Combining Micro-Scale Zero-Valent Iron and Bioremediation to Treat Chlorinated Solvent Plumes

Presenter:

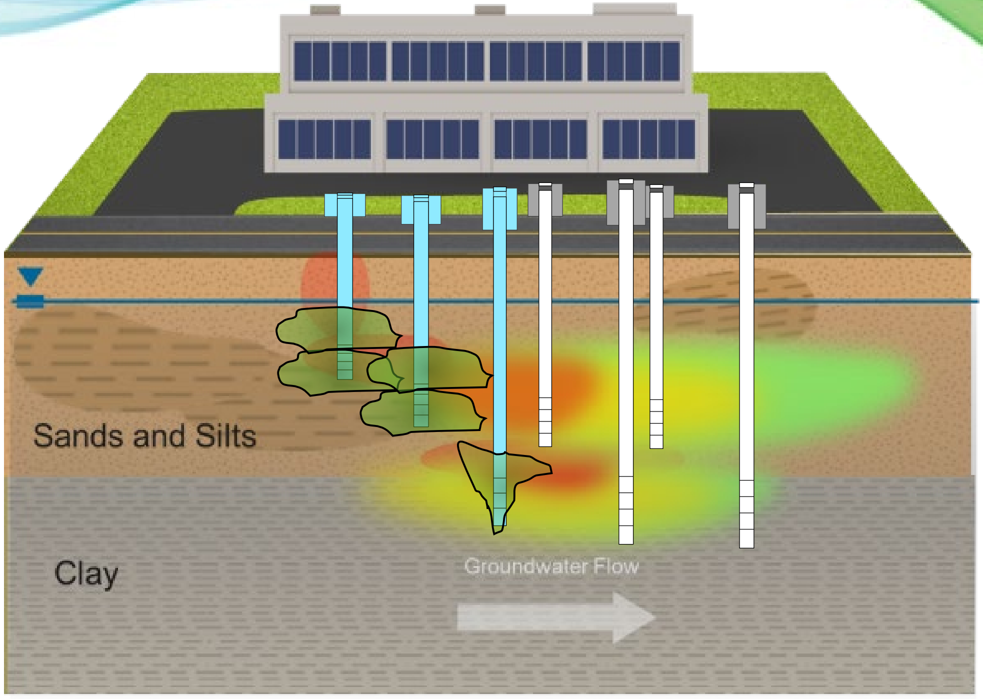
Mike Lamar, PE - CDM Smith

REMTEC & EMERGING CONTAMINANTS SUMMIT

OCTOBER 3-5, 2023

The Problem

- *In situ* remediation success is the driven by:
  - Efficient amendment delivery to the contaminated zone.
  - Amendment effectiveness and longevity
- Heterogeneity / low K zones
- Fractured bedrock
- Multiple and persistent sources affect chemical mass transfer and persistence.
  - DNAPL
  - Sorption
  - Matrix back diffusion



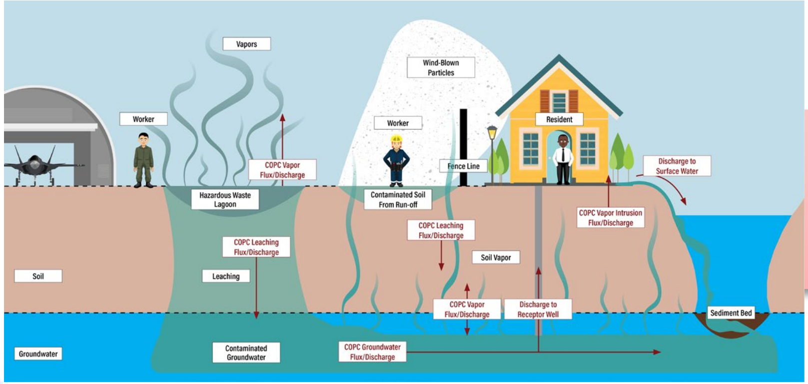
Example Case Study – image prepared using Health Canada CSM Builder Tool 2015

