Using Multiple HRSC Technologies to Develop a Detailed CSM for a Complex Fractured Bedrock Site

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Science Advisory Board for Contaminated Sites in BC

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VEI Contracting Inc.

Presentation Overview

- VEI Contracting
- Site Background
- Remedial Objective
- Remedial Approach
- Initial CSM
- Additional Data Collection Activities
- Refined CSM
- Lessons Learned
- Questions

VEI Contracting

VEI Contracting Inc.

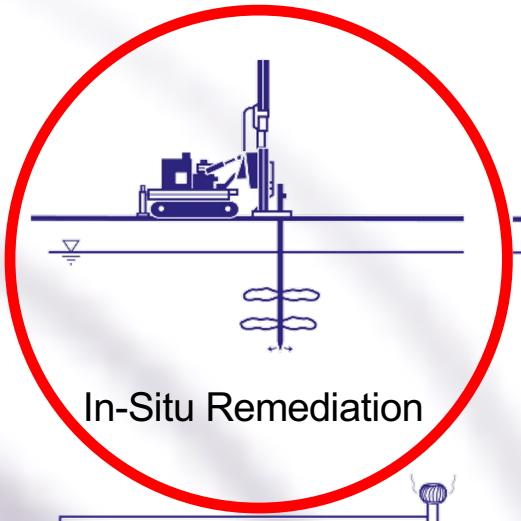
VEI Contracting Inc.

- (Formerly Vertex Environmental Inc.)
- Founded in 2003 (remedial injections)
- Specialized Environmental Remediation Contracting
- High Resolution Site Characterization (HRSC) and Remedial Design Characterization (RDC)

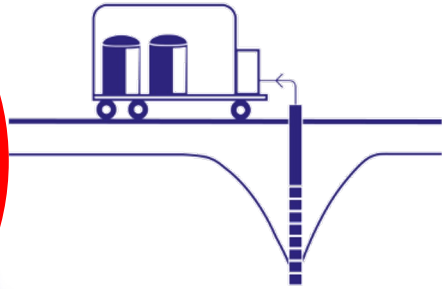
Kevin French, P.Eng

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

VEI Contracting Inc.

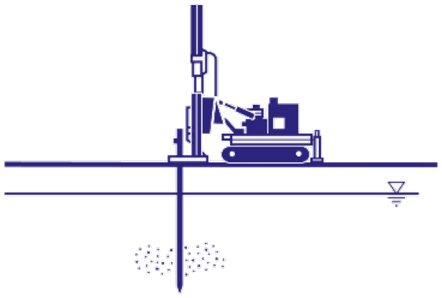


In-Situ Remediation



WTS & Dewatering

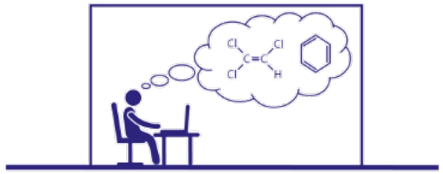
Ex-Situ Remediation



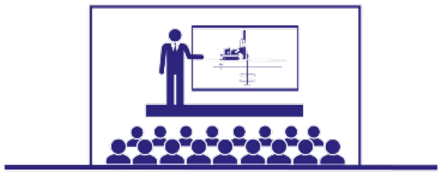
HRSC & RDC

Vapour Intrusion

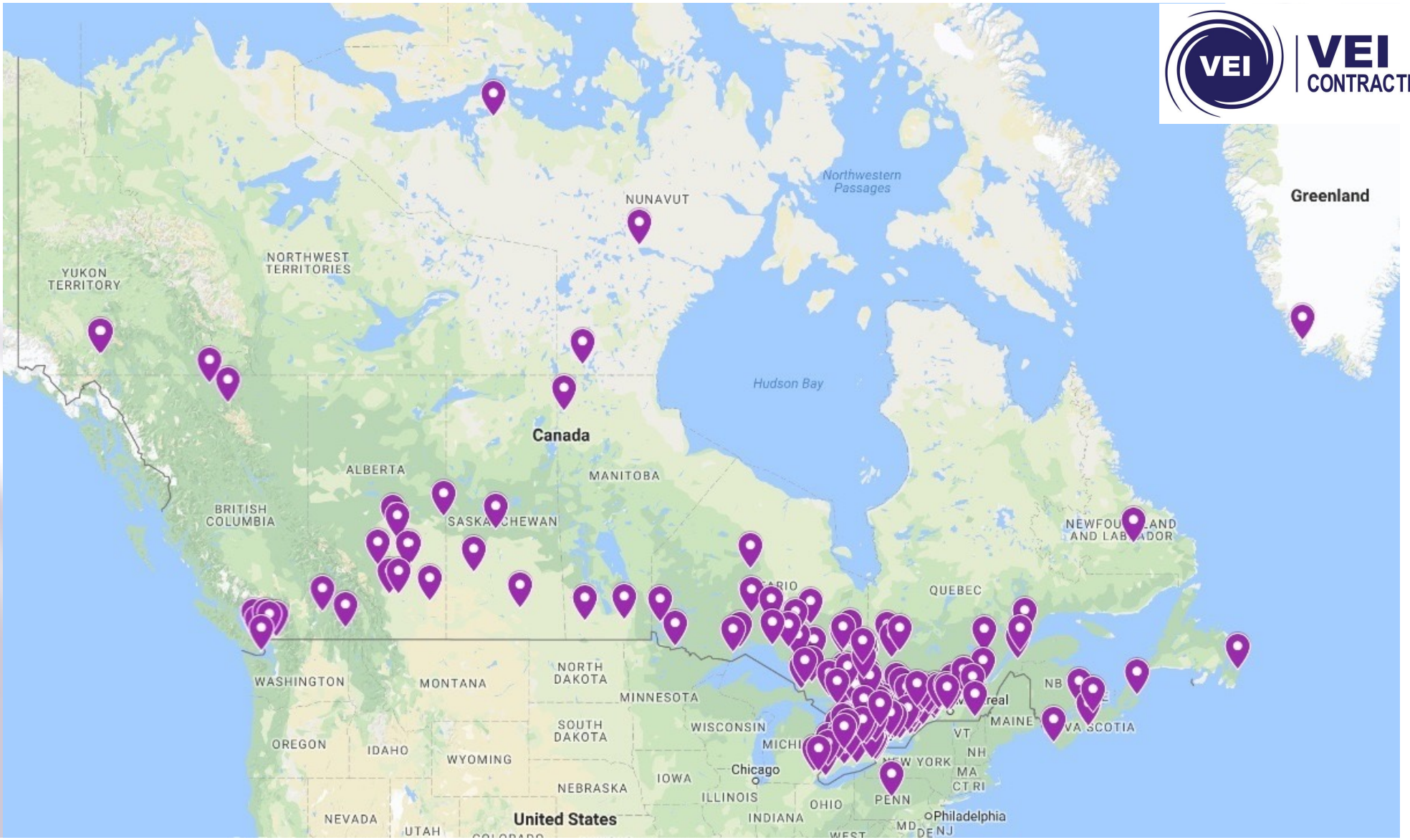
Bench-Scale Testing



Remedial Design



Outreach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Passages
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Greenland
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TERRITORIES
YUKON
TERRITORY
Hudson Bay
Canada
ALBERTA
MANITOBA
BRITISH
COLUMBIA
SASKATCHEWAN
NEWFOUNDLAND
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UTAH

Site Background

Site Background

- Confidential site owned by private individuals
- Single story commercial building currently used for warehousing
- Developed for industrial use in the 1970s for metal plating, metal fabrication, etc.
- Multiple former tanks and chemical storage areas
- Plume of chlorinated volatile organic compounds (cVOCs), mainly related to tetrachloroethylene (PCE), in bedrock groundwater

Remedial Objective

Remedial Objective

Remedial Objective:

- **Owners want to be able to sell the site with no trailing liability**
- Previous on-site remediation activities and risk assessment completed to demonstrate no unacceptable risks for continued commercial / industrial land uses
- Need to demonstrate that the plume of cVOCs in the bedrock groundwater is no longer migrating off-site
- Therefore, **remediation** (i.e., a permeable reactive barrier or PRB) **required to allow due diligence to proceed and facilitate the sale of the property**

