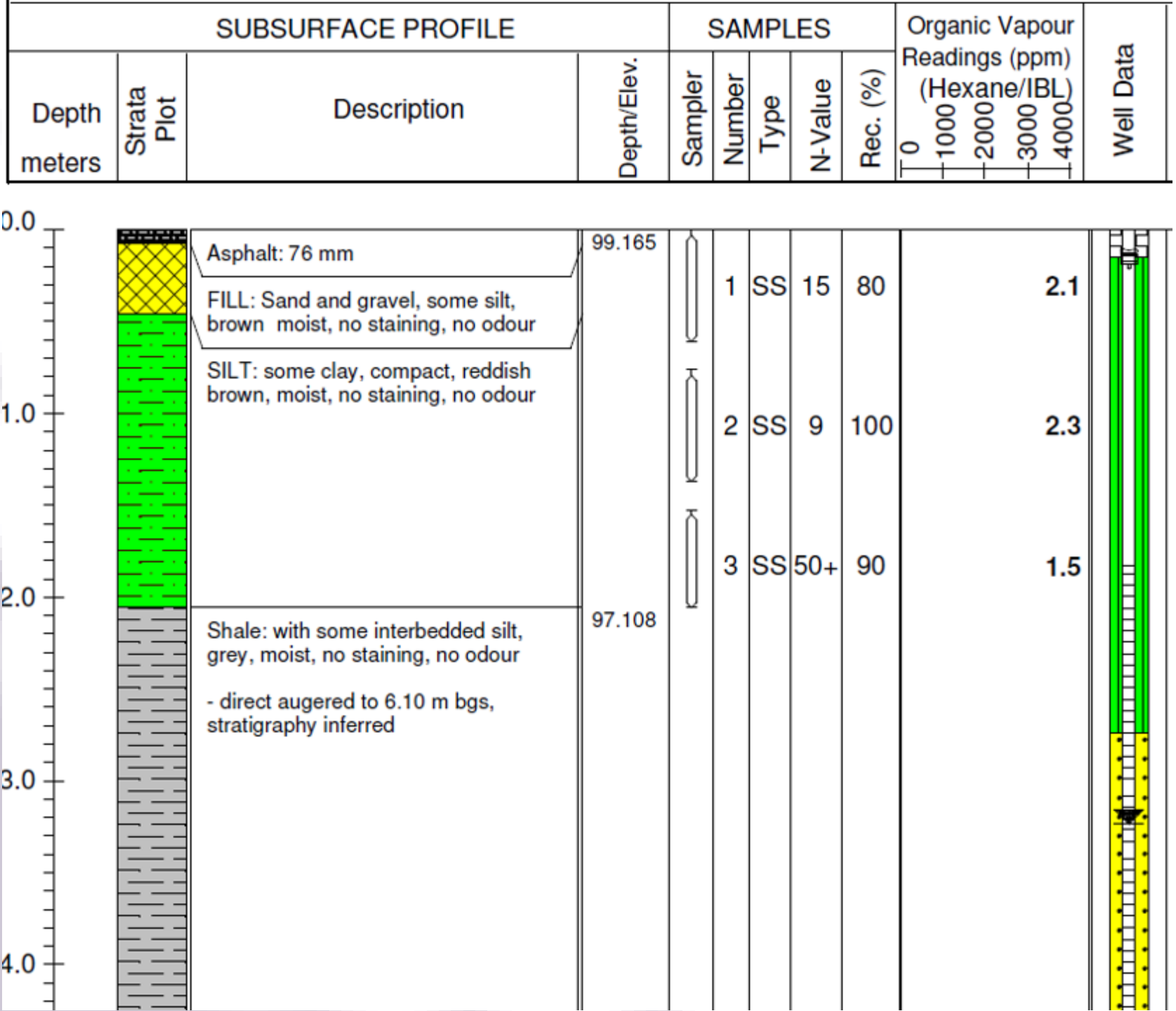
Bedrock Case Study #1

Bedrock and PHCs

Background – The Situation

- Confidential site
- A former retail fuel outlet (RFO) with:
  - Underground storage tanks (USTs)
  - Dispenser-island (pumps)
  - Automotive service operations including motor oil changes
- Petroleum hydrocarbon (PHC) contamination in bedrock groundwater
  - LNAPL (free-phased product)
  - Dissolved phase plume
- ISCO (In-Situ Chemical Oxidation) work completed (by others):
  - Injections in each of: 2015, 2016, 2017
- Vertex on-site later:
  - 2019 to 2021

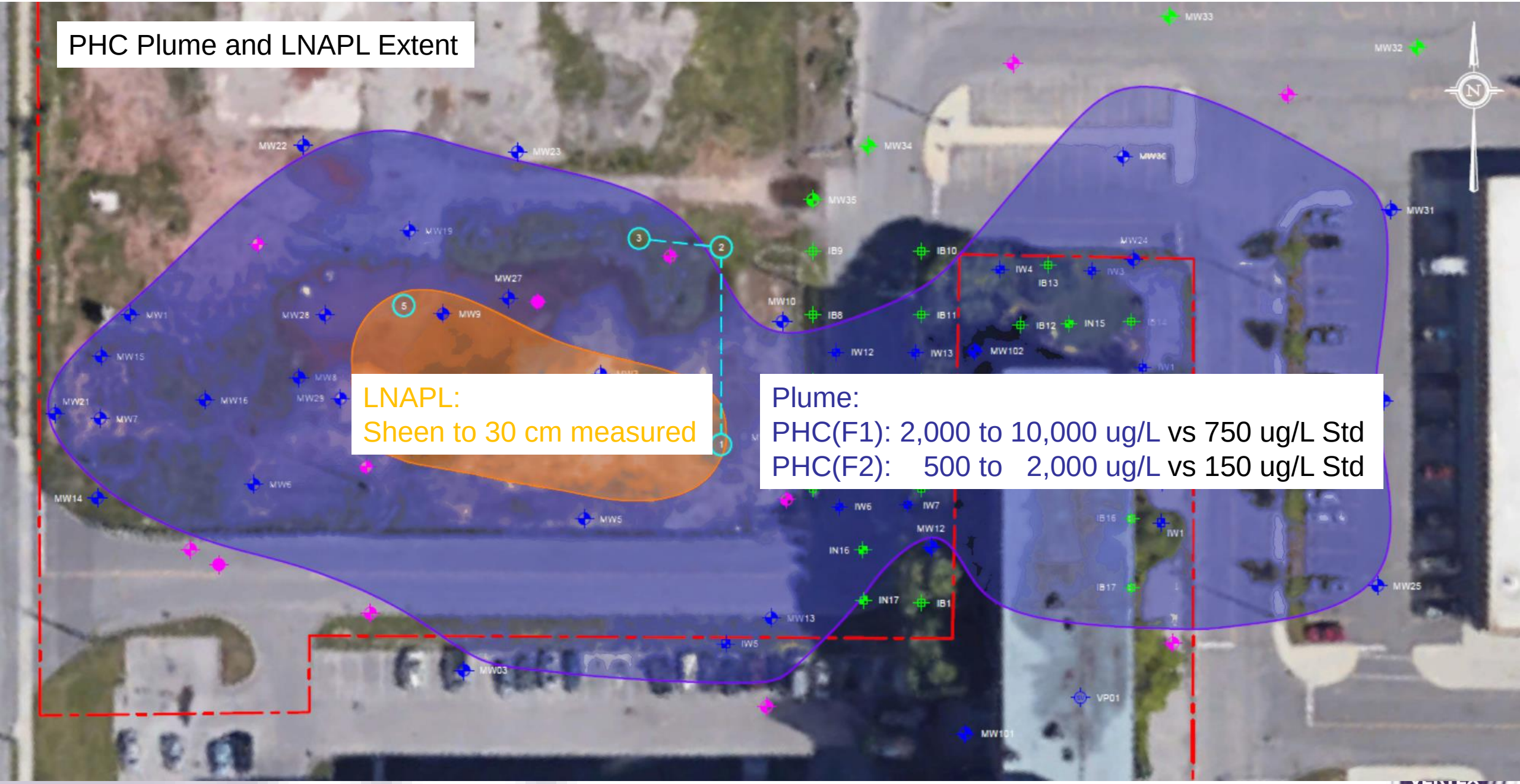
Monitoring Well Network



Subsurface
1.0 to 3.0 m – depth to Bedrock
3.0 to 3.5 m – depth to Groundwater

VERTEX

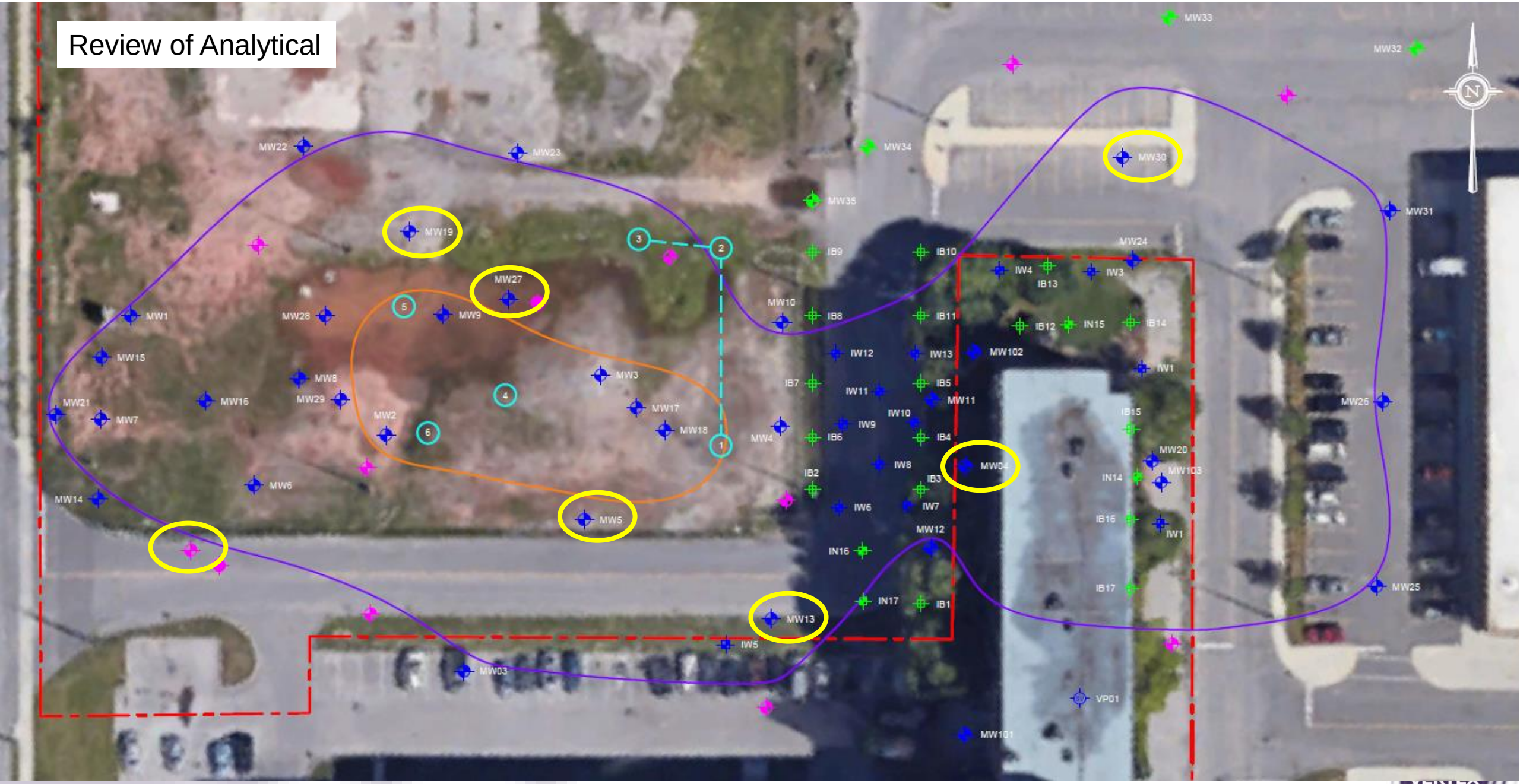
PHC Plume and LNAPL Extent

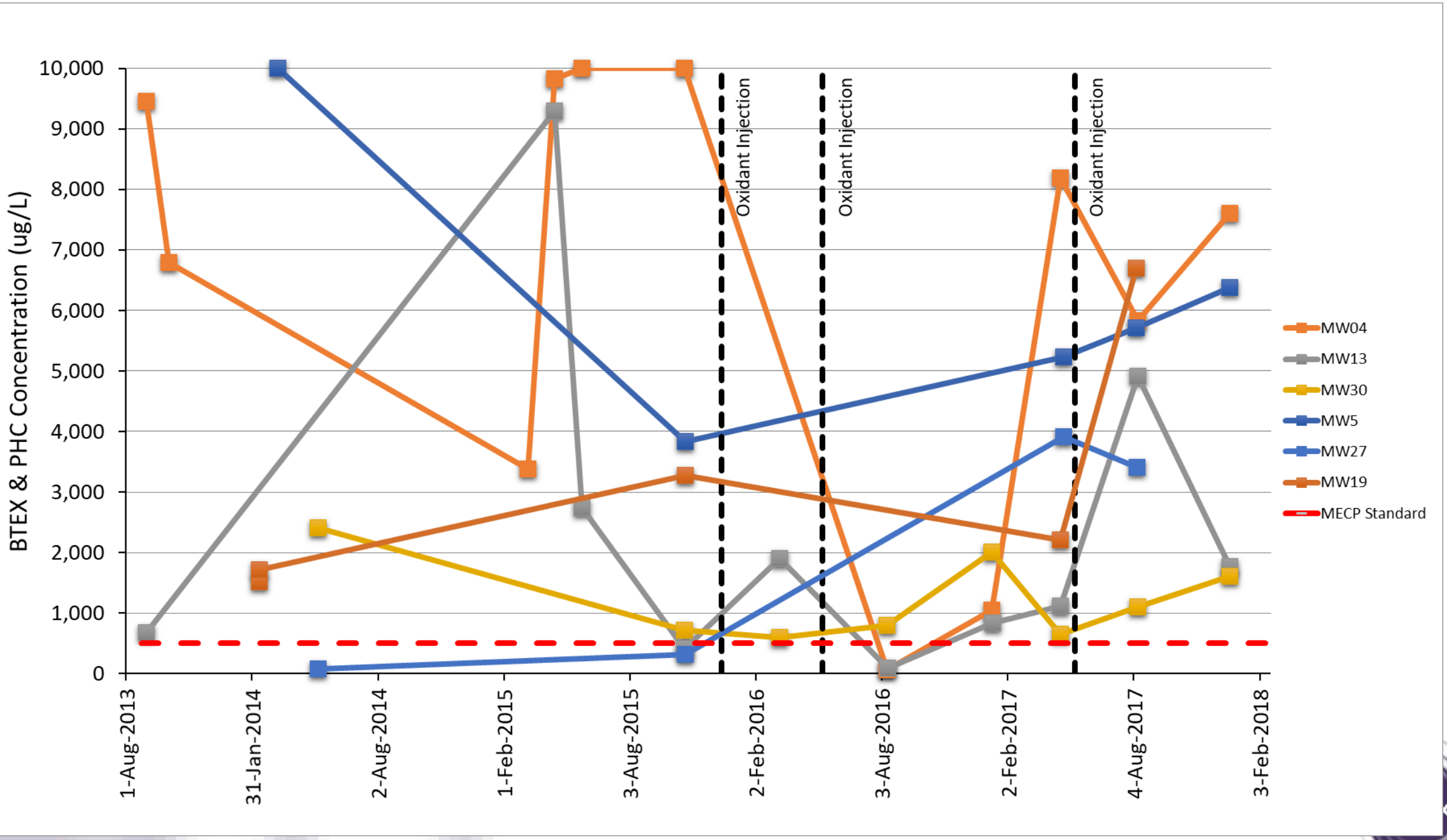


LNAPL:
Sheen to 30 cm measured

Plume:
PHC(F1): 2,000 to 10,000 ug/L vs 750 ug/L Std
PHC(F2): 500 to 2,000 ug/L vs 150 ug/L Std

Review of Analytical

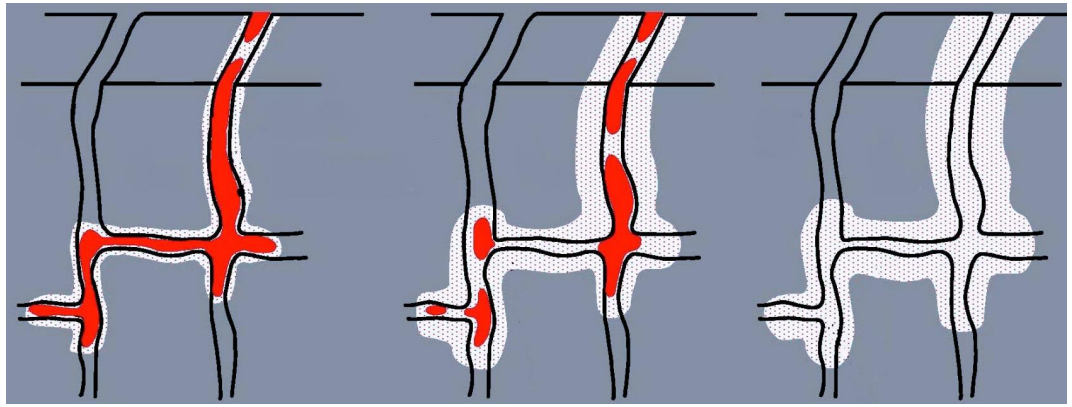



BTEX & PHC Concentration (ug/L)
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
1-Aug-2013
31-Jan-2014
2-Aug-2014
1-Feb-2015
3-Aug-2015
2-Feb-2016
3-Aug-2016
2-Feb-2017
4-Aug-2017
3-Feb-2018
Oxidant Injection
Oxidant Injection
Oxidant Injection
MW04
MW13
MW30
MW5
MW27
MW19
MECP Standard