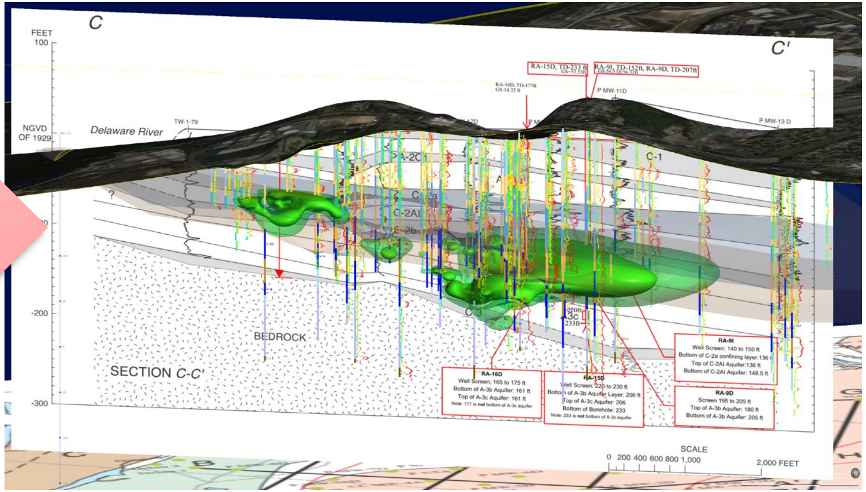
Conceptual Site Model Resolution

Develop conceptual site model at an appropriate scale to account for site heterogeneity to characterize:

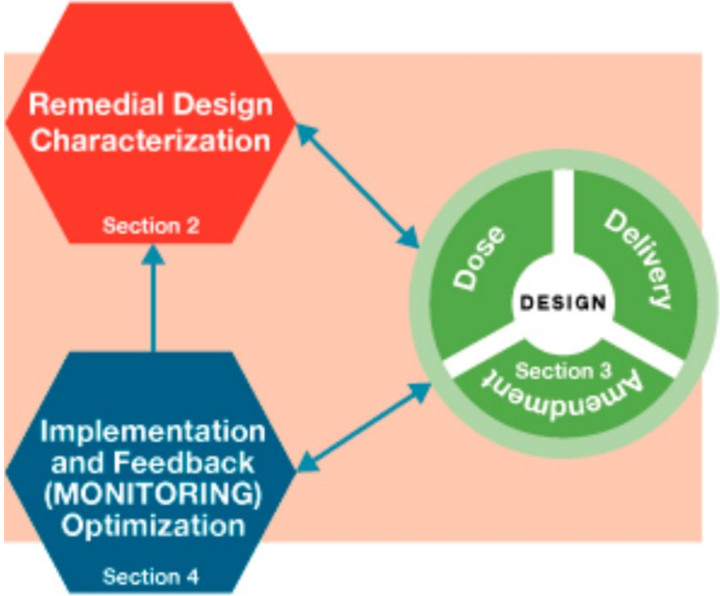
- Physical properties
- Contaminant of concern (COC) distribution
- Fate and transport

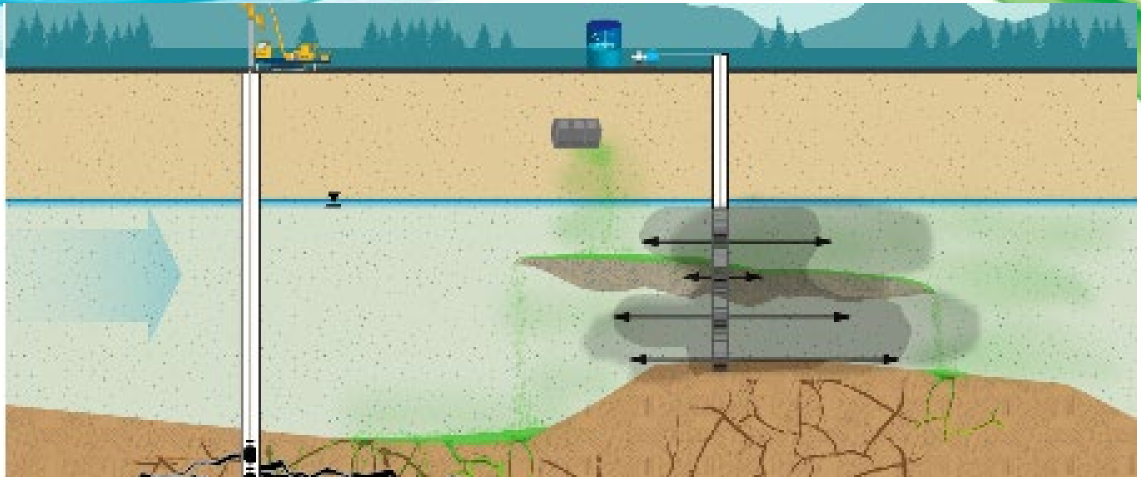
High-resolution site characterization tools collect data at much smaller scales (i.e., continuous to meter) with a greater data acquisition rate than conventional characterization tools and approaches.