Remedial Approach

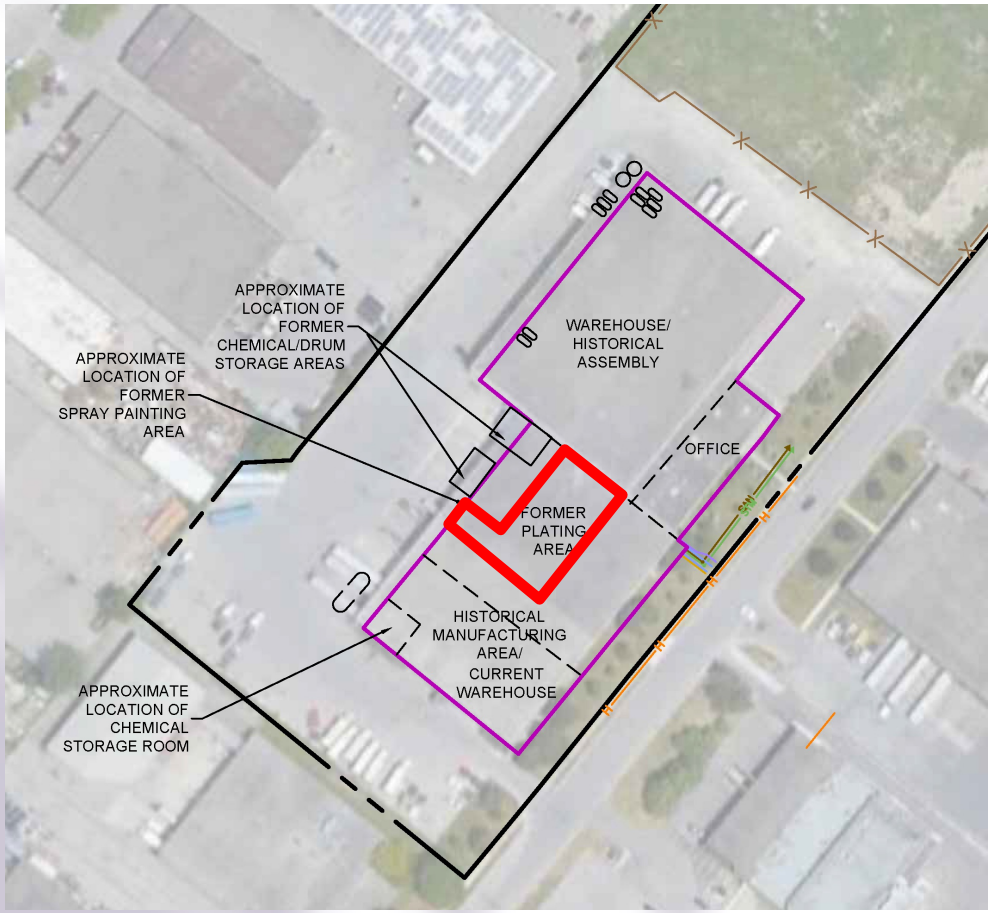
Remedial Approach

Remedial Approach:

- Plume of cVOCs in bedrock groundwater inferred to be migrating off-site to the east / southeast
- Sorbed impacts likely in the soil above the water table; not of concern for migration
- PRB needed to fully intercept and capture / treat cVOCs in bedrock groundwater before leaving the site
- **Groundwater impacts are deep (i.e., ~12 m bgs)** and located in a narrow strip of land between the site building and the sidewalk (i.e., underground services)
- **To deep / expensive to shore and excavate; therefore, an injected approach preferred**
- cVOC impacts in groundwater with likely sorbed mass in bedrock requires a particulate and persistent remedial amendment

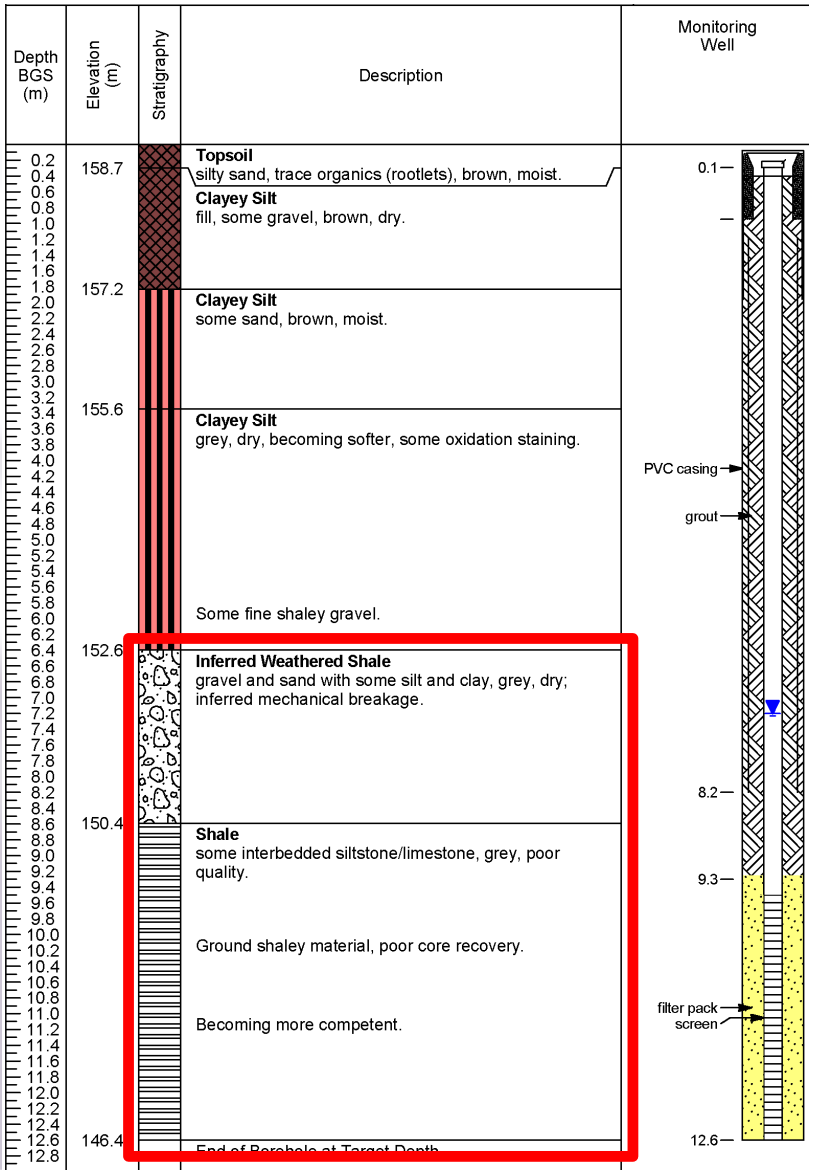
Initial Conceptual Site Model (CSM)

Initial CSM



Contamination Profile – Source:

- Source of cVOCs likely from former degreasing and plating area, but multiple source areas on-site possible
- Bulk of soil and perched overburden groundwater contamination located under the site building removed via excavation
- Bedrock groundwater contamination generally found in monitoring wells screened from 6-9 m bgs and 9-12 m bgs