The ISCO Years: 2015 to 2017

- After ISCO (In-Situ Chemical Oxidation)
  - LNAPL persisted
  - Significant PHC concentrations remained
- From the consultant's report
  - "increases….are interpreted to be a result of the oxidative conditions **causing mobilization to groundwater of contaminants from within the soil/bedrock matrix**."
  - Likely correct, but

    also likely back-diffusion

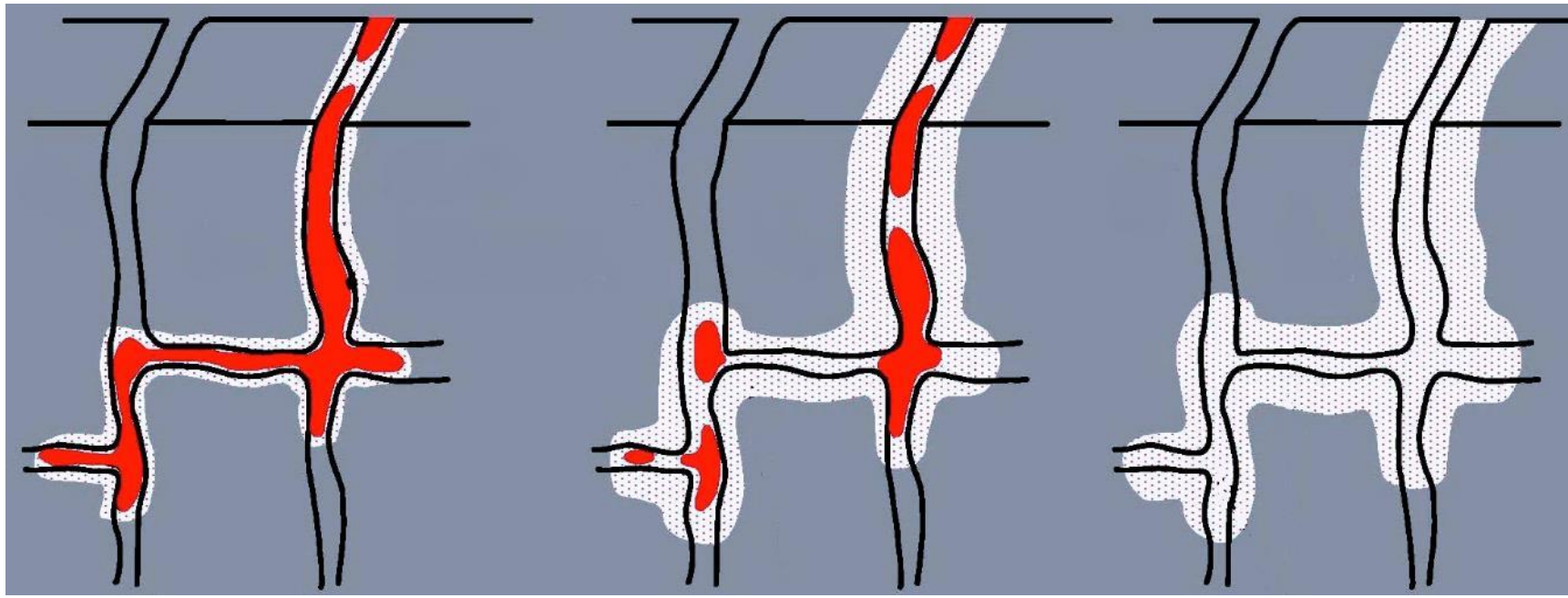


Focus of Remediation (Vertex in 2019)

LNAPL?

Don’t Fight It

<u>Excavation</u>



Early Time | Intermediate Time | Late Time

Back Diffusion?

Don’t Fight It

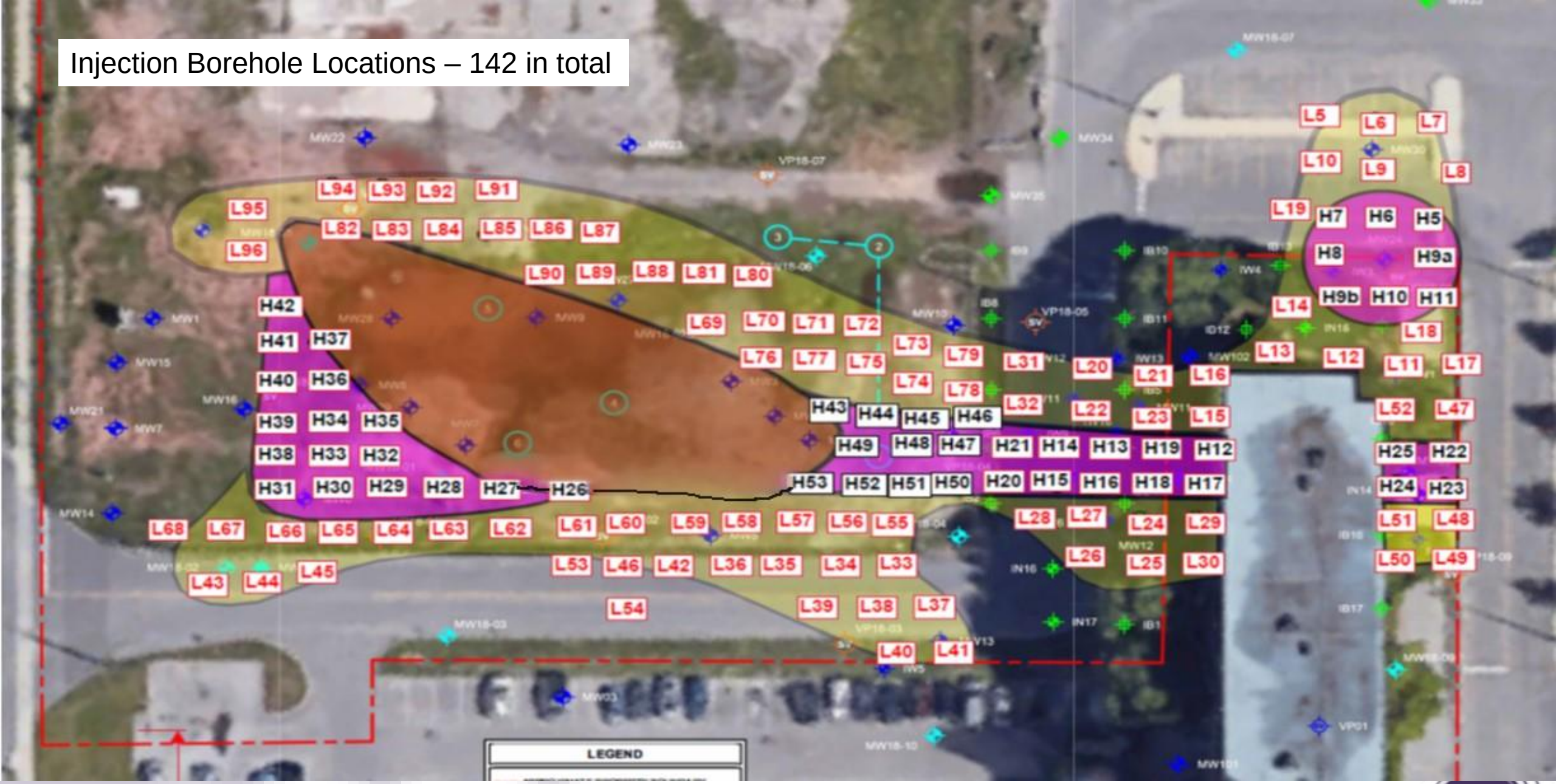
<u>Trap and Treat® BOS 200®</u>

Activated carbon-based approach

Excavation of LNAPL Area

Excavation of LNAPL Area

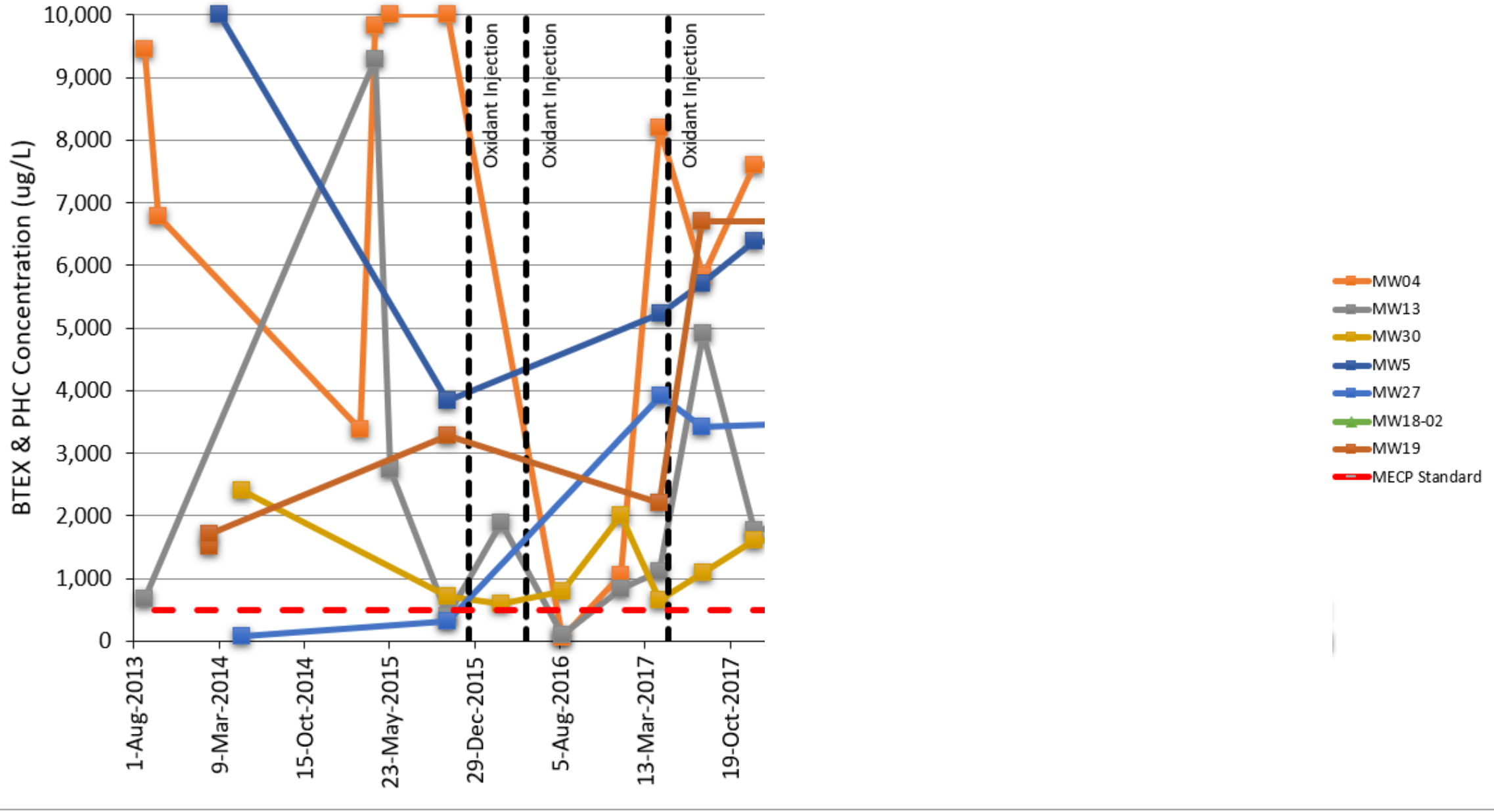
Injection Borehole Locations – 142 in total

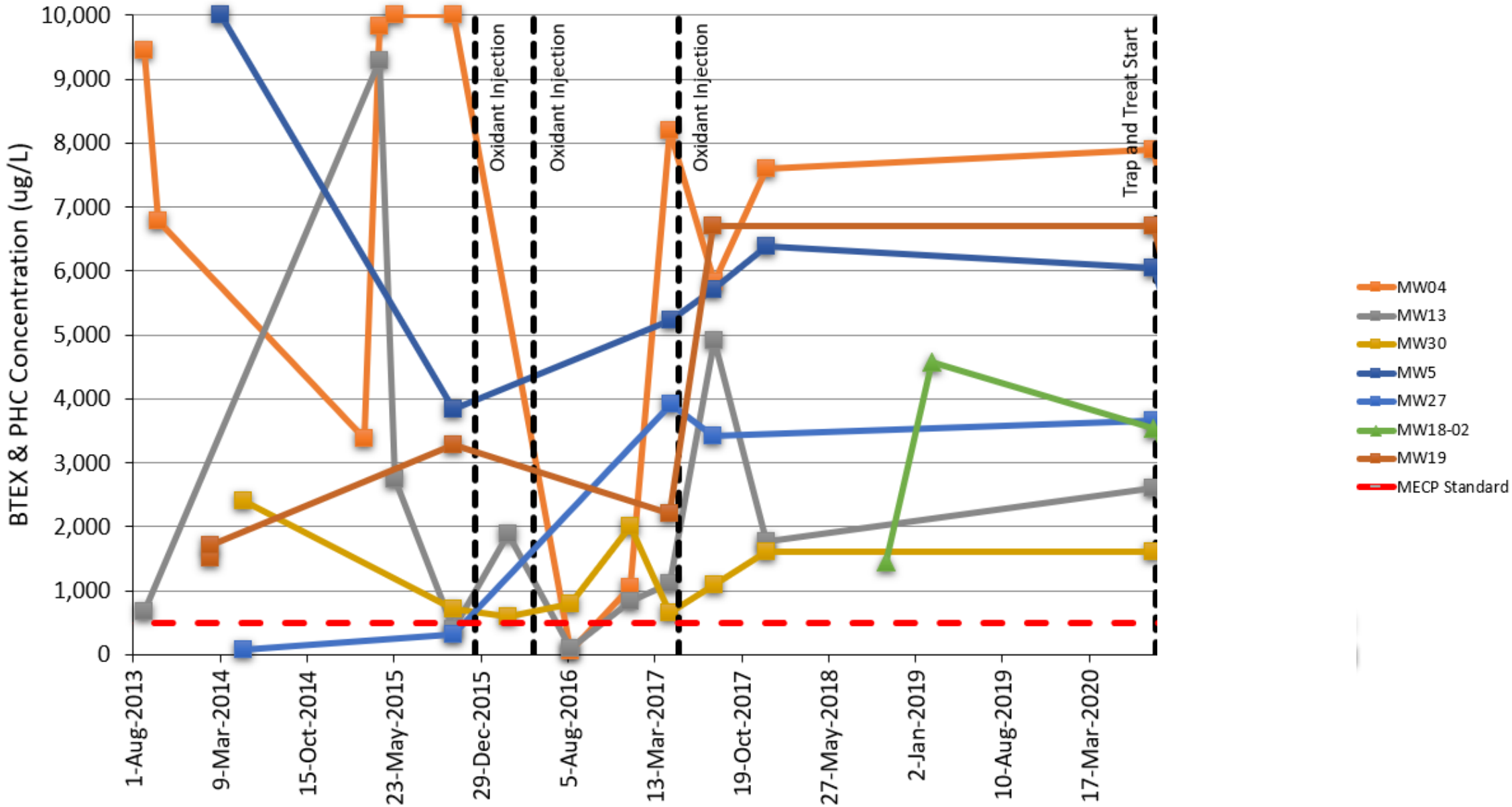


BOS 200® Injection Packer

Trap and Treat® Injection Completed (Fall 2019, Winter 2020)

Using a double pressure packer system
146,000 L BOS 200® amendment slurry injected