How to plan injection into heterogeneous aquifers?





Optimizing Injection Strategies and In Situ Remediation Performance

Optimizing Injection Strategies and In Situ Remediation Performance (OIS-ISRP-1, 2020)

Interstate Technology and Regulatory Council (www.itrcweb.org)

SUMMIT

Delivery Strategies

"Widely used = ●", "Site-specific = ▣", and "Not applicable = NA"

Delivery Technique / Hydrogeologic Characteristics Unified Soil Classification System	Direct Push Injection (DPI) [D1]	Injection Through Wells & Boreholes [D2]	Electrokinetics This is injection through wells. [D3]	Solid Injection [D4]: Hydraulic Delivery Through Wells & Boreholes [D5]	Solid Injection [D4]: Pneumatic Delivery Through Open Boreholes [D6]	Permeable Reactive Barriers (PRBs) [D7]
Gravels	● (Sonic)	●	NA	NA	NA	●
Cobbles	● (Sonic)	●	NA	NA	NA	●
Sandy Soils (Sm, Sc, Sp, Sw)	●	●	NA	▣	▣	●
Silty Soils (Ml, Mh)	●	▣	●	●	●	●
Clayey Soils (Cl, Ch, Oh)	●	▣	●	●	●	●
Weathered Bedrock	●	●	▣	●	●	▣
Competent/Fractured Bedrock	NA	●	NA	▣	▣	▣
K ≤ 10^{-3} to 10^{-4} (Low Perm Soils)	●	▣	●	●	●	●
K ≥ 10^{-3} (High Perm Soils)	●	●	▣	▣	▣	●
Depth > Direct Push Capabilities	NA	●	▣	▣	▣	▣

ITRC OIS-ISRP-1 Table 3-4

Determine *In Situ* Delivery Mechanism

Injection Wells	Direct Push Injection	Fracturing
Re-usable Simple to implement Limited to low viscosity / particle size amendments Limits ability to adapt Well maintenance / fouling	Single event Some specialization Vertically targeted Limited to aqueous amendments Limited to certain lithology types	Single event Highly specialized Vertically targeted Allows wide range of amendments Performed with DPT or in boreholes (via packers)

Next Step: Add Amendments (Reductive Treatments)

In Situ Bioremediation	In Situ Chemical Reduction	Adsorption
⑩ Soluble amendments (lactate, molasses) ⑩ Insoluble amendments (vegetable oils) ⑩ Solids	⑩ Zero-valent iron ⑩ Micro-scale ⑩ Colloidal ⑩ Nano-scale	⑩ Activated carbon ⑩ Colloidal ⑩ GAC ⑩ PAC