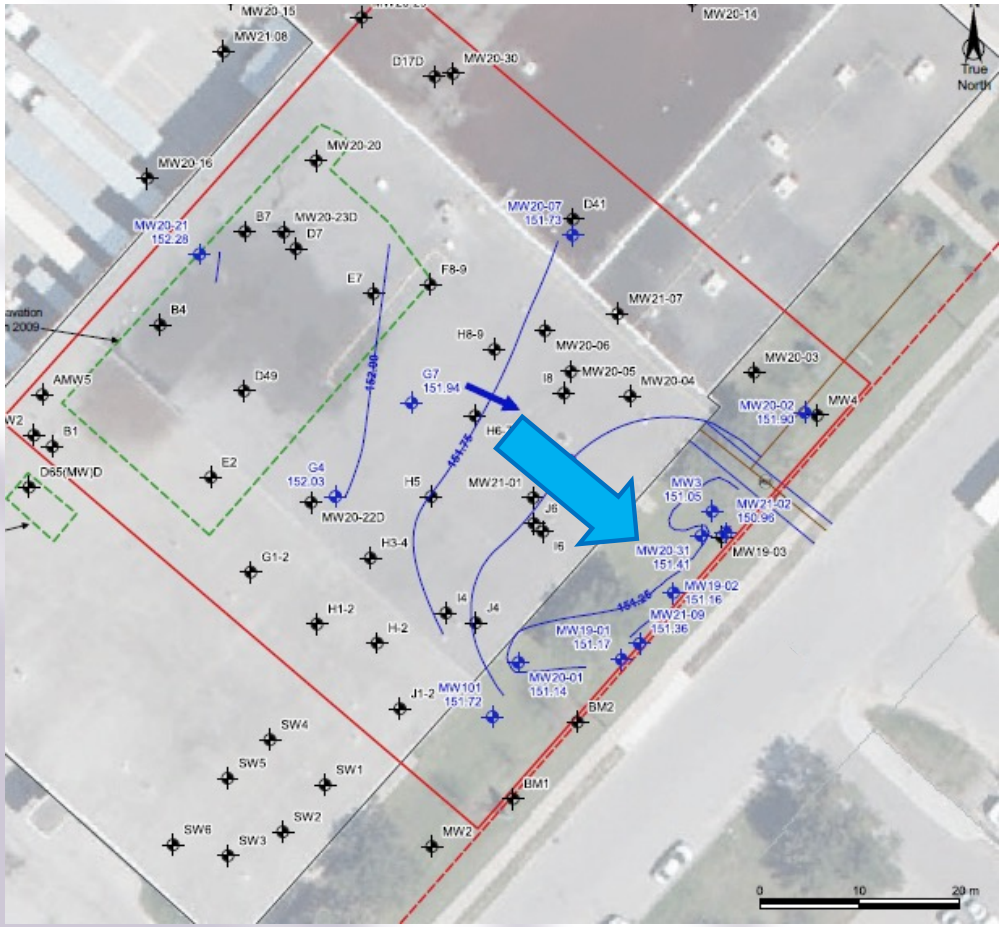


Initial CSM

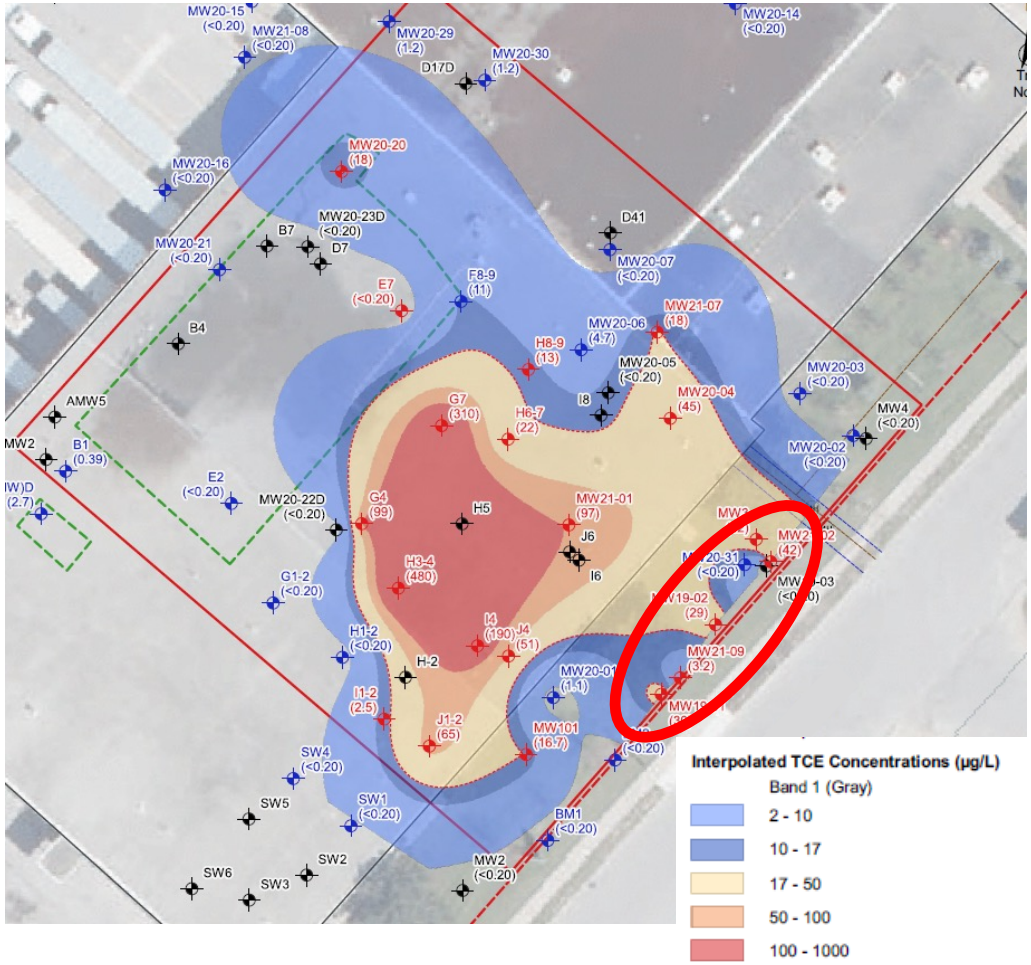
Geology/Hydrogeology:

- Native silty clay (to ~6.1 – 7.6 m bgs) over **weathered / fractured shale**, which becomes more competent below 11.0 – 11.9 m bgs
- **Groundwater table at depths of approx. 7.0 – 7.9 m bgs**
- K values range from 1.2×10^{-6} to 3.7×10^{-8} m/s in shallow unit, though highly variable across the site
- Linear groundwater flow velocities estimated to range from 11 – 160 m/year across the site

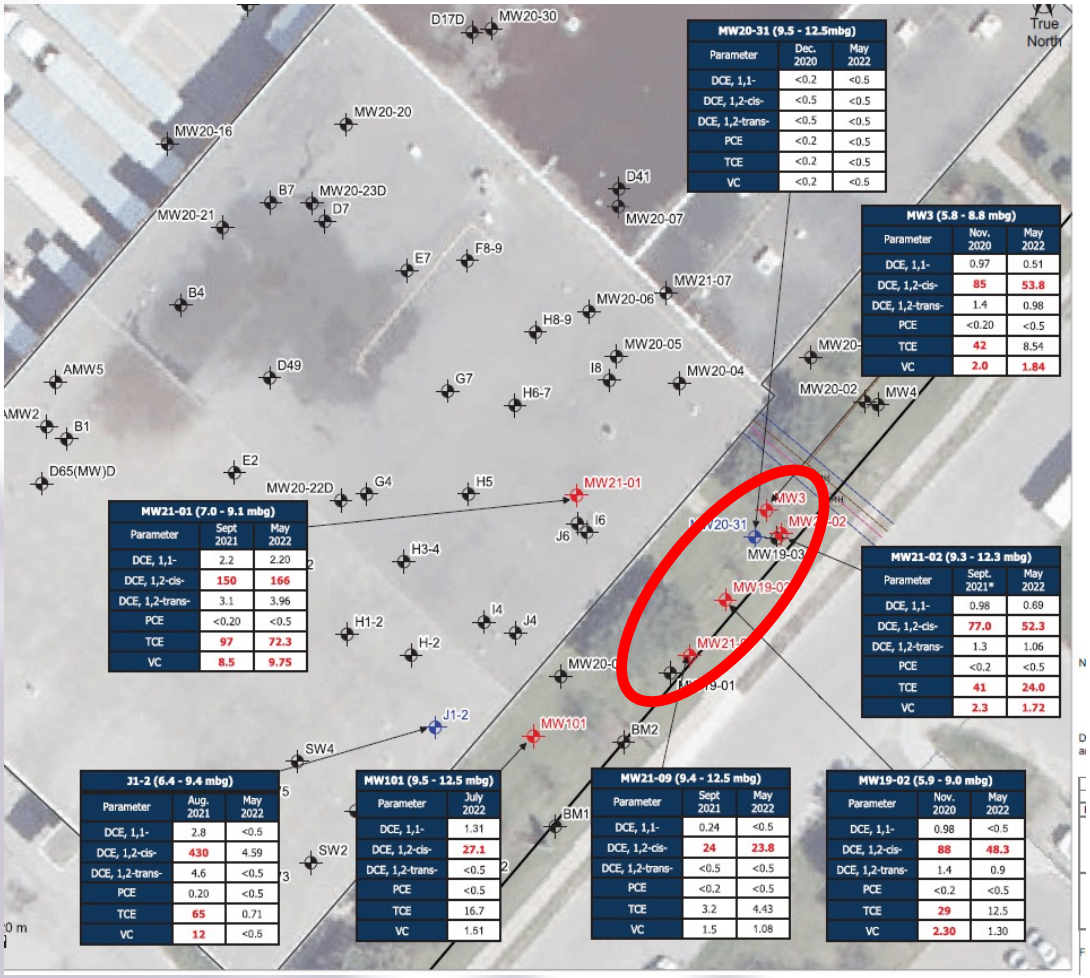
Inferred Bedrock Groundwater Flow Direction



Interpolated TCE Distribution in Bedrock Groundwater



Initial CSM



Initial Remedial Injection Design:

- Target east / southeast portion of the site where cVOC plume in bedrock groundwater is leaving the property
- Target bedrock groundwater over depth interval of approx. 8.0 – 12.0 m bgs
- Two off-set rows of injection points on an approx. 4.6 m spacing
- Inject a 9% wt./wt. slurry of BOS 100® at a rate of approx. 650 L/m

Initial CSM

Data Gaps / Unknowns:

- Actual groundwater flow and transport conditions
- Vertical distribution of bedrock fractures and bedding planes
- Bedrock fracture porosity
- Interconnectivity of bedrock fractures and bedding planes
- Sorbed contaminant mass in bedrock
- Main contaminant flow zones, etc.

Therefore, a more refined CSM was required prior to remediation!