BTEX & PHC Concentration (ug/L)
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
Oxidant Injection
Oxidant Injection
Oxidant Injection
1-Aug-2013
9-Mar-2014
15-Oct-2014
23-May-2015
29-Dec-2015
5-Aug-2016
13-Mar-2017
19-Oct-2017
MW04
MW13
MW30
MW5
MW27
MW18-02
MW19
MECP Standard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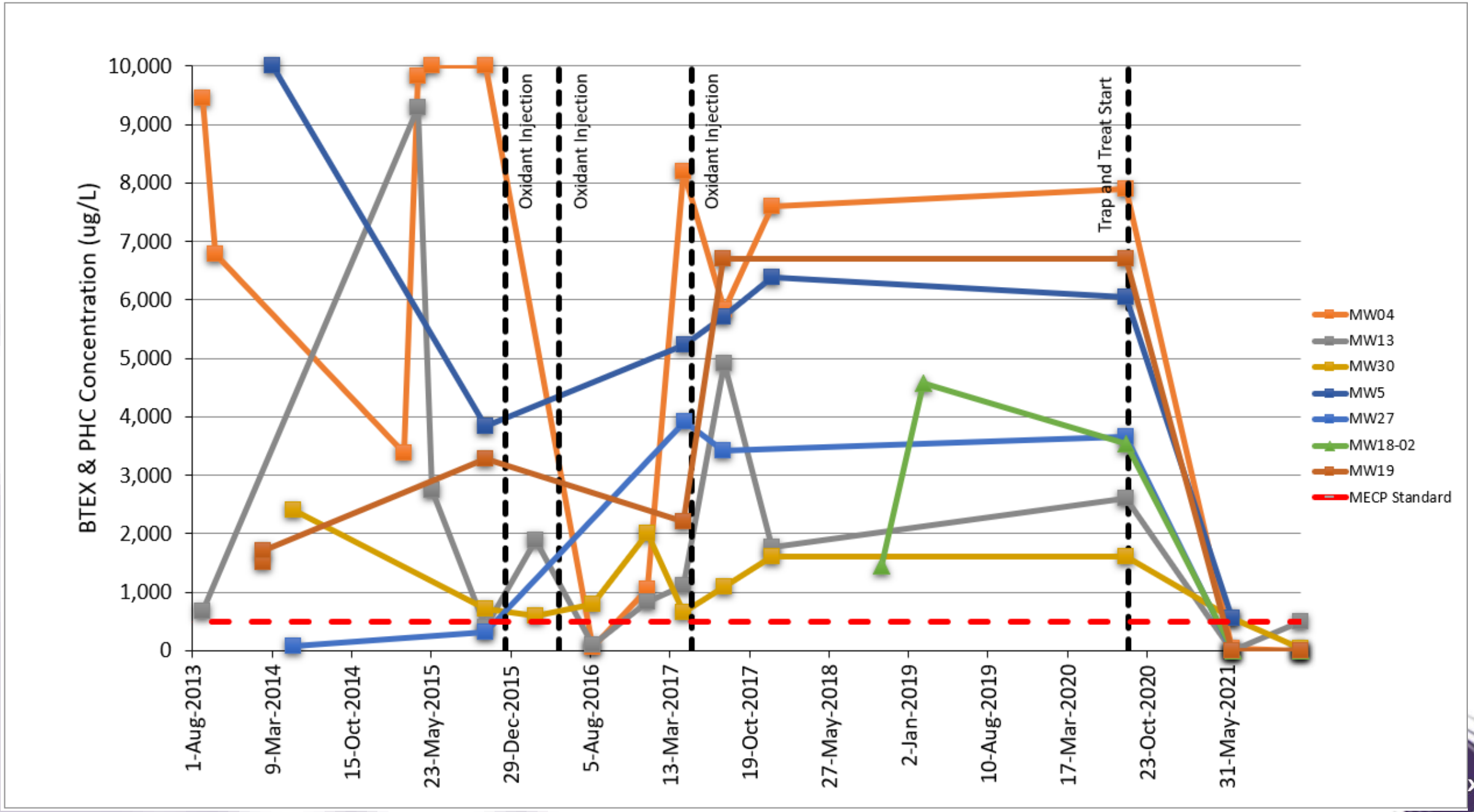
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
Oxidant Injection
Oxidant Injection
Oxidant Injection
Trap and Treat Start
1-Aug-2013
9-Mar-2014
15-Oct-2014
23-May-2015
29-Dec-2015
5-Aug-2016
13-Mar-2017
19-Oct-2017
27-May-2018
2-Jan-2019
10-Aug-2019
17-Mar-2020
MW04
MW13
MW30
MW5
MW27
MW18-02
MW19
MECP Standard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10,000
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8,000
7,000
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5,000
4,000
3,000
2,000
1,000
0
Oxidant Injection
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Trap and Treat Start
1-Aug-2013
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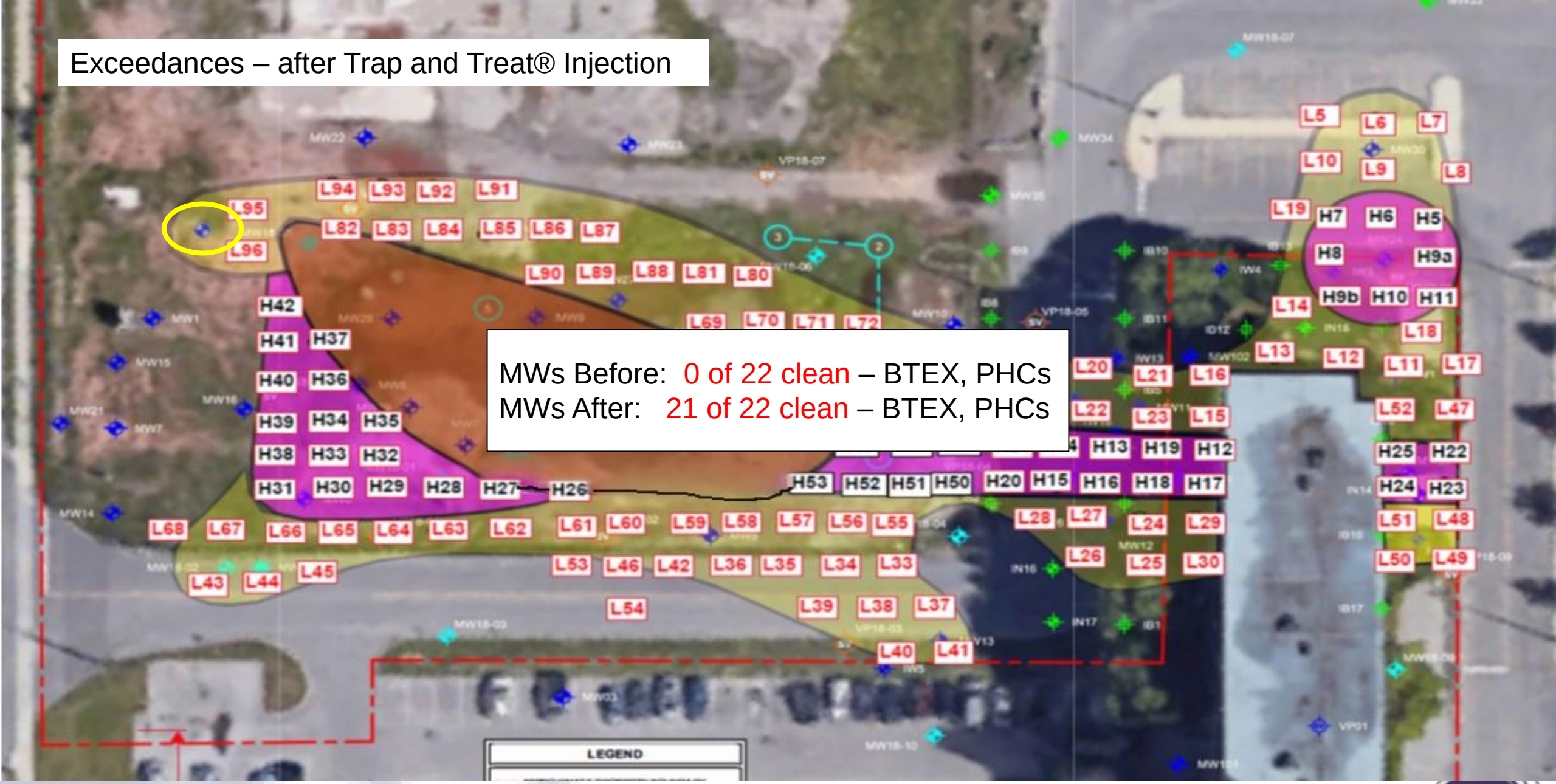
13-Mar-2017
19-Oct-2017
27-May-2018
2-Jan-2019
10-Aug-2019
17-Mar-2020
23-Oct-2020
31-May-2021
MW04
MW13
MW30
MW5
MW27
MW18-02
MW19
MECP Standard

Exceedances – after Trap and Treat® Injection



Bedrock Case Study #1 Wrap-Up

Remediation of bedrock with PHCs (including LNAPL):

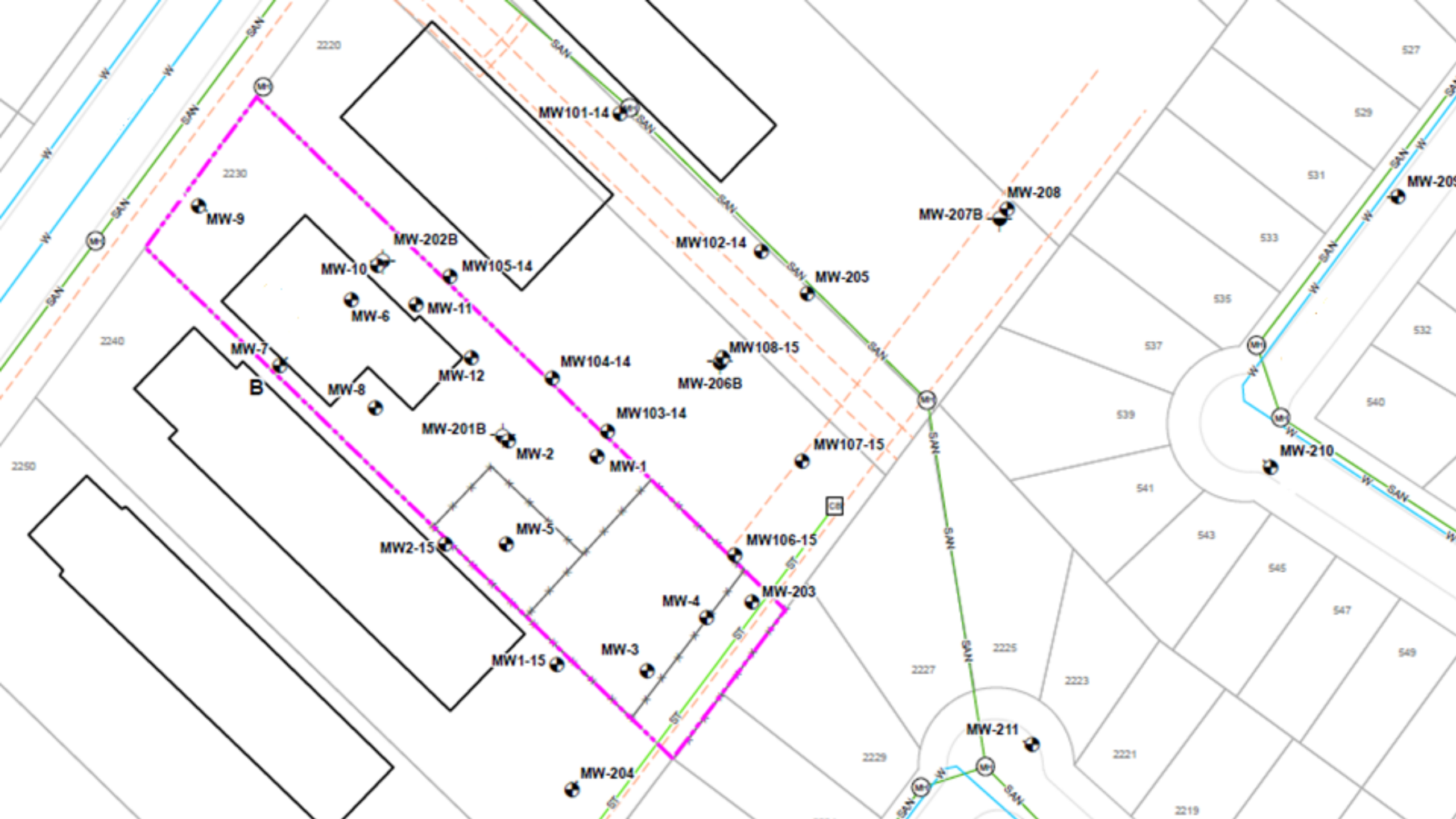
- ISCO should only be applied after careful consideration
  - ISCO has difficulty with LNAPL
  - ISCO has difficulty with bedrock secondary porosity (especially with back diffusion)
- Excavation (in 2020)
  - Direct removal of LNAPL
- Trap and Treat® BOS 200® (2020 – 2021)
  - Adsorbs the PHC plume
  - Treats the PHC plume
  - Directly addresses bedrock back diffusion
- Results (as of end of 2021):
  - 21 of 22 MWs clean

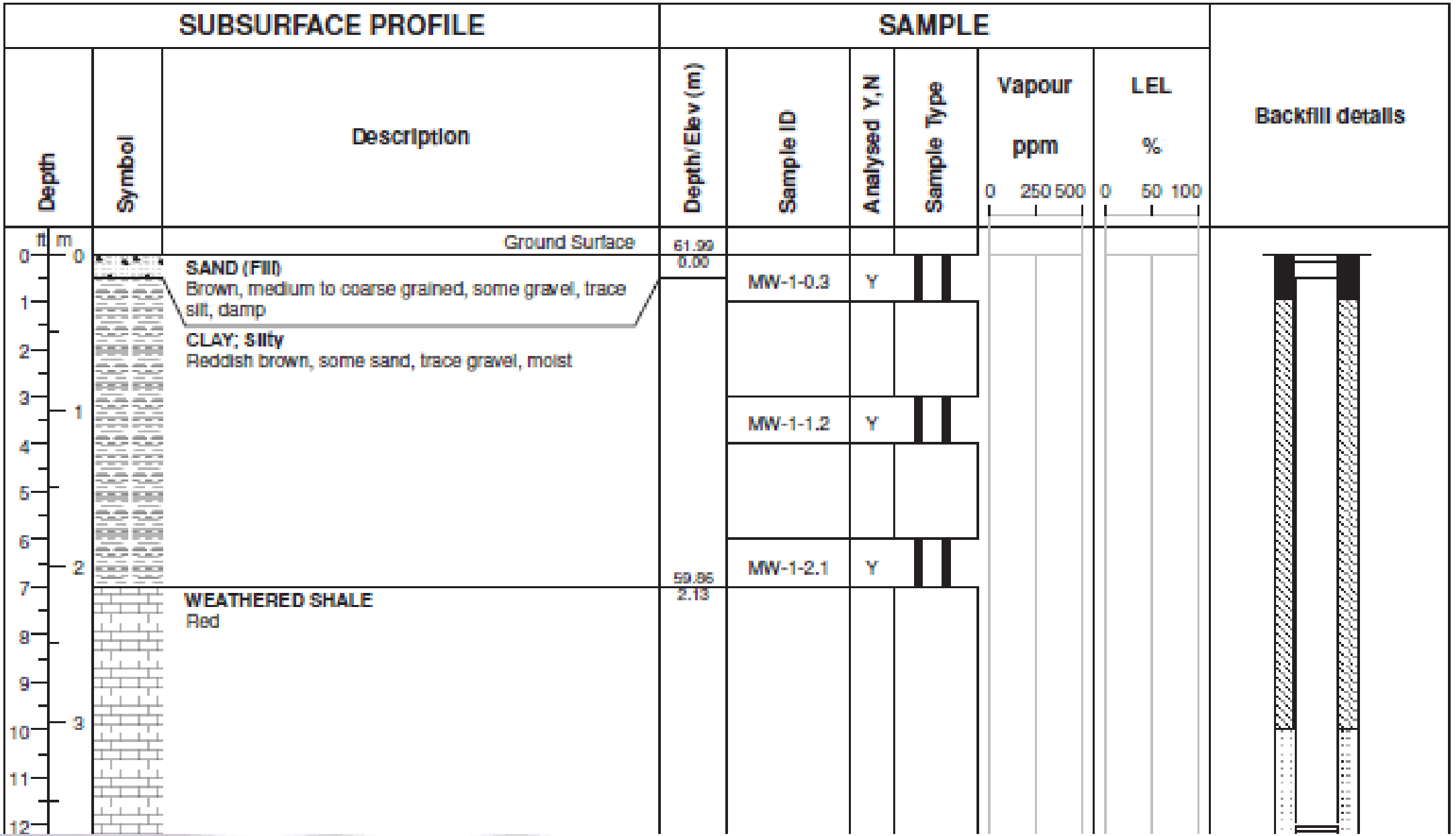
Bedrock Case Study #2

Bedrock and Heavy Metals (Hex Chrome)

Background – The Situation

- Confidential site
- A hexavalent chromium plating facility:
  - Underground tanks containing with the chromium plating solution
  - Tanks leaked
  - Historical spills
- Neighbour does a Phase II ESA
- Chrome contamination identified in bedrock groundwater
  - Hexavalent chromium
  - Total chromium
- Bench and Pilot Scale testing completed
  - Full-scale designed and commencing November 2022

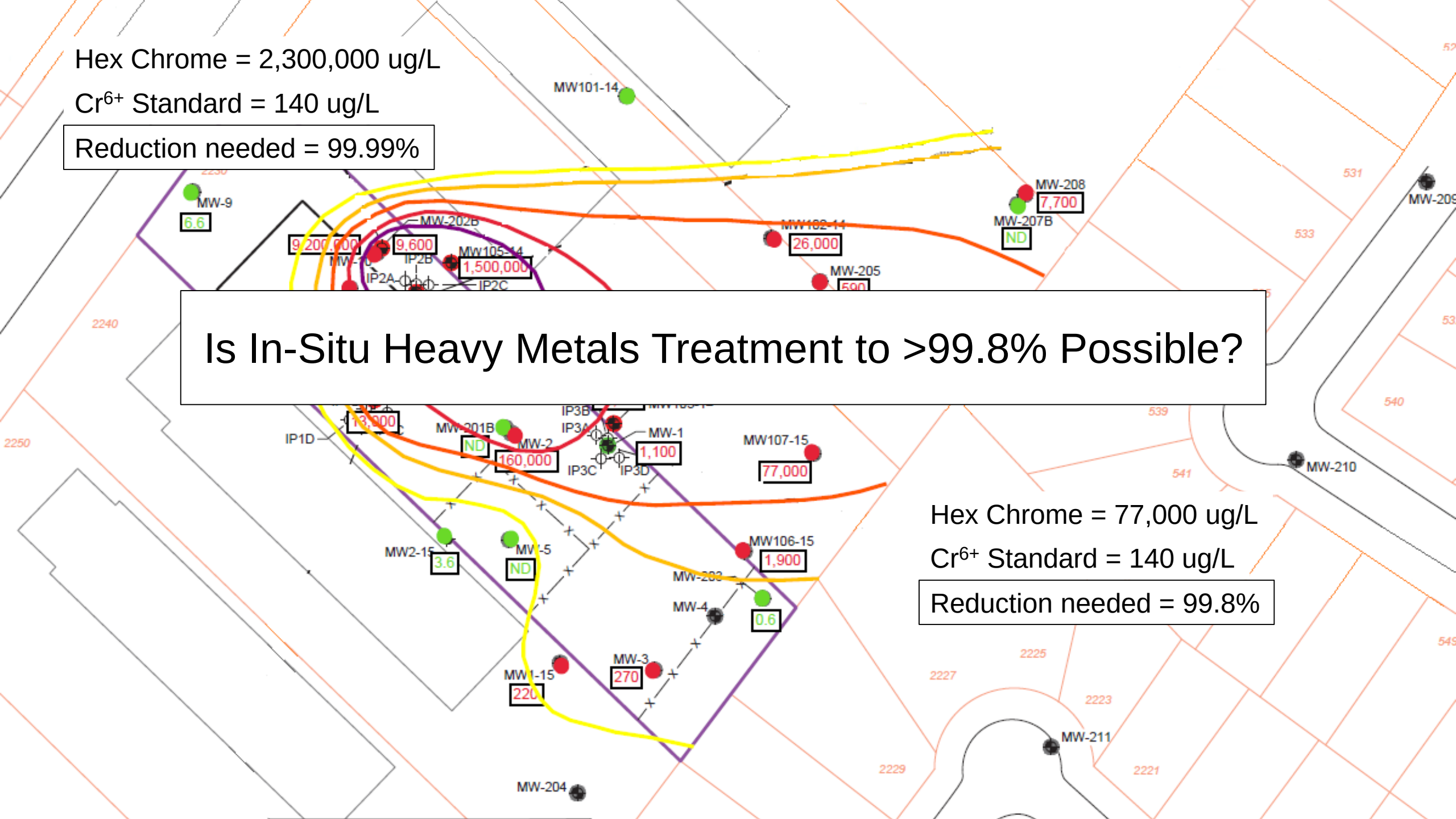

MW-9
MW-202B
MW-10
MW105-14
MW-6
MW-11
MW-7
MW-12
MW-8
MW104-14
MW-201B
MW-2
MW103-14
MW-1
MW2-15
MW-5
MW106-15
MW-203
MW-4
MW-3
MW1-15
MW-204
MW101-14
MW102-14
MW-205
MW-207B
MW-208
MW108-15
MW-206B
MW107-15
MW-210
MW-211
B
2220
2230
2240
2250
2225
2227
2229
2223
2221
2219
527
529
531
533
535
537
539
540
541
543
545
547
549
532
SAN
W
ST


SUBSURFACE PROFILE
SAMPLE
Depth
Symbol
Description
Depth/Elev (m)
Sample ID
Analysed Y,N
Sample Type
Vapour ppm
0 250 500
LEL %
0 50 100
Backfill details
ft m
Ground Surface
61.99
0.00
SAND (Fill)
Brown, medium to coarse grained, some gravel, trace silt, damp
CLAY; silty
Reddish brown, some sand, trace gravel, moist
MW-1-0.3
Y
MW-1-1.2
Y
MW-1-2.1
Y
59.86
2.13
WEATHERED SHALE
Red

Hex Chrome = 2,300,000 ug/L

Cr^{6+} Standard = 140 ug/L

Reduction needed = 99.99%



Is In-Situ Heavy Metals Treatment to >99.8% Possible?

Hex Chrome = 77,000 ug/L

Cr^{6+} Standard = 140 ug/L

Reduction needed = 99.8%

Bench-Scale Testing with Site Groundwater

Hex Chrome Case Study

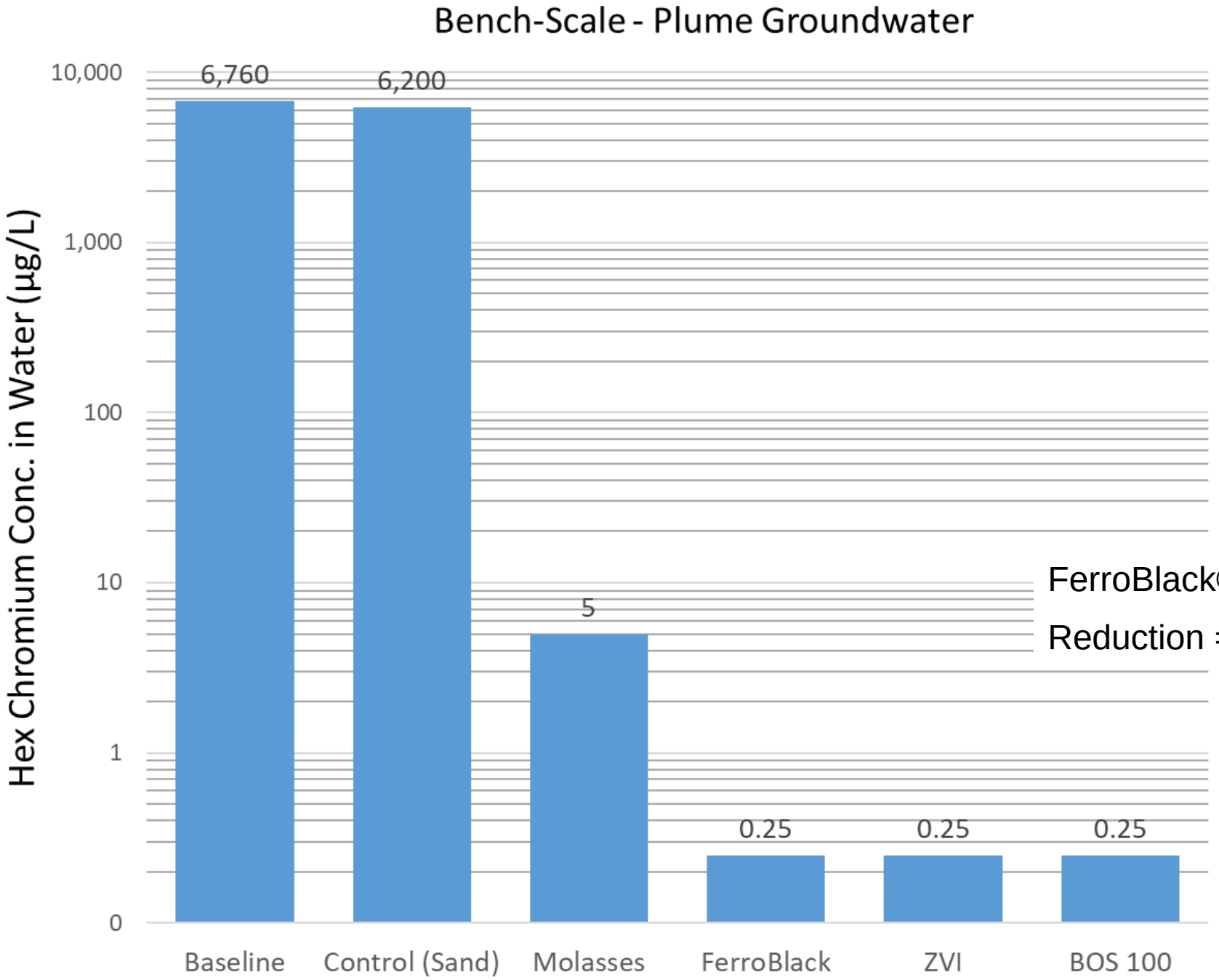
Hex Chrome – Bench-Scale Testing

<u>Remediation Amendments Tested</u>

- Molasses
- FerroBlack®
- Zero Valent Iron (ZVI)
- Trap & Treat® BOS 100®

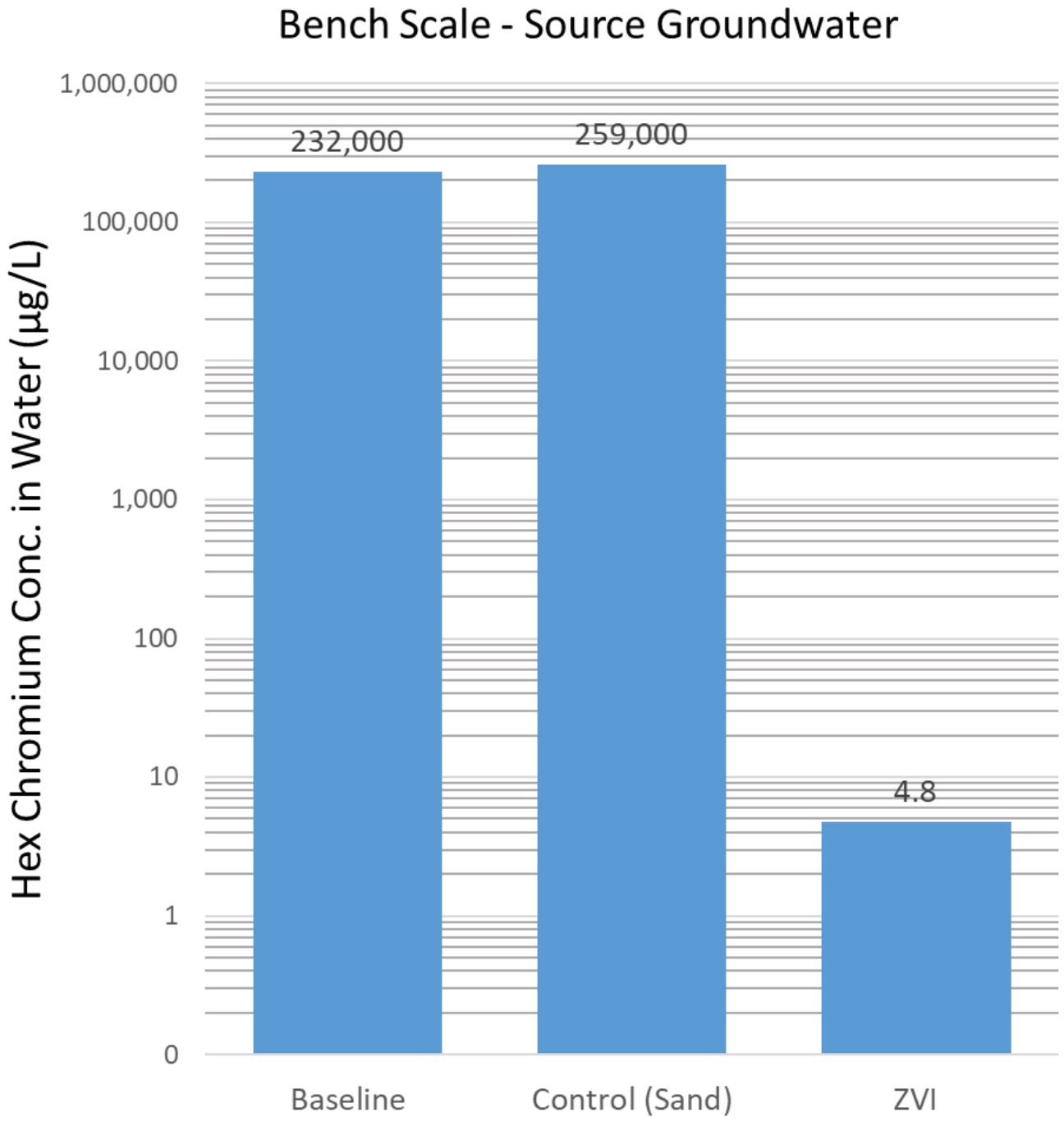
<u>Method</u>

- 1 L containers
- Silica sand and remedial amendment
- Groundwater added
- Placed in dark, let sit one week, sampled