Additional Data Collection Activities

Additional Data Collection Activities

Injection Tracer Testing:

- A tracer injection test was completed to understand groundwater flow and transport conditions
- 2,000 L of a tracer solution containing **40 mg/L of Rhodamine WT dye and 8,000 mg/L of potassium bromide** and chased with 100 L of water
- Injected at one existing well location (“I4”) located to the southwest of the pilot-scale injection area and screened from 6.4 – 9.4 m bgs in the bedrock
- Injection pressure <5 psi and flow rate 5 – 10 L/min
- Monitored for visual, EC and Br for six months using loggers and via sampling in transgradient and downgradient monitoring well locations

Additional Data Collection Activities

Injection Tracer Testing (cont'd.):

- **No evidence of tracers detected** at any location monitored within that timeframe
  - 8,000 mg/L of KBr was designed to result in an EC reading of approx. 4,000 to 5,000 µS/cm above background EC reading of ~3,000 µS/cm, but corresponding **density effects may have affected tracer solution migration patterns**
- Therefore, test was inconclusive, except in proving that **groundwater flow may be less than ~6.1 m/yr** in that area of the site and in that bedrock depth interval

Additional Data Collection Activities

Drilling and Sampling Activities:

- Four bedrock injection points (IPs) installed at the site (i.e., IP-01 to IP-04)
- Continuous soil sampling at two locations (i.e., IP-02 and IP-04)
- Bedrock cored at one location (i.e., IP-01)
- 12.5 cm diameter PVC casings set in place into top of bedrock
- All IPs then drilled/cored into bedrock leaving a 10 cm diameter open hole from approx. 5.8 – 12.2 m bgs
- All IPs developed via purging and extraction using a vacuum truck to remove cuttings and develop the open bedrock holes

Additional Data Collection Activities

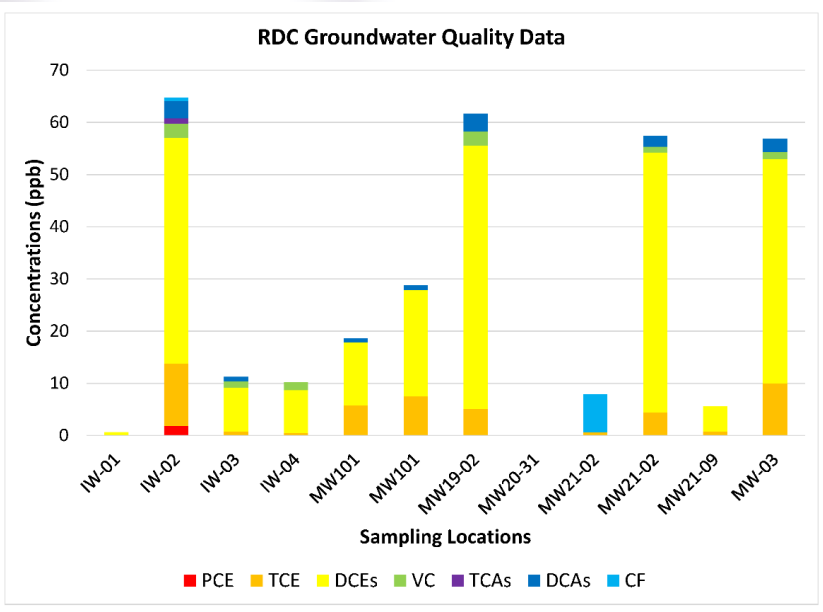
Drilling and Sampling Activities (cont'd.):

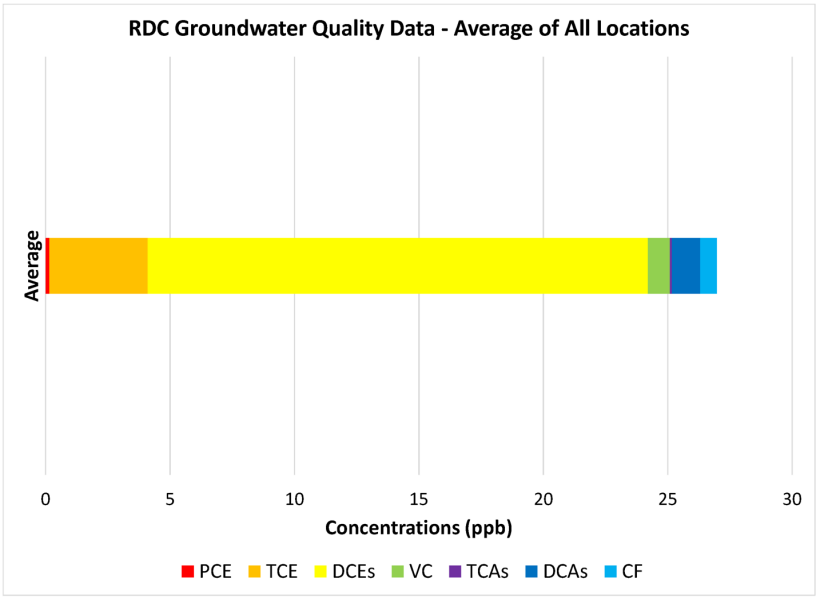
- Top of weathered shale bedrock encountered at approx. 5.5 – 6.1 m bgs
- Water table encountered at 6.0 – 7.8 m bgs
- At the cored location (i.e., IP-01) fracture zones in the bedrock were encountered from approx. 5.8 – 6.6 m, 7.0 m, 7.3 – 7.6 m, 8.8 – 9.3 m, 10.1 – 10.4 m bgs
- Therefore, visually more **weathered and fractured near the bedrock / overburden interface and becoming more competent with depth (i.e., as expected)**

Additional Data Collection Activities

Remedial Design Characterization (RDC) Sampling and Analysis:

- 20 soil, 6 bedrock and 10 groundwater samples submitted to Remediation Products Inc.'s (RPI's) laboratory Denver, CO for pro bono laboratory analyses of cVOCs
- Mainly dichloroethlyenes (DCEs) and trichloroethylene (TCE) detected in bedrock groundwater samples, with a small amount of vinyl chloride and some other cVOCs

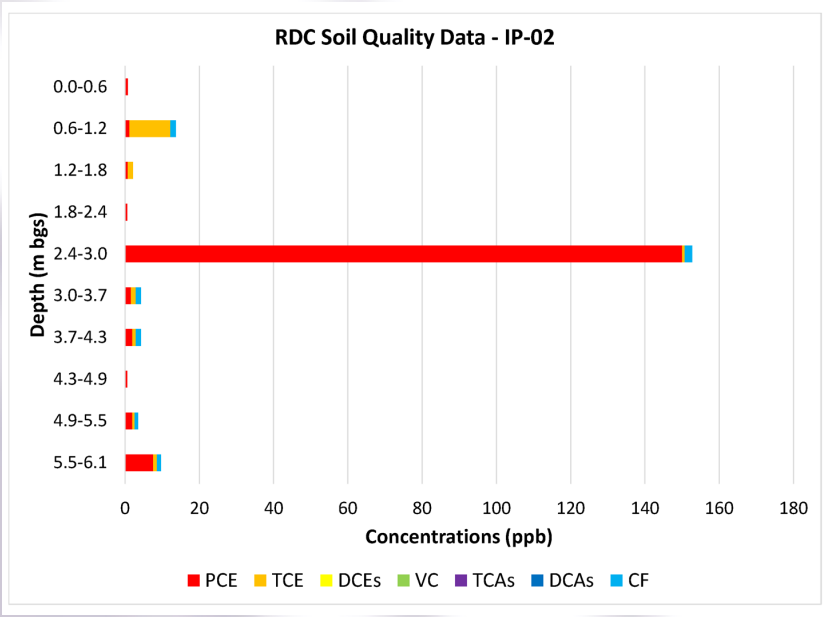


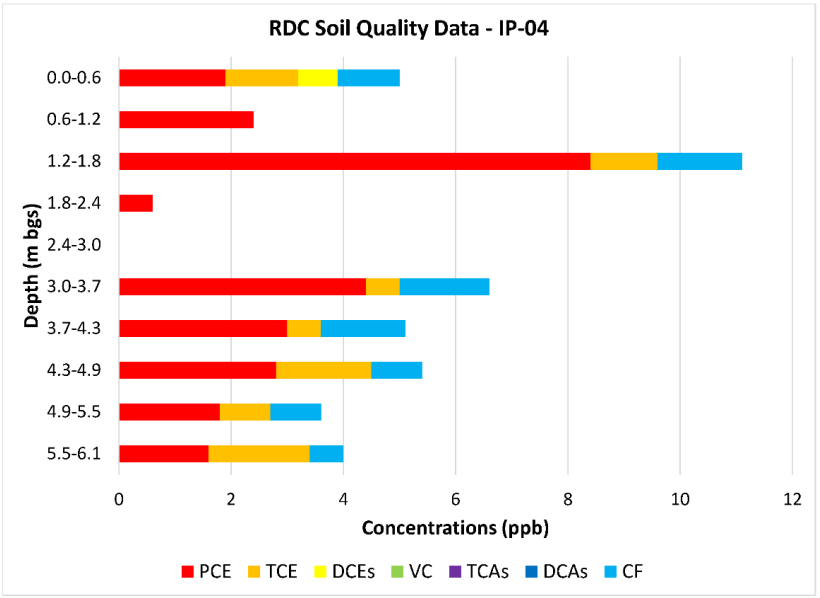


Additional Data Collection Activities

RDC Sampling and Analysis (cont'd.):