FerroBlack®, ZVI, BOS 100®

Reduction = 99.996%

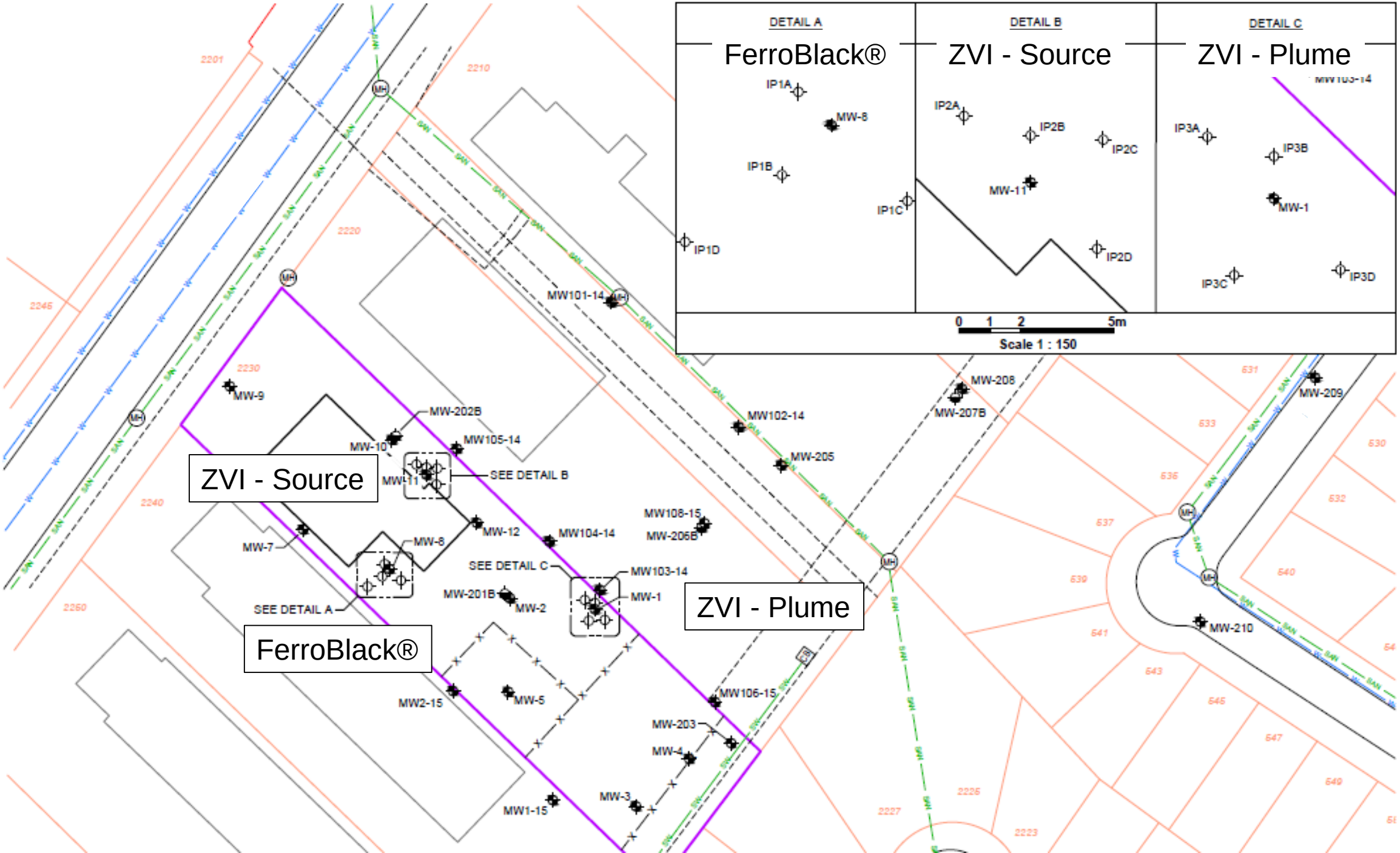


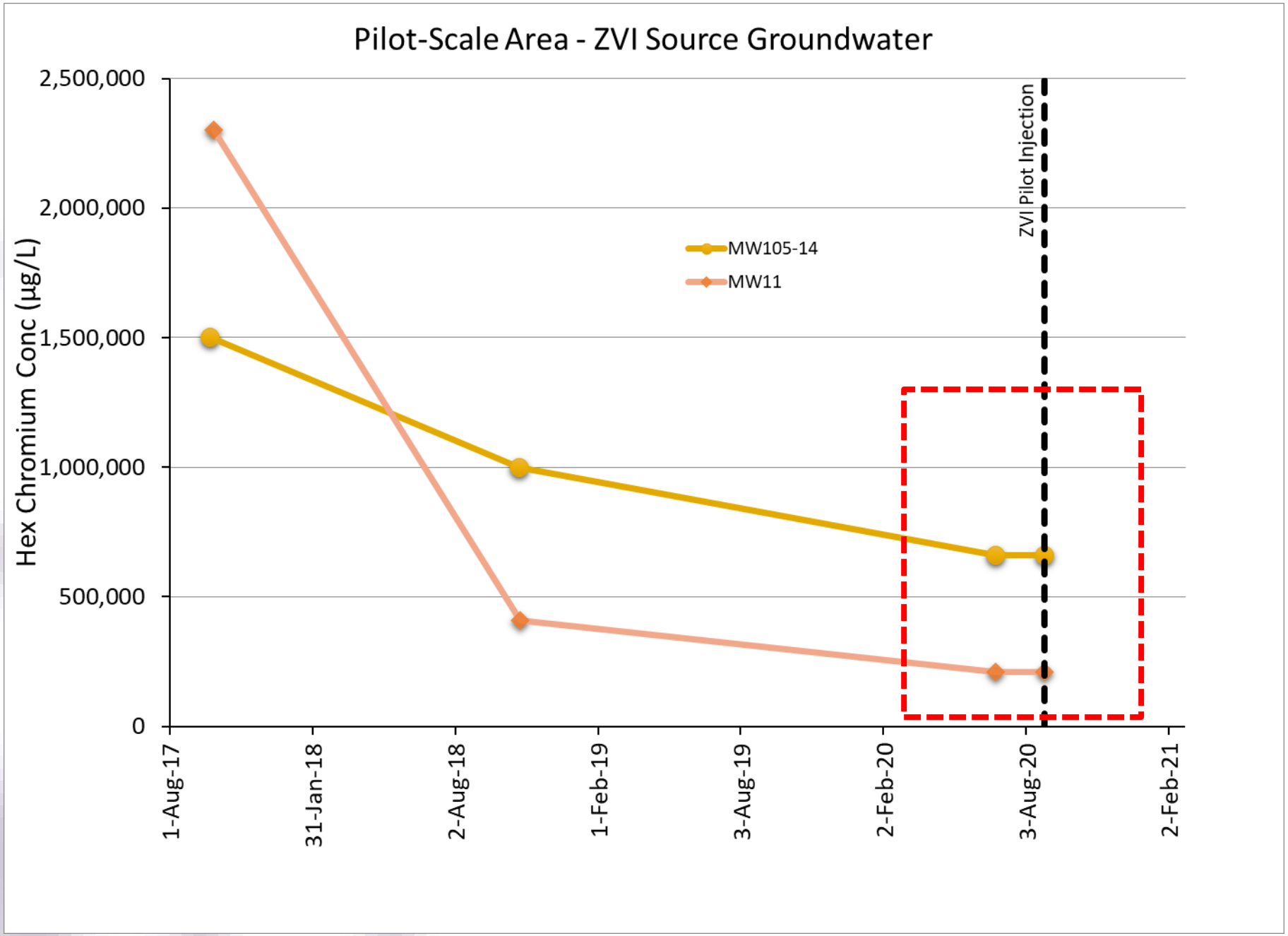
ZVI

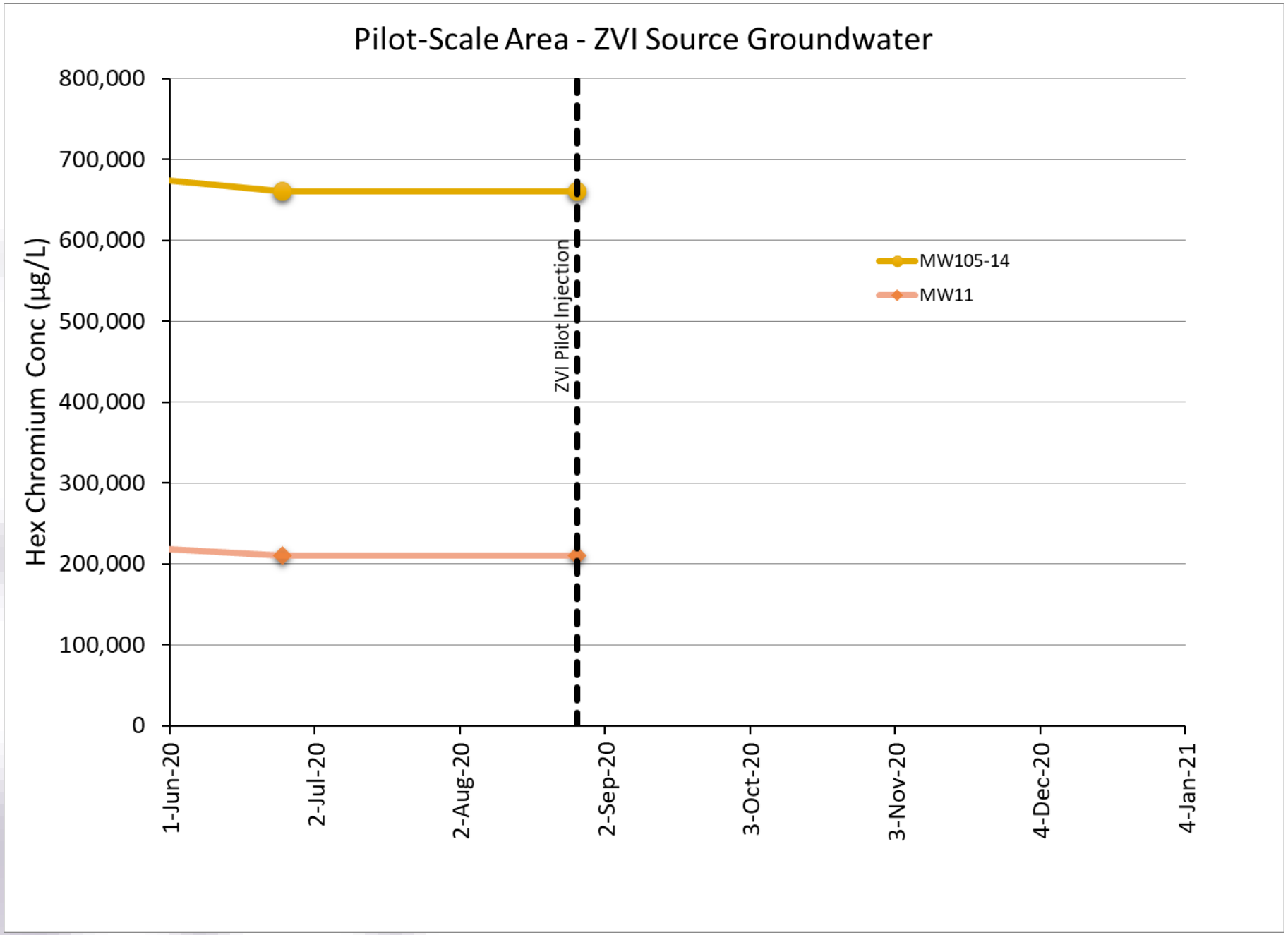
Reduction = 99.998%

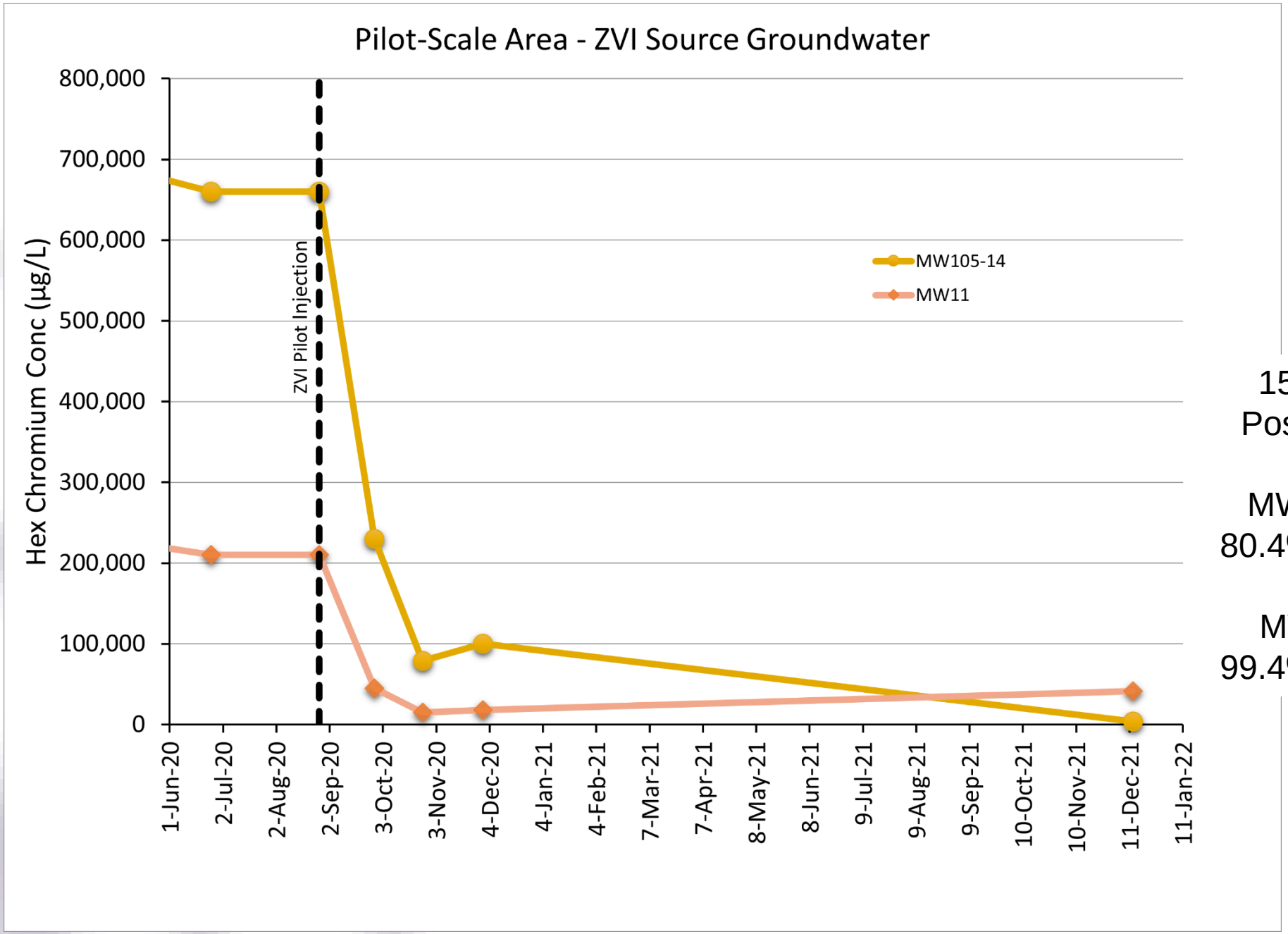
Pilot-Scale Testing on-Site

Hex Chrome Case Study


DETAIL A
FerroBlack®
IP1A
MW-8
IP1B
IP1C
IP1D
DETAIL B
ZVI - Source
IP2A
IP2B
IP2C
MW-11
IP2D
DETAIL C
ZVI - Plume
IP3A
IP3B
MW-1
IP3C
IP3D
0 1 2 5m
Scale 1 : 150
ZVI - Source
FerroBlack®
ZVI - Plume
MW-9
MW-202B
MW-10
MW105-14
MW-11
SEE DETAIL B
MW-7
MW-8
MW-12
MW104-14
SEE DETAIL A
SEE DETAIL C
MW-201B
MW-2
MW103-14
MW-1
MW2-15
MW-5
MW1-15
MW-3
MW-4
MW-203
MW106-15
MW101-14
MW102-14
MW-205
MW108-15
MW-206B
MW-207B
MW-208
MW-209
MW-210


Pilot-Scale Area - ZVI Source Groundwater
Hex Chromium Conc (µg/L)
2,500,000
2,000,000
1,500,000
1,000,000
500,000
0
1-Aug-17
31-Jan-18
2-Aug-18
1-Feb-19
3-Aug-19
2-Feb-20
3-Aug-20
2-Feb-21
ZVI Pilot Injection
MW105-14
MW11

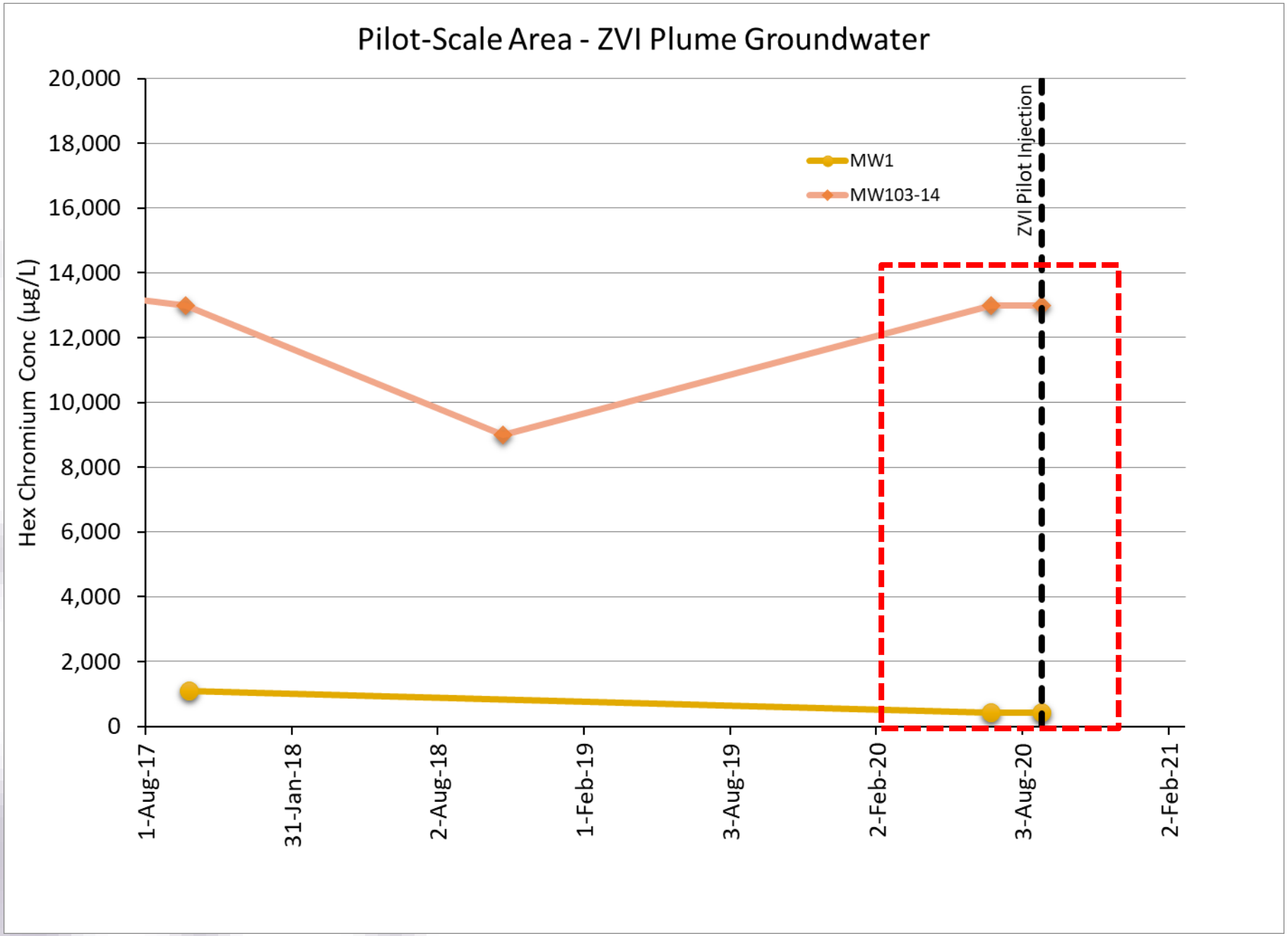

Pilot-Scale Area - ZVI Source Groundwater
Hex Chromium Conc (µg/L)
800,000
700,000
600,000
500,000
400,000
300,000
200,000
100,000
0
ZVI Pilot Injection
MW105-14
MW11
1-Jun-20
2-Jul-20
2-Aug-20
2-Sep-20
3-Oct-20
3-Nov-20
4-Dec-20
4-Jan-21

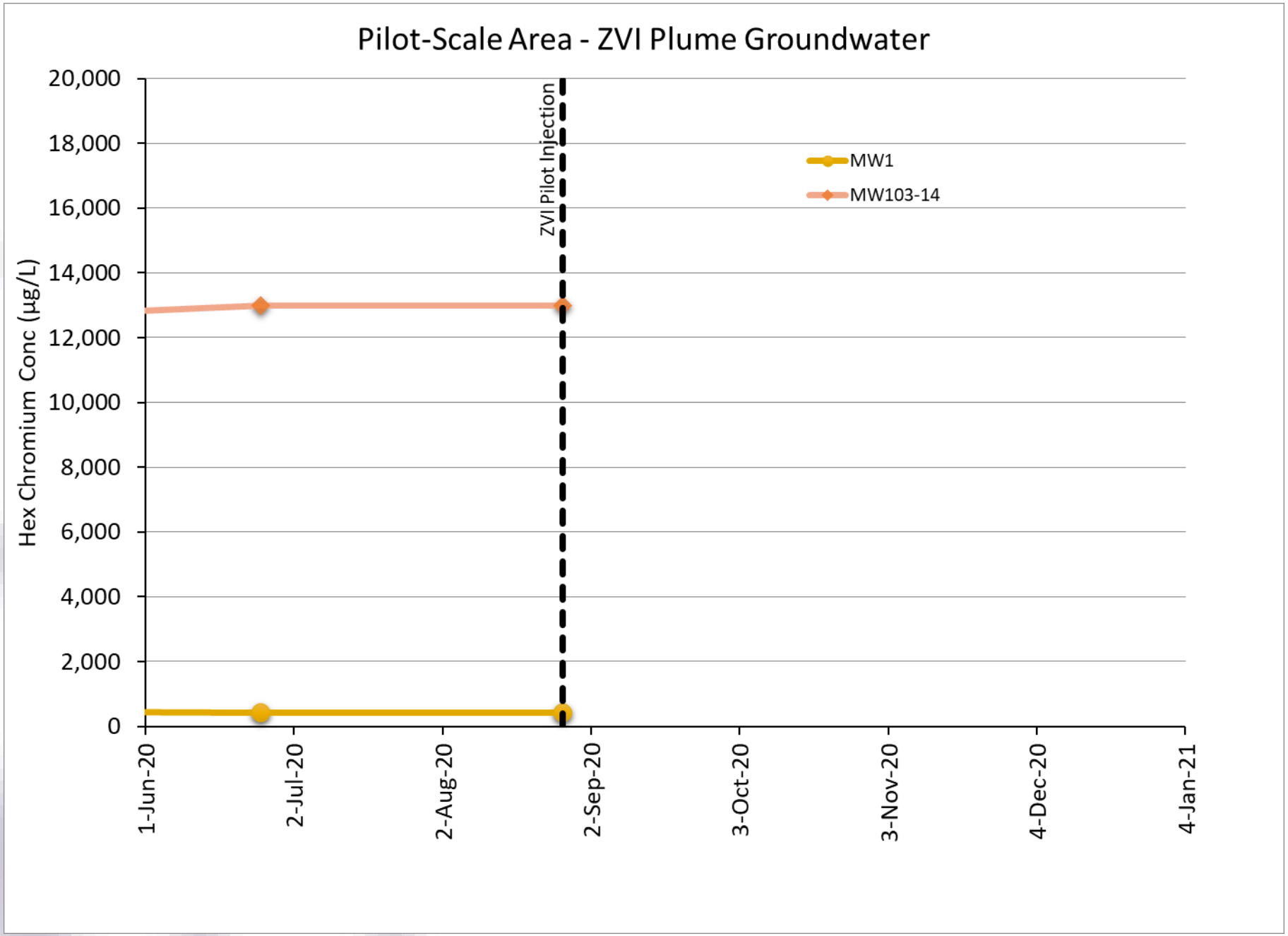


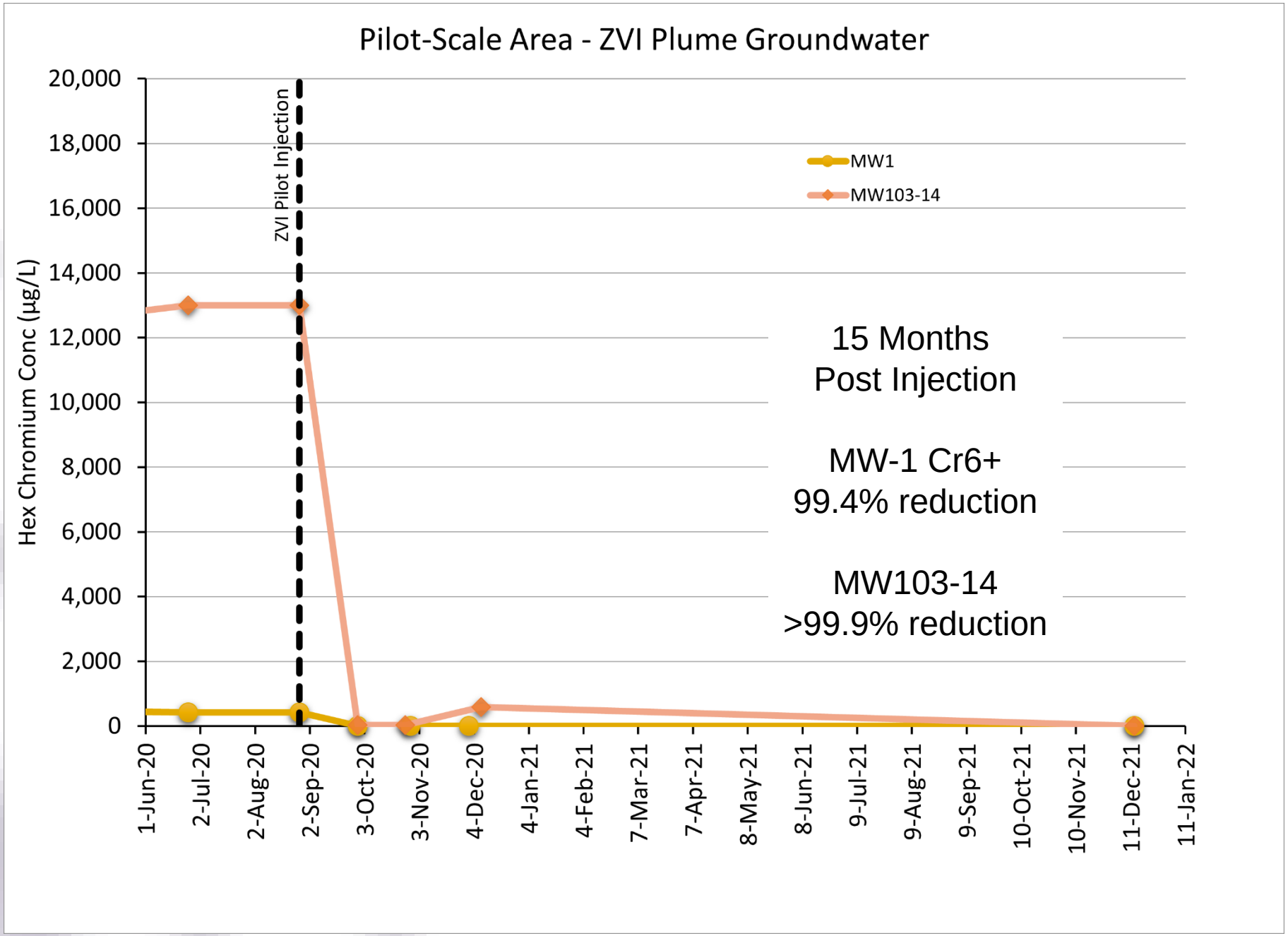
15 Months
Post Injection

MW-11 Cr6+
80.4% reduction

MW105-14
99.4% reduction


Pilot-Scale Area - ZVI Plume Groundwater
Hex Chromium Conc (µg/L)
20,000
18,000
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
MW1
MW103-14
ZVI Pilot Injection
1-Aug-17
31-Jan-18
2-Aug-18
1-Feb-19
3-Aug-19
2-Feb-20
3-Aug-20
2-Feb-21

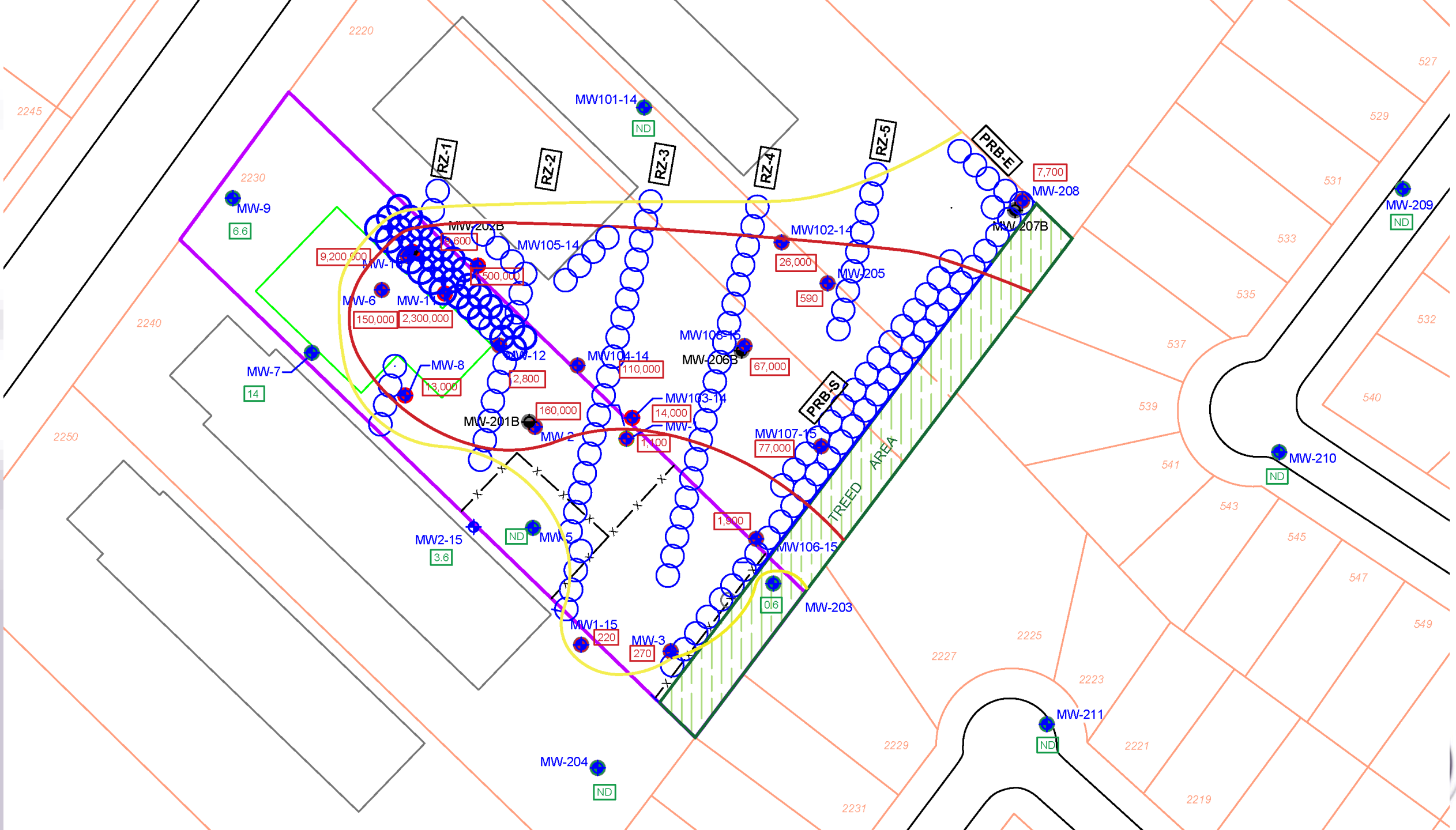

Pilot-Scale Area - ZVI Plume Groundwater
Hex Chromium Conc (µg/L)
20,000
18,000
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
ZVI Pilot Injection
MW1
MW103-14
1-Jun-20
2-Jul-20
2-Aug-20
2-Sep-20
3-Oct-20
3-Nov-20
4-Dec-20
4-Jan-21


Pilot-Scale Area - ZVI Plume Groundwater
Hex Chromium Conc (µg/L)
20,000
18,000
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
ZVI Pilot Injection
MW1
MW103-14
15 Months
Post Injection
MW-1 Cr6+
99.4% reduction
MW103-14
>99.9% reduction
1-Jun-20
2-Jul-20
2-Aug-20
2-Sep-20
3-Oct-20
3-Nov-20
4-Dec-20
4-Jan-21
4-Feb-21
7-Mar-21
7-Apr-21
8-May-21
8-Jun-21
9-Jul-21
9-Aug-21
9-Sep-21
10-Oct-21
10-Nov-21
11-Dec-21
11-Jan-22

Bedrock Case Study #2 Wrap-Up

Remediation of Bedrock with Heavy Metals (Hex Chrome):

- Groundwater treatment is possible (in the field)
  - At bench-scale: >99.9%
  - At pilot-scale: ~80% to 90% (Source) to ~99% to 99.9% (Plume)
- ZVI is a feasible solution for both source and plume areas
- Full-scale commencing implementation November 2022
  - Staged approach combining:
    - Downgradient property line PRB (shared with off-site residential)
    - Source area loading of ZVI
    - Reactive zones of ZVI in transects across plume


RZ-1
RZ-2
RZ-3
RZ-4
RZ-5
PRB-E
PRB-S
TREED AREA
MW101-14
ND
MW-9
6.6
MW-202B
600
MW105-14
9,200,000
500,000
MW-6
150,000
MW-11
2,300,000
MW-7
14
MW-8
13,000
MW-12
2,800
MW104-14
110,000
MW-201B
160,000
MW-2
1,100
MW103-14
14,000
MW2-15
3.6
ND
MW-5
MW1-15
220
MW-3
270
MW-204
ND
MW102-14
26,000
MW-205
590
MW106-15
67,000
MW-206B
MW107-15
77,000
1,900
MW106-15
0.6
MW-203
7,700
MW-208
MW-207B
MW-209
ND
MW-210
ND
MW-211
ND
2220
2245
2230
2240
2250
527
529
531
533
535
532
537
539
540
541
543
545
547
549
2225
2227
2223
2229
2221
2231
2219

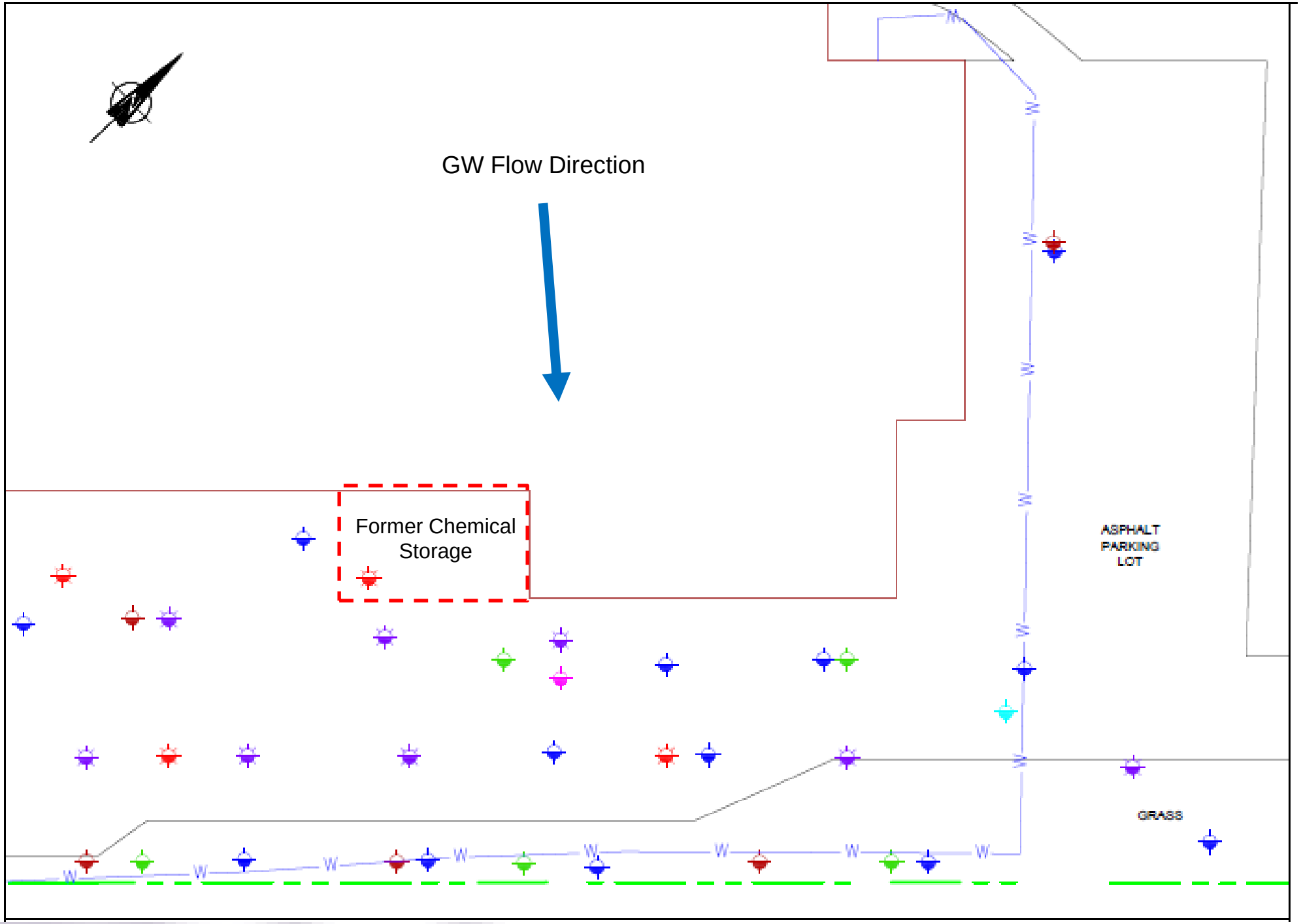
Bedrock Case Study #3

Bedrock and Chlorinated Solvents (cVOCs)