- Mainly tetrachloroethylene (PCE) and TCE detected in soil samples collected from above the groundwater table (i.e., below remedial criteria)
- Barely any DCEs and no VC detected; but chloroform (CF) also present in most samples

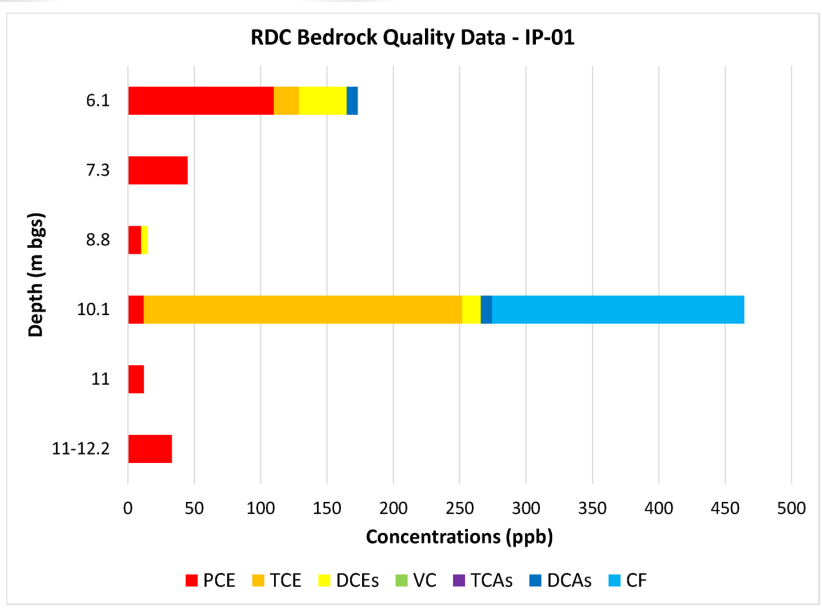


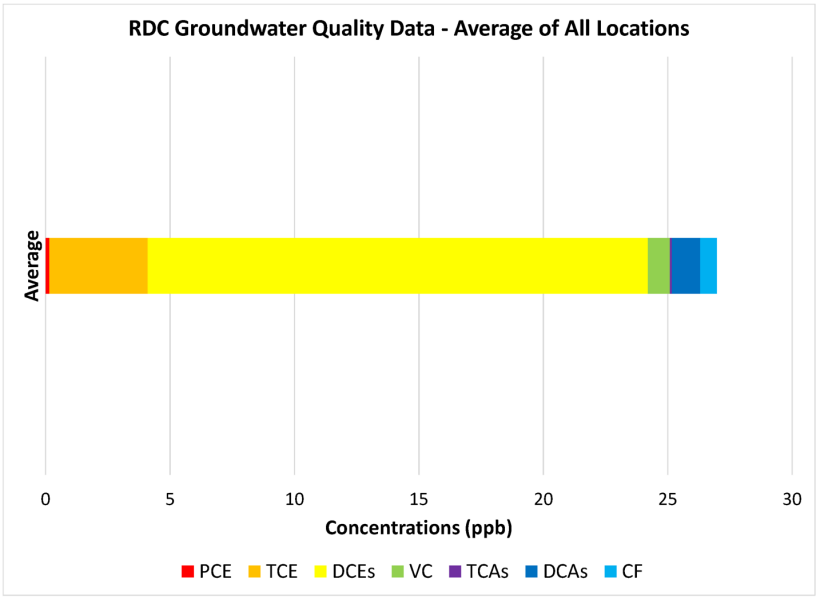


Additional Data Collection Activities

RDC Sampling and Analysis (cont'd.):

- Mainly PCE, TCE and CF detected in bedrock samples as well (i.e., below remedial criteria)
- Heavier molecular weight cVOCs are more predominant in the bedrock matrix as compared to bedrock groundwater quality
- **Newly detected cVOC mass in bedrock needs to be accounted for in the PRB design**



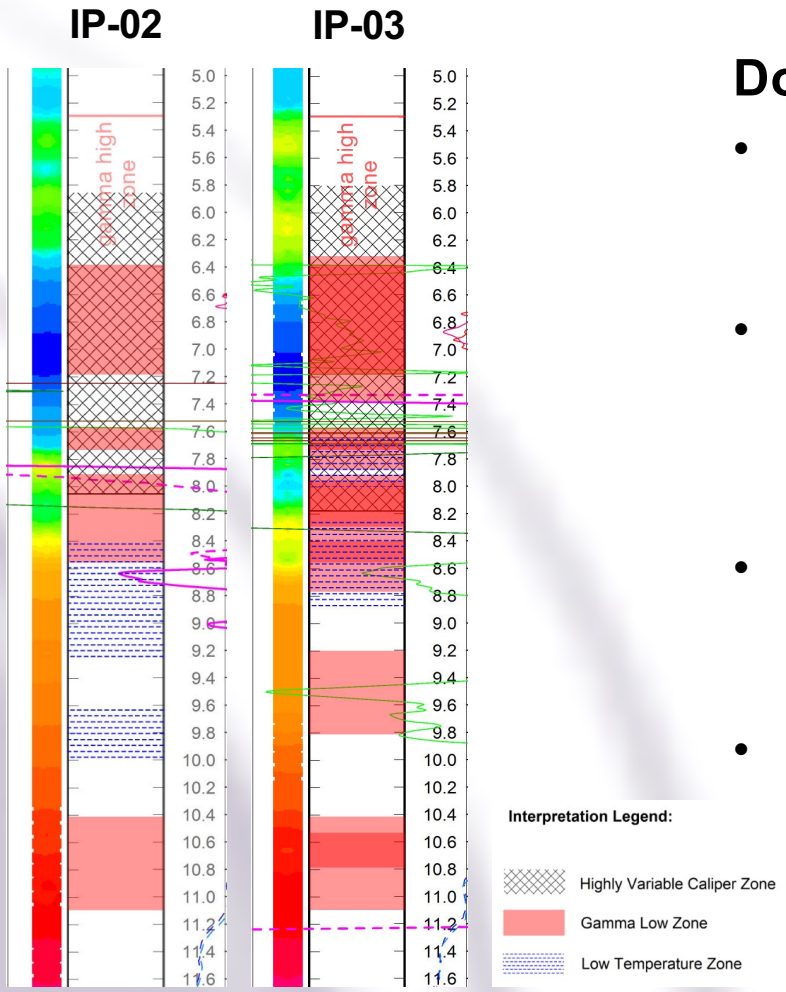


Additional Data Collection Activities

Downhole Geophysics:

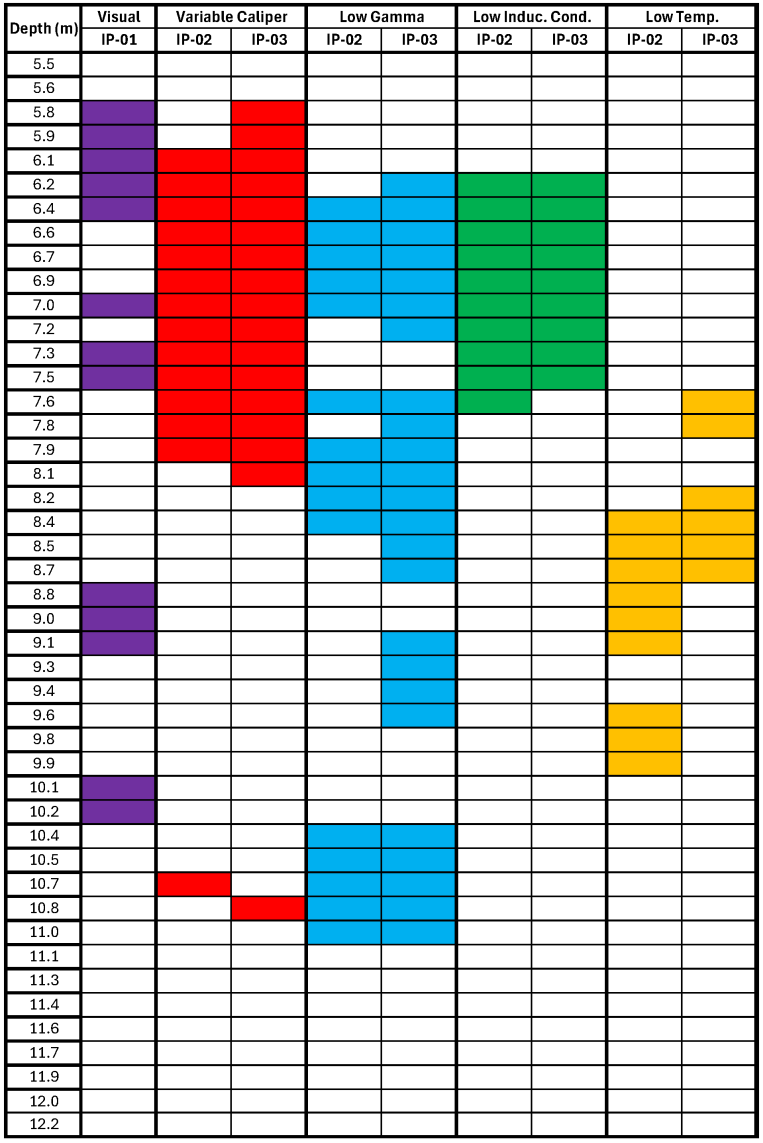
- Downhole geophysical surveys completed at locations IP-02 and IP-03 over a depth interval from approx. 6.1 – 12.2 m bgs develop a greater understanding of bedrock fracture conditions and flow patterns at the site
- Data collected included caliper, gamma, inductive conductivity, single point resistance, temperature, fluid conductivity, spontaneous potential and camera
- **Highly variable caliper, low gamma, inductive conductivity and low temperature** were the main readings used in conjunction with the camera to identify significant fracture and flow zones in the bedrock

Additional Data Collection Activities



Downhole Geophysics (cont'd.):

- **Highly variable caliper readings** detected from approx. 6.1 – 8.1 m and at 10.8 m bgs in IP-02, and from approx. 5.8 – 8.2 m and at approx. 11.0 m bgs in IP-03
- **Low gamma readings** detected from approx. 6.4 – 7.2 m, 7.6 – 7.8 m, 7.9 – 8.5 m and 10.4 – 11.1 m bgs in IP-01, and from approx. 6.2 – 7.2 m, 7.6 – 7.9 m, 7.9 – 8.8 m, 9.1 – 9.8 m and 10.4 – 11.1 m bgs in IP-03
- **Low inductive conductivity** readings detected from approx. 6.2 – 7.8 m bgs in IP-02, and from approx. 6.2 – 7.5 m bgs in IP-03
- **Low temperature readings** detected from approx. 8.4 – 9.3 m and 9.6 – 10.1 m bgs in IP-02, and from approx. 7.6 – 7.9 m and 8.2 – 8.8 m bgs in IP-03



Additional Data Collection Activities

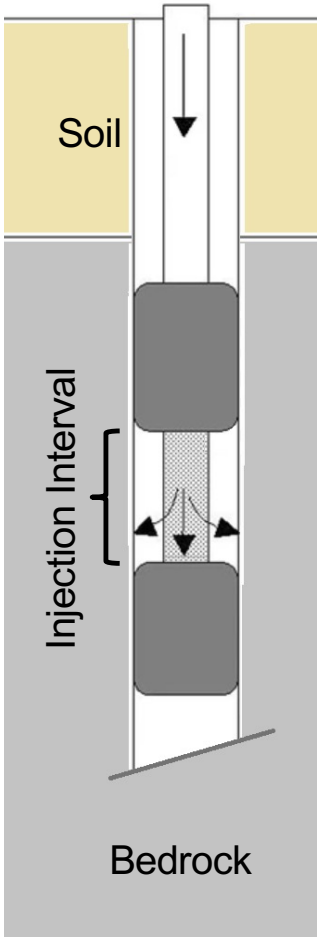
Downhole Geophysics (cont'd.):

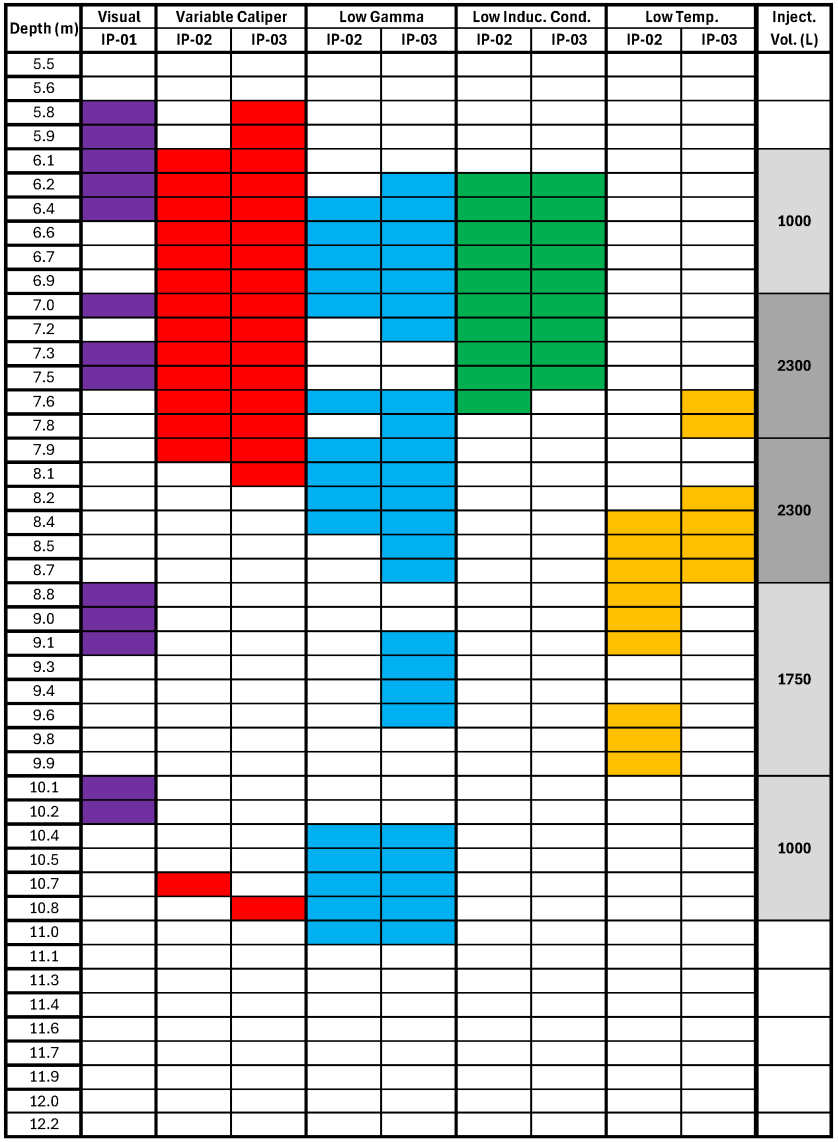
- Results of downhole geophysics compared to visual assessment of bedrock fractures / beddings planes indicate:
  - **Significant fracture and flow zones in the bedrock are located from approx. 6.2 – 8.1 m bgs**, and
  - To a lesser extent from approx. 5.8 – 6.2 m, 8.1 – 11.1 m bgs
  - **Likely no significant fracture or flow zones below approx. 11.1 m bgs**

Additional Data Collection Activities

Pilot-Scale Injection Activities:

- 8,300 L of potable water containing 750 kg of Trap & Treat® BOS 100®, representing an approx. 9% wt./wt. slurry, was injected into the four IPs using pressure packer techniques to assess injection flow rates and pressures, injection radius of influence and treatment effectiveness
- Injections took place at various vertical intervals ranging from 6.1 – 11.0 m bgs and at various loading rates ranging from 400 – 1,400 L/m
- Injection pressures ranged from 50 – 500 psi, averaging 200 psi
- Injection flow rates ranged from 40 – 350 Lpm
- Visual presence of **BOS 100® particulate observed** at monitoring wells MW19-01 and MW21-09, located **approx. 9.1 – 10.7 m away from the IPs** during injection