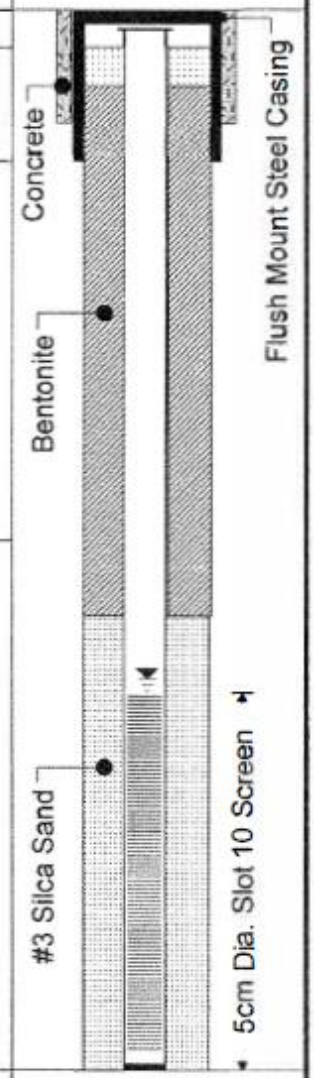
Background – The Situation

- Confidential site
- Historical steel manufacturing operation:
  - Use of degreasing solvents
  - Improper chemical storage and spills
  - TCE, DCE isomers & VC present in bedrock groundwater
- Developer purchased
  - Industrial/commercial redevelopment
- ISCO work completed (by others)
  - Historic permanganate injections
- Install PRB to manage off-site liability (by Vertex)
- Injections completed (May 2022)


Site Location
200 m


GW Flow Direction
Former Chemical Storage
ASPHALT PARKING LOT
GRASS

Depth	Sample No.	N-Value	Recovery (%)	Soil Vapour Concentration (ppm)	Graphic Log	Geology Description	Depth/Elev (m)	Well Completion
ft / m						Ground Surface	0.0	
0 / 0						***ASPHALT***	-0.2	
	SS1	14	100	0		***SAND*** Little silt, trace clay, medium dense, coarse-grained, well graded, light brown, dry, no odour, no staining.	-0.6	
2	SS2	18	100	0		***SILT TILL*** Some clay, trace sand, very stiff, low plasticity, blocky, dark brown, slightly moist, no odour, no staining.		
4	SS3	27	100	0				
6 / 2	SS4A	>100	100	0			-2.1	
	SS4B	>100	50	0		***SHALE*** Red-brown, moist, no odour, no staining.		
8	SS5	>100	50	0				
10	SS6	>100	50	0				
12 / 4	SS7	>100	20	0			-4.3	
14						End of Borehole		

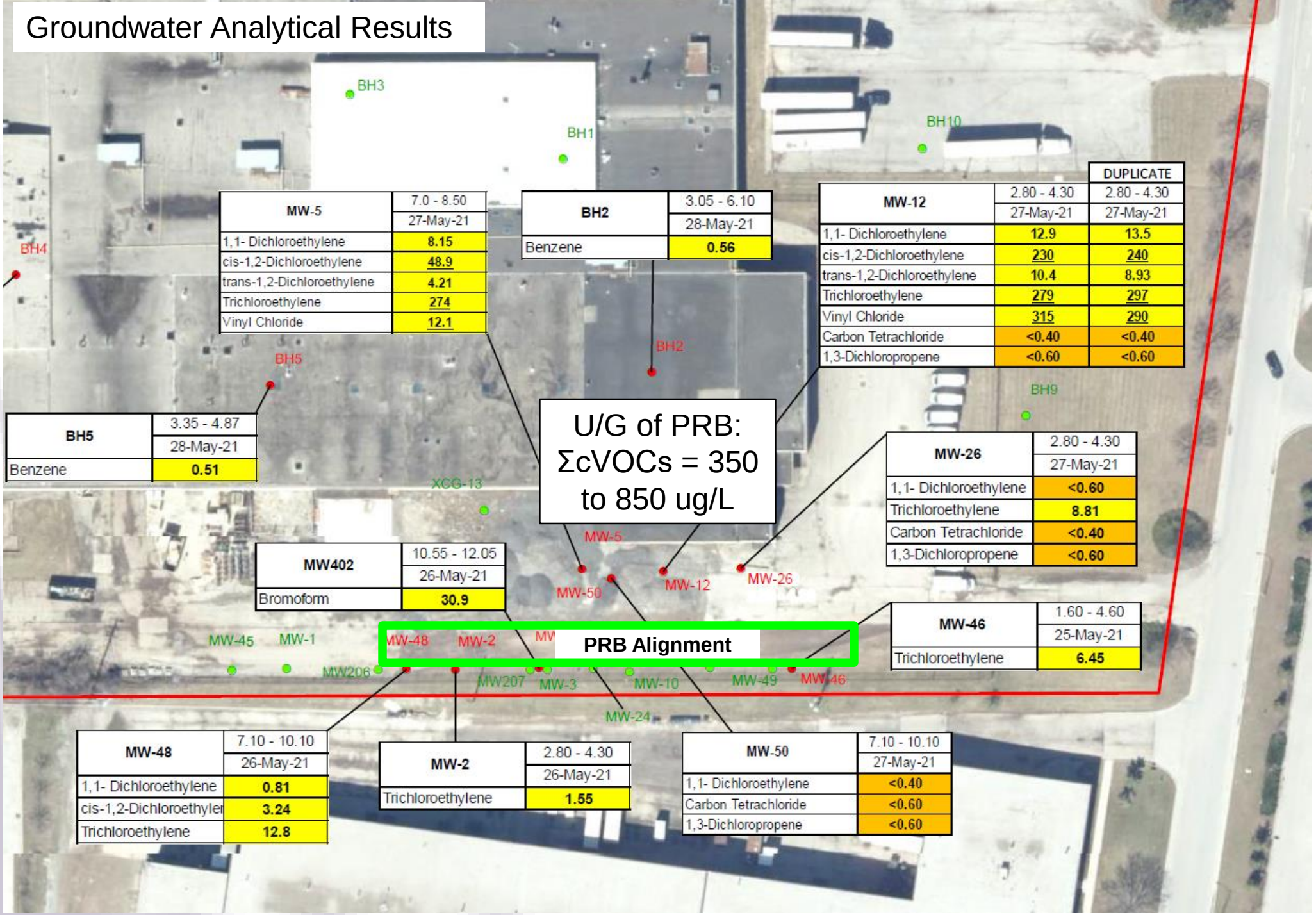


Subsurface

2.0 to 2.5 m – depth to Bedrock

2.5 to 3.0 m – depth to Groundwater

Groundwater Analytical Results



MW-5	7.0 - 8.50
	27-May-21
1,1- Dichloroethylene	8.15
cis-1,2-Dichloroethylene	48.9
trans-1,2-Dichloroethylene	4.21
Trichloroethylene	274
Vinyl Chloride	12.1

BH2	3.05 - 6.10
	28-May-21
Benzene	0.56

MW-12	2.80 - 4.30	DUPLICATE
	27-May-21	27-May-21
1,1- Dichloroethylene	12.9	13.5
cis-1,2-Dichloroethylene	230	240
trans-1,2-Dichloroethylene	10.4	8.93
Trichloroethylene	279	297
Vinyl Chloride	315	290
Carbon Tetrachloride	<0.40	<0.40
1,3-Dichloropropene	<0.60	<0.60

BH5	3.35 - 4.87
	28-May-21
Benzene	0.51

MW-26	2.80 - 4.30
	27-May-21
1,1- Dichloroethylene	<0.60
Trichloroethylene	8.81
Carbon Tetrachloride	<0.40
1,3-Dichloropropene	<0.60

MW402	10.55 - 12.05
	26-May-21
Bromoform	30.9

MW-46	1.60 - 4.60
	25-May-21
Trichloroethylene	6.45

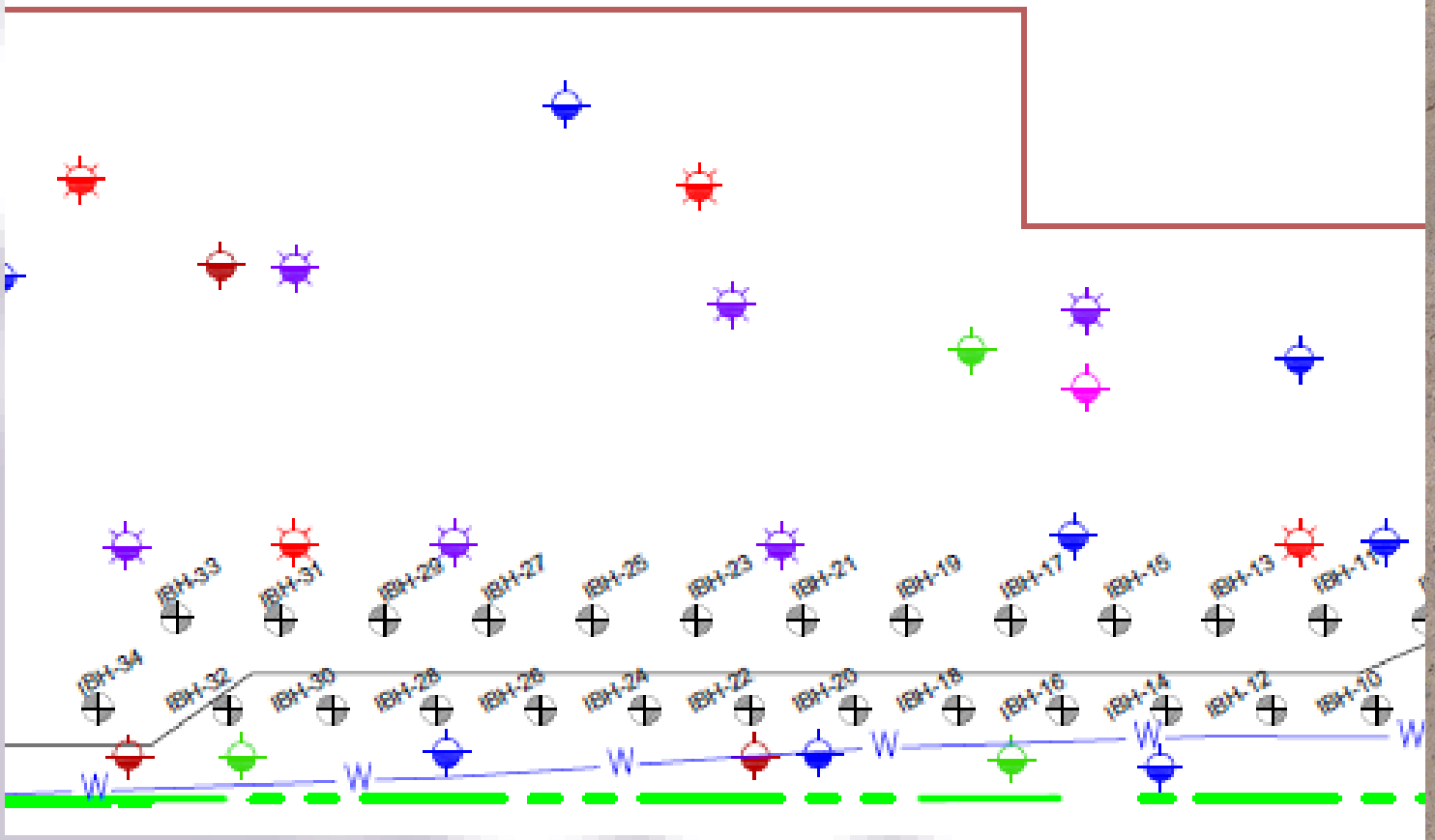
MW-48	7.10 - 10.10
	26-May-21
1,1- Dichloroethylene	0.81
cis-1,2-Dichloroethylene	3.24
Trichloroethylene	12.8

MW-2	2.80 - 4.30
	26-May-21
Trichloroethylene	1.55

MW-50	7.10 - 10.10
	27-May-21
1,1- Dichloroethylene	<0.40
Carbon Tetrachloride	<0.60
1,3-Dichloropropene	<0.60

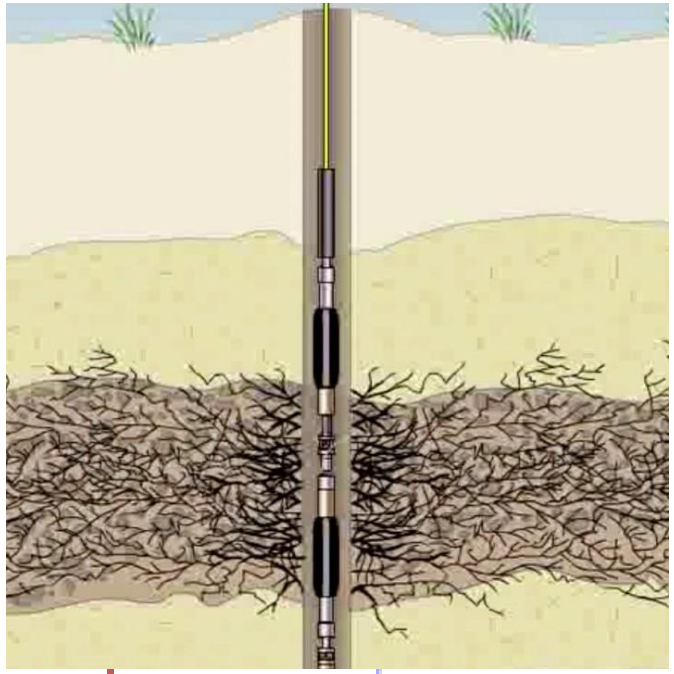
Injected PRB Installation:

- Install 34 injection boreholes (IBHs)
- PVC casing set to 3 mbgs
- Open borehole to 12 mbgs
- Straddle packer to inject BOS 100®

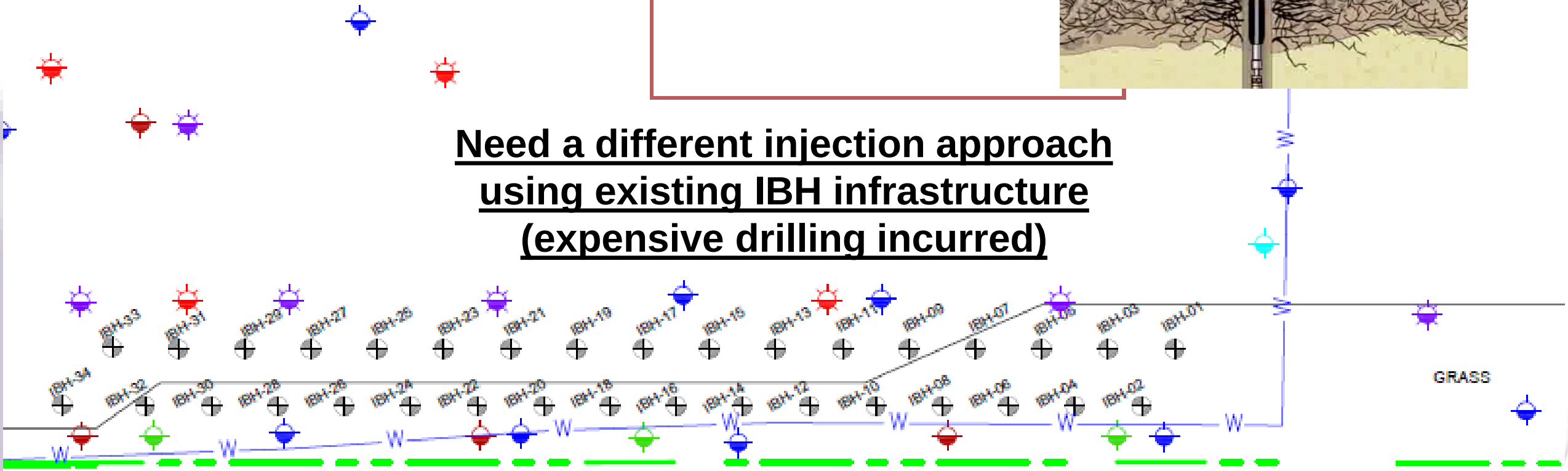


Injected PRB Installation:

- Shale bedrock highly weathered/fractured
- Resulted in frequent IBH cave-in / packers lost
- Difficult to move packer up and down the IBH
- Lower injection production rate
- Proved not feasible = **Stratigraphy**



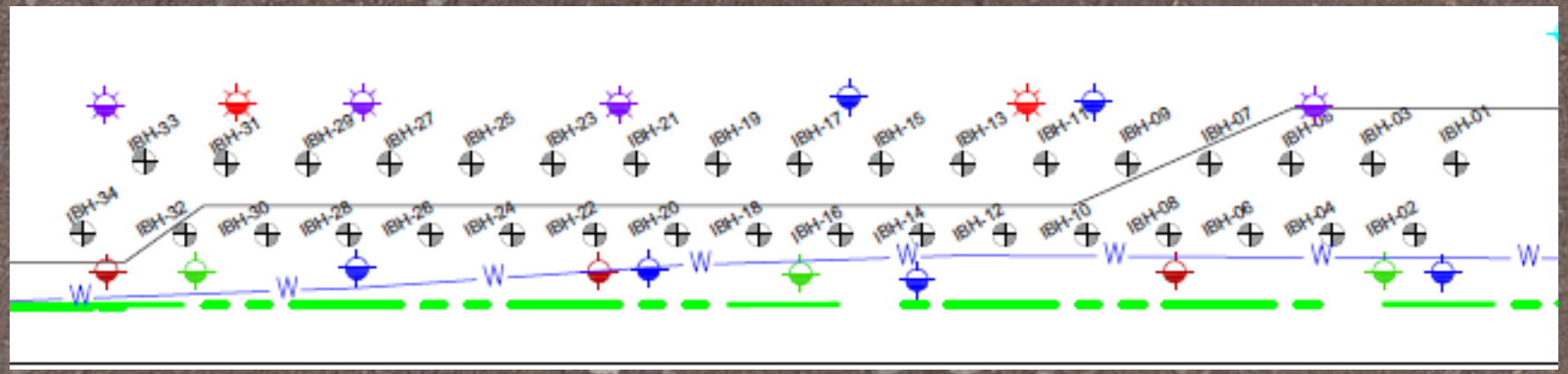
Need a different injection approach using existing IBH infrastructure (expensive drilling incurred)



GeoTAP™ (Pre-Drill) Method

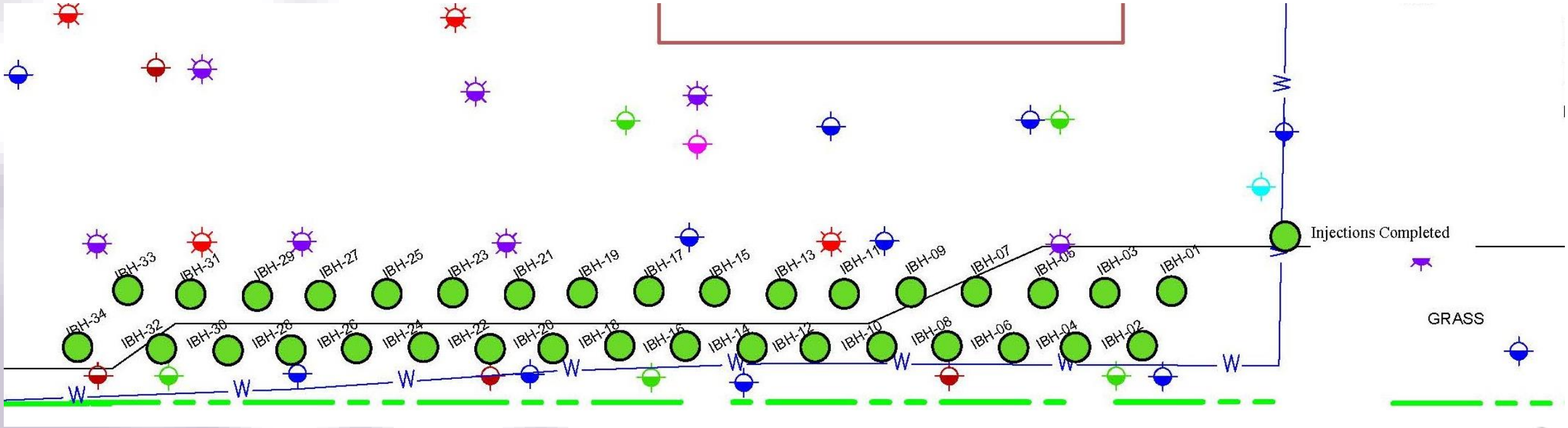
Methodology:

- Clear out any cave-in material in the IBHs using variety of methods including:
  - “Extract” material out with hydrovac
  - “Sample” material out with direct-push macro cores
  - “Flush” material out with air hammer tooling
- Backfill “cleared” IBH with bentonite chips and hydrate
- Allow 48 hours for bentonite seal to setup prior to injection

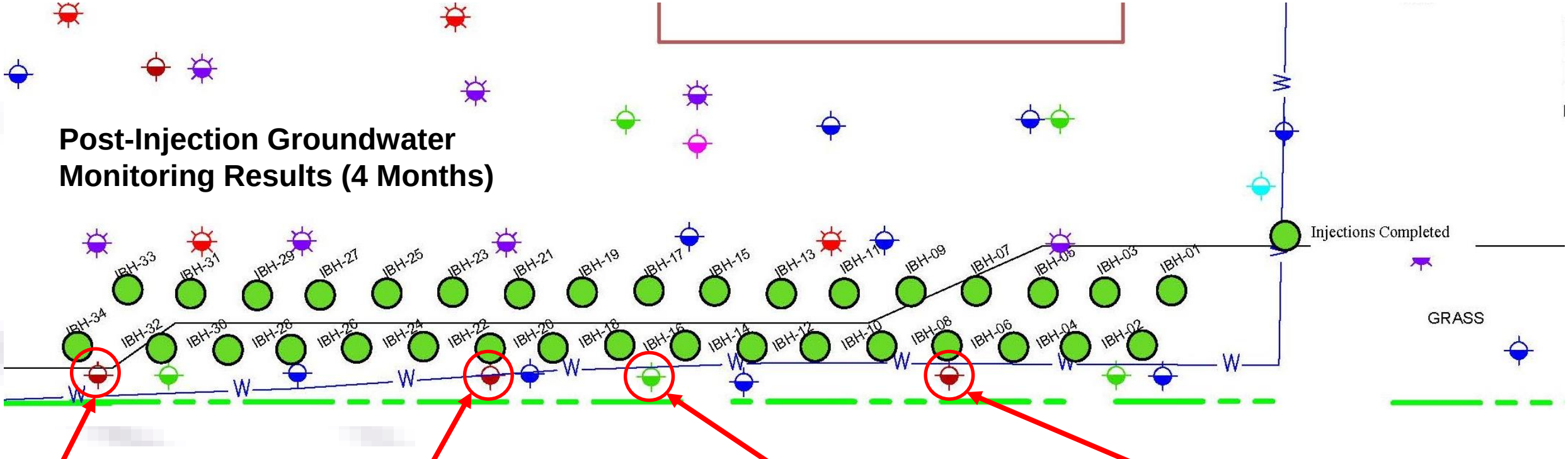


BOS 100® GeoTAP™ Injection:

- IBHs successfully cleared and backfilled
- Bentonite backfill provided appropriate seal for injections
- Successfully injected a total of 87,000 L of BOS 100® as planned
- Visual and hydraulic influence noted at adjacent MWs



Post-Injection Groundwater Monitoring Results (4 Months)

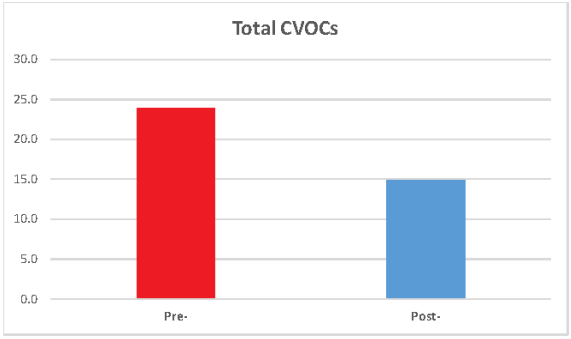


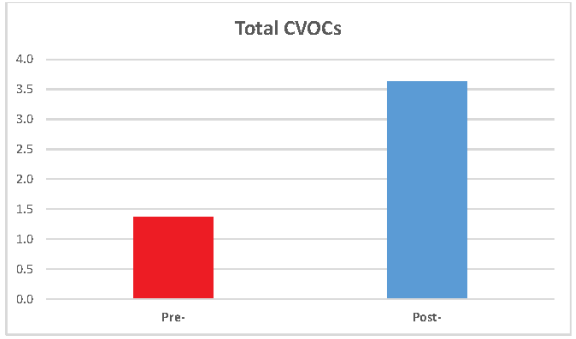
Parameter (ug/L)	2021	2022	Percent Change	
TCE	14.00	2.26	84%	Reduction
C12DCE	4.2	3.10	26%	Reduction
VC	5.7	9.5	67%	Increase

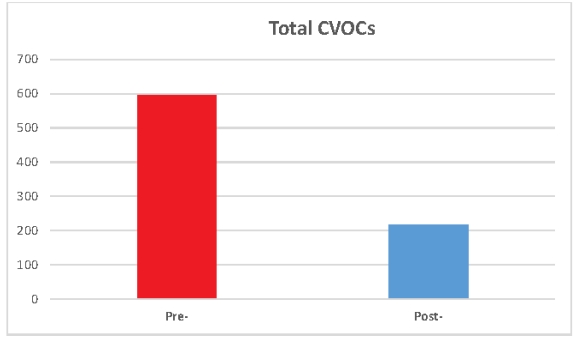
Parameter (ug/L)	2021	2022	Percent Change	
TCE	0.67	<0.20	>80%	Reduction
C12DCE	<0.50	0.88	>76%	Increase
VC	<0.20	2.6	>1200%	Increase

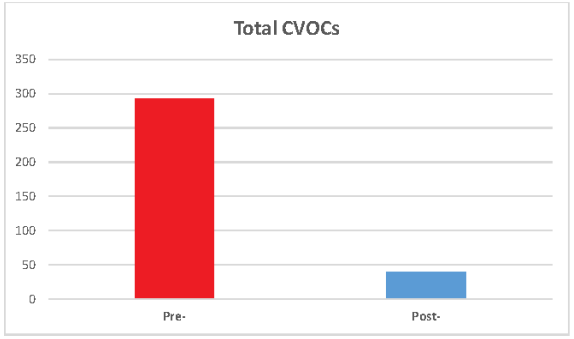
Parameter (ug/L)	2017-2019 Average	2022 Average	Percent Change	
TCE	364.6	136	63%	Reduction
C12DCE	180	52	71%	Reduction
VC	50.95	29	44%	Reduction

Parameter (ug/L)	2017	2022	Percent Change	
TCE	200	3.52	98%	Reduction
C12DCE	37	9.95	73%	Reduction
VC	56	26.7	52%	Reduction

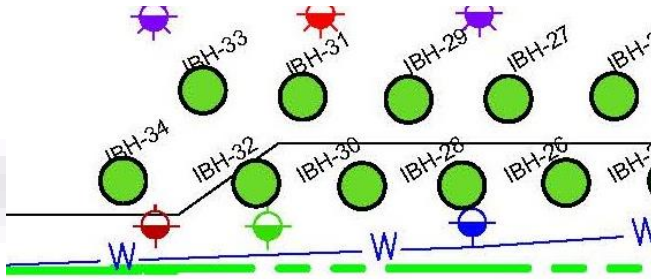


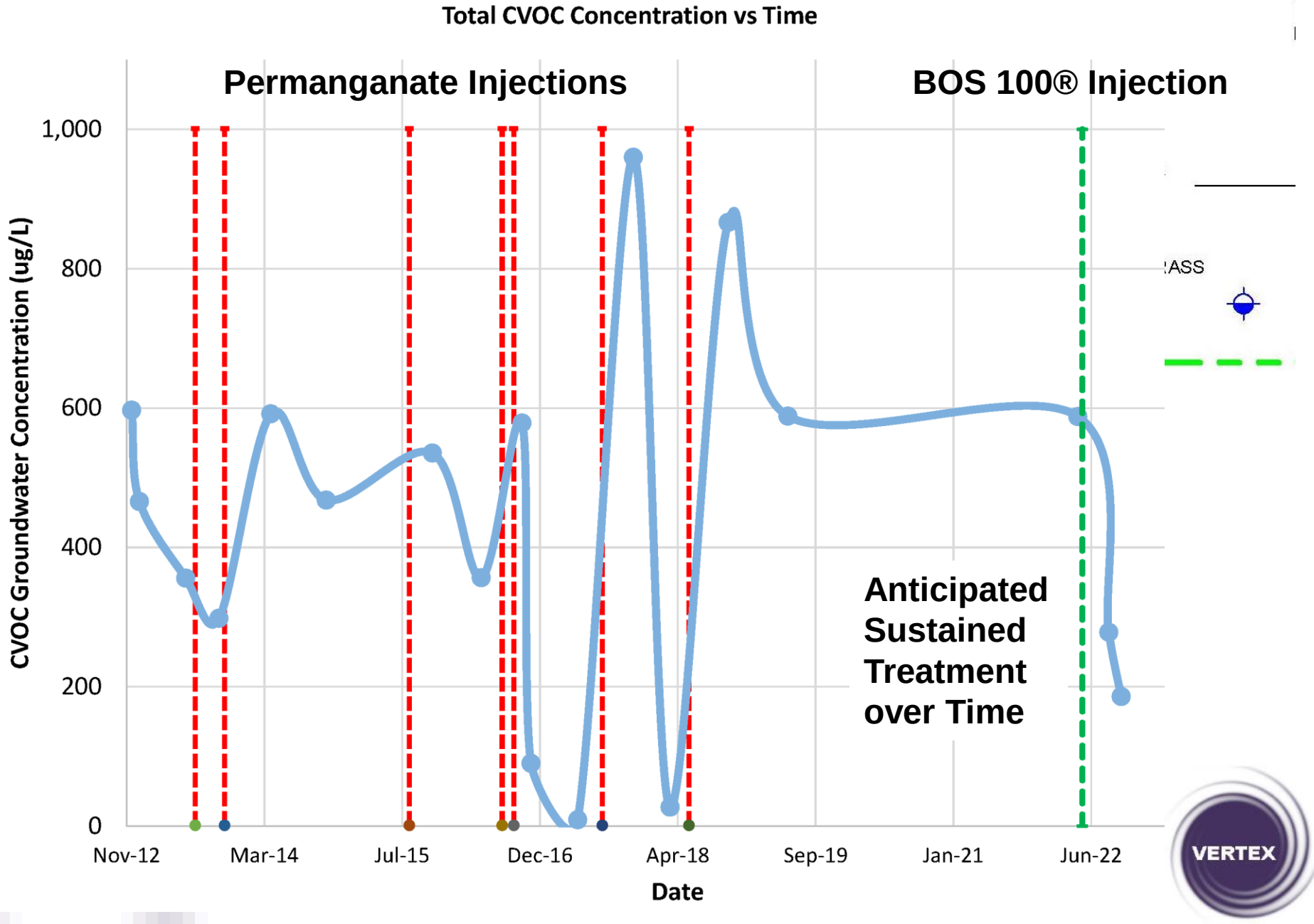






Historic Groundwater Monitoring Results Over Time





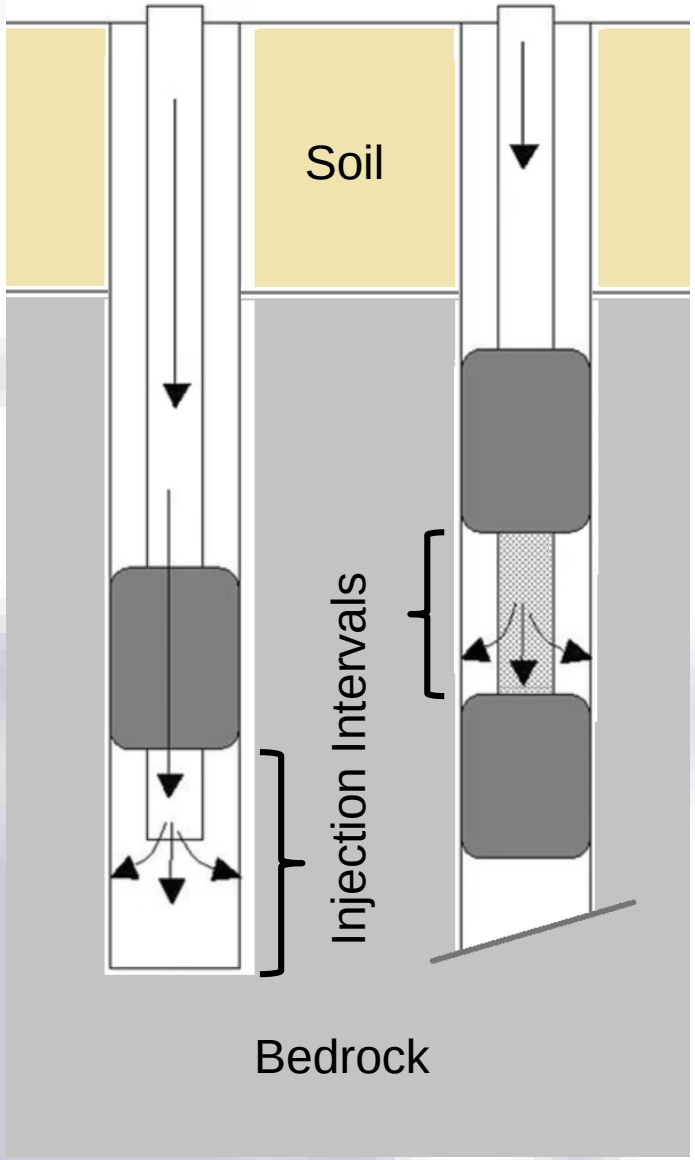
Bedrock Case Study #3 Wrap-Up

Remediation of Bedrock with Chlorinated Solvents:

- Original Open Borehole / Straddle Packer Injection Proposed
  - Friable shale bedrock, lots of cave-ins
  - Packers lost, very slow production rates
  - Approach considered not feasible due to stratigraphy
- Adapted Injection Method
  - Implemented alternative GeoTAP™ method
  - Utilized exiting open bedrock boreholes, cleared out & backfilled for subsequent direct push injection
- Trap and Treat® BOS 100® injection
  - Designed to control migration and back diffusion of cVOCs
  - Created a long-lasting PRB in difficult stratigraphy

Take Aways / Lessons Learned

Take Aways / Lessons Learned



Performing Bedrock Remediation:

- Address LNAPL / DNAPL by aggressive means
  - Excavation (Case Study #1)
- Back diffusion
  - Use a persistent / particulate remedial amendment that can overcome back diffusion:
    - Trap and Treat® (Case Study #1 and #3)
    - Zero Valent Iron (Case Study #2)
- Difficult stratigraphy
  - Adapt to site-specific conditions using alternative bedrock injection approach (Case Study #3)
- In-situ injections approaches can work
  - With proper remedial design, persistent amendments, appropriate drilling and injection techniques

Bedrock Remediation: What once was considered Impossible is now Routine!

Questions?

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