Additional Data Collection Activities

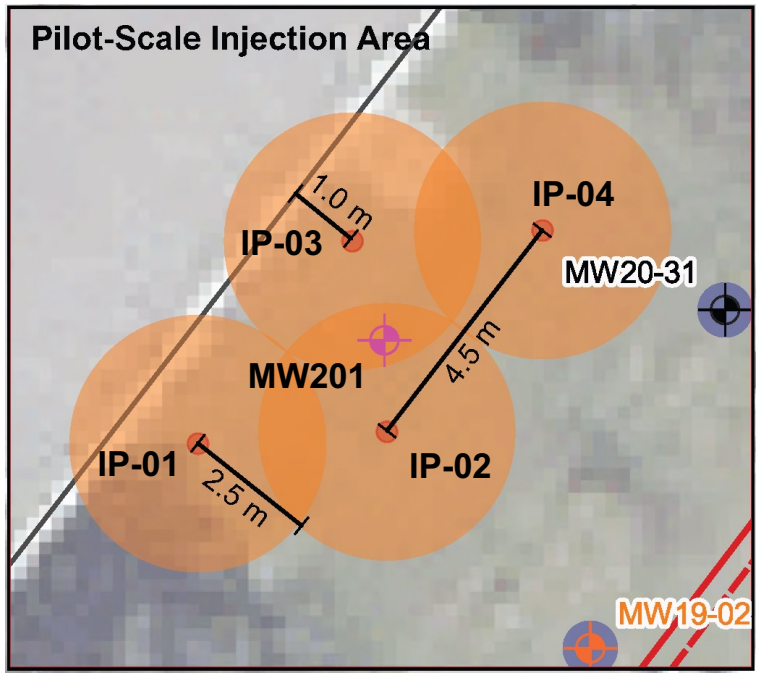
Pilot-Scale Injection Activities (cont'd.):

- Pilot-scale injection program not completed exactly as planned
  - Slightly smaller diameter cored bedrock hole at IP-01 restricted packer deployment
- Part of the pilot-scale test was to assess injection volume / radius of influence relationship
- **Most of the amendment volume was able to be injected in general accordance with expectations based on downhole geophysics**

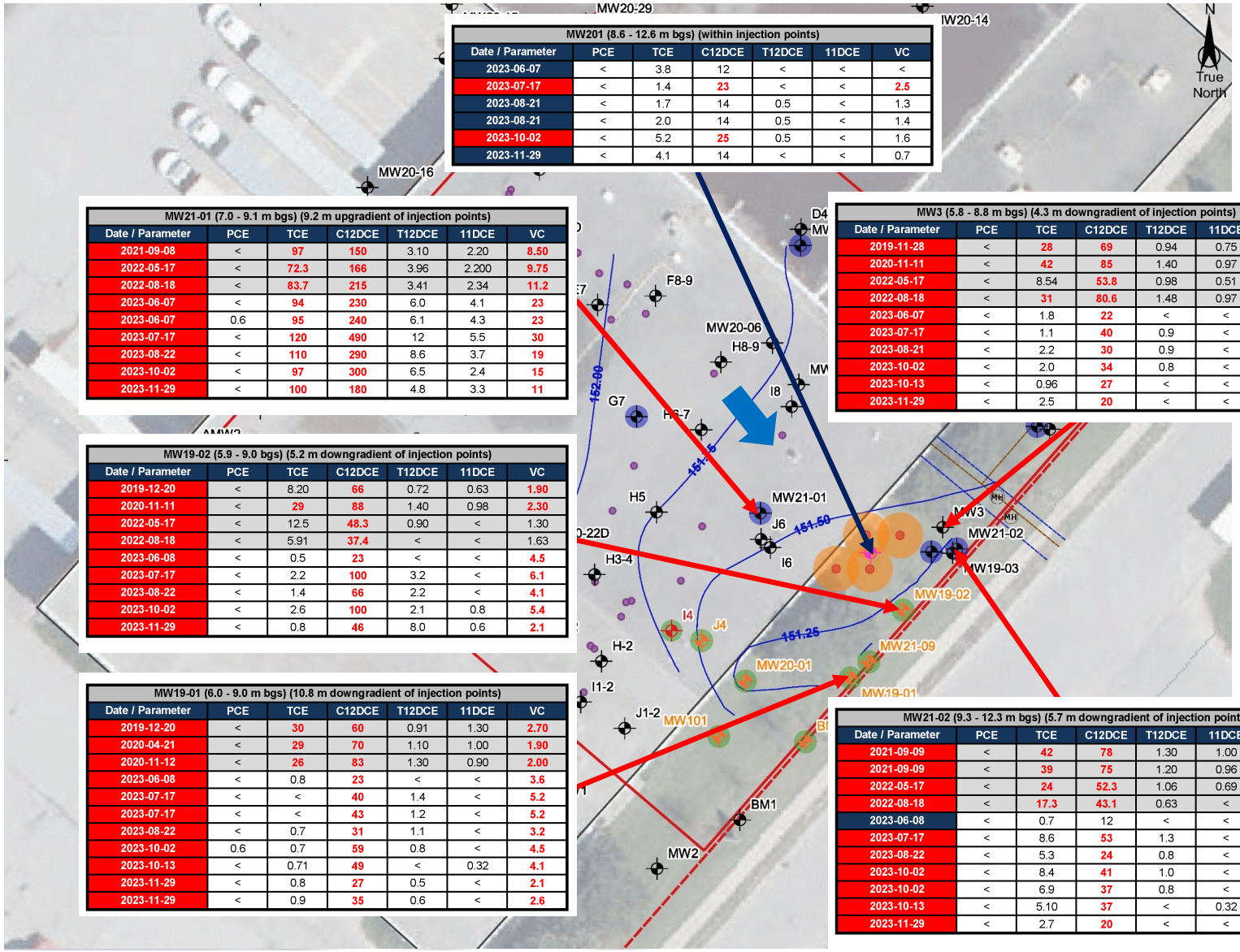
Additional Data Collection Activities

Performance Monitoring Activities:

- Following the pilot-scale injection testing activities a new monitoring well (i.e., MW201) was installed to a depth of approx. 11.9 m bgs in the center of the pilot-scale injection area
- Groundwater sampling and laboratory analysis was completed post-injection at MW201 as well as at five other monitoring wells (i.e., MW3, MW19-01, MW19-02, MW21-01 and MW21-02) for approx. 9 months (i.e., 5 – 6 sampling events each location)



Post-Injection Groundwater Monitoring Results:



MW201 (8.6 - 12.6 m bgs) (within injection points)

Date / Parameter	PCE	TCE	C12DCE	T12DCE	11DCE	VC
2023-06-07	<	3.8	12	<	<	<
2023-07-17	<	1.4	23	<	<	2.5
2023-08-21	<	1.7	14	0.5	<	1.3
2023-08-21	<	2.0	14	0.5	<	1.4
2023-10-02	<	5.2	25	0.5	<	1.6
2023-11-29	<	4.1	14	<	<	0.7

MW21-01 (7.0 - 9.1 m bgs) (9.2 m upgradient of injection points)

Date / Parameter	PCE	TCE	C12DCE	T12DCE	11DCE	VC
2021-09-08	<	97	150	3.10	2.20	8.50
2022-05-17	<	72.3	166	3.96	2.200	9.75
2022-08-18	<	83.7	215	3.41	2.34	11.2
2023-06-07	<	94	230	6.0	4.1	23
2023-06-07	0.6	95	240	6.1	4.3	23
2023-07-17	<	120	490	12	5.5	30
2023-08-22	<	110	290	8.6	3.7	19
2023-10-02	<	97	300	6.5	2.4	15
2023-11-29	<	100	180	4.8	3.3	11

MW3 (5.8 - 8.8 m bgs) (4.3 m downgradient of injection points)

Date / Parameter	PCE	TCE	C12DCE	T12DCE	11DCE	VC
2019-11-28	<	28	69	0.94	0.75	1.50
2020-11-11	<	42	85	1.40	0.97	2.00
2022-05-17	<	8.54	53.8	0.98	0.51	1.84
2022-08-18	<	31	80.6	1.48	0.97	2.91
2023-06-07	<	1.8	22	<	<	<
2023-07-17	<	1.1	40	0.9	<	2.0
2023-08-21	<	2.2	30	0.9	<	1.1
2023-10-02	<	2.0	34	0.8	<	1.5
2023-10-13	<	0.96	27	<	<	1.3
2023-11-29	<	2.5	20	<	<	<

MW19-02 (5.9 - 9.0 bgs) (5.2 m downgradient of injection points)

Date / Parameter	PCE	TCE	C12DCE	T12DCE	11DCE	VC
2019-12-20	<	8.20	66	0.72	0.63	1.90
2020-11-11	<	29	88	1.40	0.98	2.30
2022-05-17	<	12.5	48.3	0.90	<	1.30
2022-08-18	<	5.91	37.4	<	<	1.63
2023-06-08	<	0.5	23	<	<	4.5
2023-07-17	<	2.2	100	3.2	<	6.1
2023-08-22	<	1.4	66	2.2	<	4.1
2023-10-02	<	2.6	100	2.1	0.8	5.4
2023-11-29	<	0.8	46	8.0	0.6	2.1

MW19-01 (6.0 - 9.0 m bgs) (10.8 m downgradient of injection points)

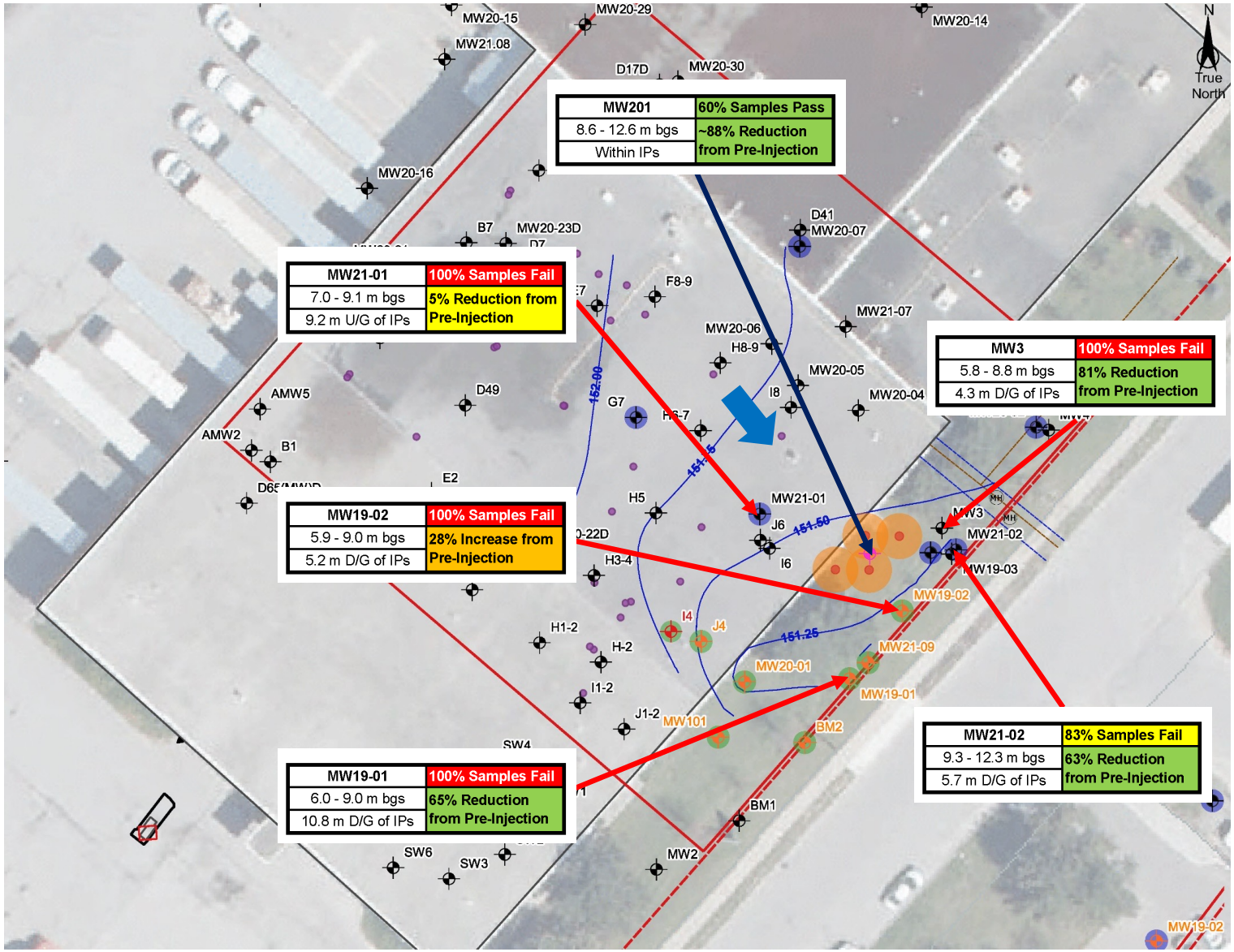
Date / Parameter	PCE	TCE	C12DCE	T12DCE	11DCE	VC
2019-12-20	<	30	60	0.91	1.30	2.70
2020-04-21	<	29	70	1.10	1.00	1.90
2020-11-12	<	26	83	1.30	0.90	2.00
2023-06-08	<	0.8	23	<	<	3.6
2023-07-17	<	<	40	1.4	<	5.2
2023-07-17	<	<	43	1.2	<	5.2
2023-08-22	<	0.7	31	1.1	<	3.2
2023-10-02	0.6	0.7	59	0.8	<	4.5
2023-10-13	<	0.71	49	<	0.32	4.1
2023-11-29	<	0.8	27	0.5	<	2.1
2023-11-29	<	0.9	35	0.6	<	2.6

MW21-02 (9.3 - 12.3 m bgs) (5.7 m downgradient of injection points)

Date / Parameter	PCE	TCE	C12DCE	T12DCE	11DCE	VC
2021-09-09	<	42	78	1.30	1.00	2.30
2021-09-09	<	39	75	1.20	0.96	2.30
2022-05-17	<	24	52.3	1.06	0.69	1.72
2022-08-18	<	17.3	43.1	0.63	<	1.03
2023-06-08	<	0.7	12	<	<	<
2023-07-17	<	8.6	53	1.3	<	2.4
2023-08-22	<	5.3	24	0.8	<	1.0
2023-10-02	<	8.4	41	1.0	<	1.6
2023-10-02	<	6.9	37	0.8	<	1.4
2023-10-13	<	5.10	37	<	0.32	1.5
2023-11-29	<	2.7	20	<	<	<

Blue sampling date = Pass
Red sampling date = Fail

Parameter	Criteria (ppb)
PCE	17
TCE	17
C12DCE	17
T12DCE	17
11DCE	17
VC	1.7



Post-Injection Groundwater Monitoring Results:

- Following the pilot-scale injection activities **significant reductions in cVOCs observed at MW201 and good reductions in cVOCs observed at most other downgradient locations**

Refined CSM

Refined CSM

Initial Geology/Hydrogeology:

- Native silty clay (to ~6.1 – 7.6 m bgs) over weathered / fractured shale, which becomes more competent below 11.0 – 11.9 m bgs
- Groundwater table at depths of approx. 7.0 – 7.9 m bgs
- K values range from $1.2x10^{-6}$ to $3.7x10^{-8}$ m/s in shallow unit, though highly variable across the Site
- Linear groundwater flow velocities estimated to range from 11 – 160 m/year across the site, depending on assumed bedrock porosity

Refined Geology/Hydrogeology:

- Native silty clay (to ~5.5 – 6.1 m bgs) over weathered / fractured shale, which becomes more competent below 11.1 m bgs
  - Significant fracture and flow zones in the bedrock are located from approx. 6.2 – 8.1 m bgs
- Groundwater table at depths of approx. 6.0 – 7.8 m bgs
- Groundwater flow velocity estimated at perhaps less than ~6.1 m/yr
- Sorbed mass of cVOCs in soil above groundwater table as well as heavier molecular weight cVOCs in bedrock below the groundwater table

Refined CSM

Initial Remedial Injection Design:

- Target southeast portion of the site where cVOC plume in bedrock groundwater is leaving the property
- Target bedrock groundwater over depth interval of approx. 7.9 – 12.0 m bgs
- Two off-set rows of injection points on an approx. 4.6 m spacing
- Inject a 9% wt./wt. slurry of BOS 100® at a rate of approx. 650 L/m

Therefore, the initial PRB design would have failed due to missing the upper bedrock groundwater zone!

Refined Remedial Injection Design:

- Target southeast portion of the site where cVOC plume in bedrock groundwater is leaving the property
- Target bedrock groundwater over depth interval of approx. 5.8 – 11.1 m bgs (i.e., shallower but thicker)
- Two off-set rows of injection points on an approx. 6.1 m spacing (i.e., wider so less drilling costs for 10 vs 14 IPs)
- Inject a 9% wt./wt. slurry of BOS 100® at a rate of approx. 1,050 L/m
- Cumulative changes results in increased BOS 100® loading of approx. 33% for the PRB

Lessons Learned

Lessons Learned

- Contaminated bedrock sites are complicated – especially when needing to remediate via injection approaches
- **Bedrock coring and downhole geophysics are crucial** in identifying significant fracture and flow zones in the bedrock to be targeted by remedial injections
- RDC sampling and analysis can assist in **identifying sorbed contaminant mass** in the soil and/or bedrock matrix that **can back diffuse over time** and increase loading on remedial amendments
- **Pilot-scale injection testing** is used to confirm vertical injection intervals as well as assess full-scale design parameters (i.e., injection flow rates / pressures, injection ROI)
- Post-injection performance monitoring assesses effectiveness and longevity of treatment
- These additional data are then used to **develop a final remedial design** that carries a **much higher degree of certainty** in meeting performance objectives
- **Bedrock remediation requires a particulate and persistent remedial amendment** and, therefore, **Trap & Treat® BOS 100® for cVOCs is preferred**

Thank You for Your Time!

Questions?

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