- Note: Amendment and delivery methods likely inter-related

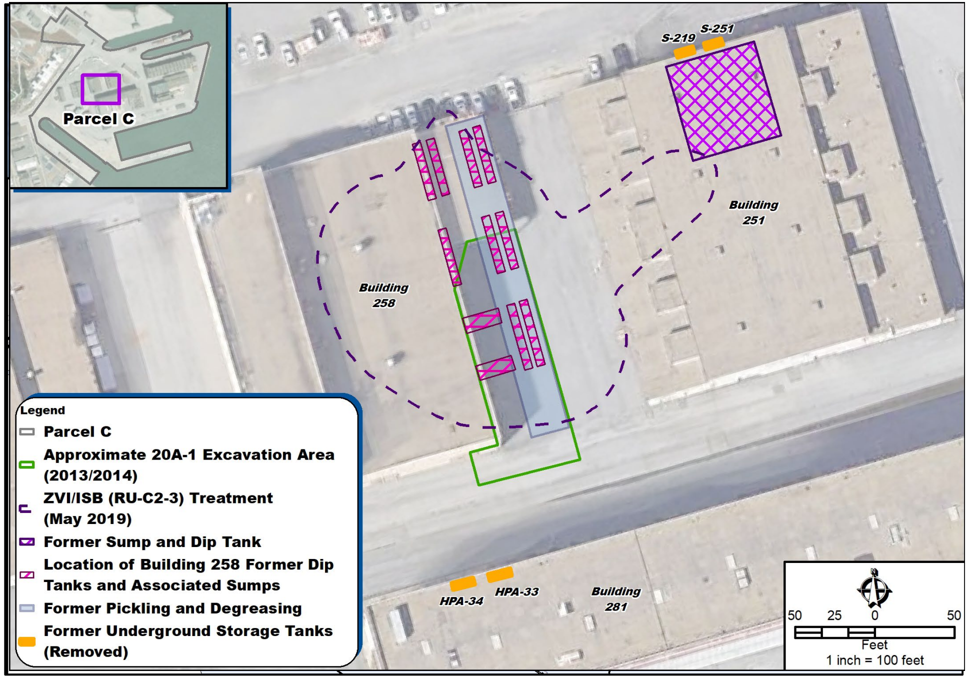
Two Case Studies

- **Site #1** – Combined micro-scale ZVI and EVO Injection via Fracturing in Low Permeability Aquifer
- **Site #2** - Biorecirculation using ZVI Amended Wells in Fractured Bedrock

CASE STUDY 1
Hunters Point Naval Shipyard
San Francisco, CA

Background

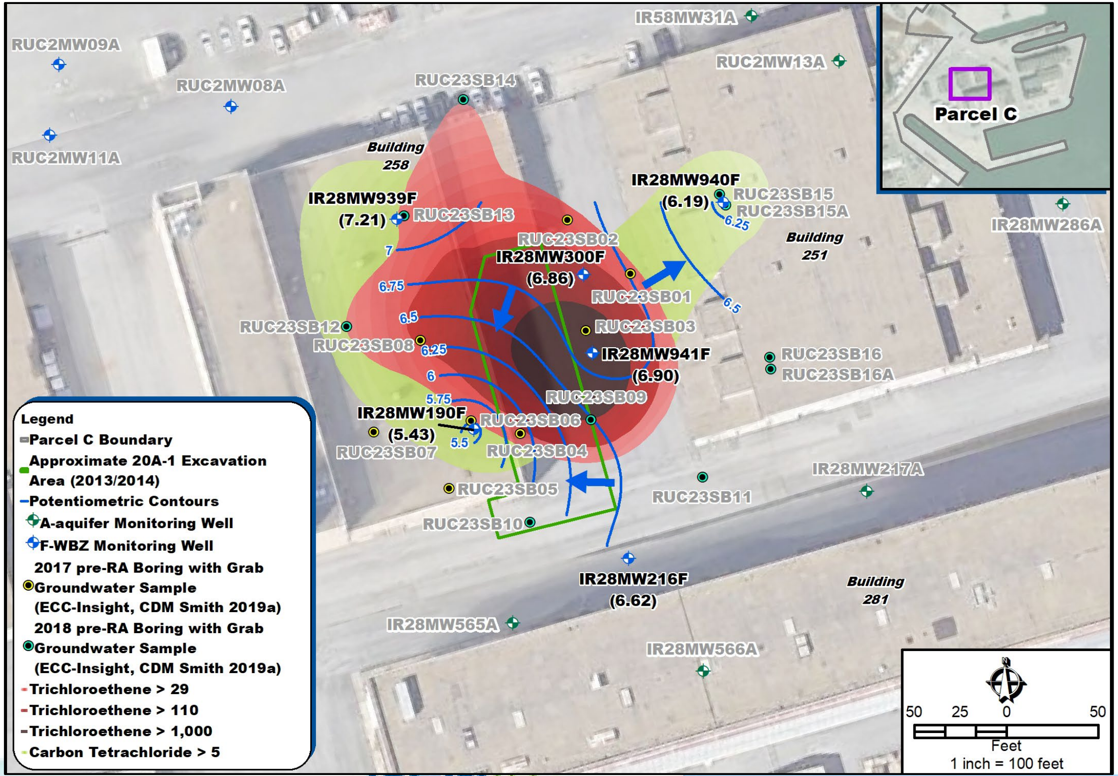
- Hunters Point Naval Shipyard San Francisco, CA
- Building 258
  - Pipe manufacturing
  - Pickling and degreasing
- BRAC site – cleanup to transfer property to City of San Francisco for redevelopment
- Contaminants
  - Trichloroethene (TCE) and daughters
  - Carbon tetrachloride (CT) and daughters
  - Other (e.g., trichlorofluoromethane [TCFM])
- Adaptive, multi-component treatment strategy
  - In situ chemical reduction (ISCR)
  - In situ bioremediation (ISB)



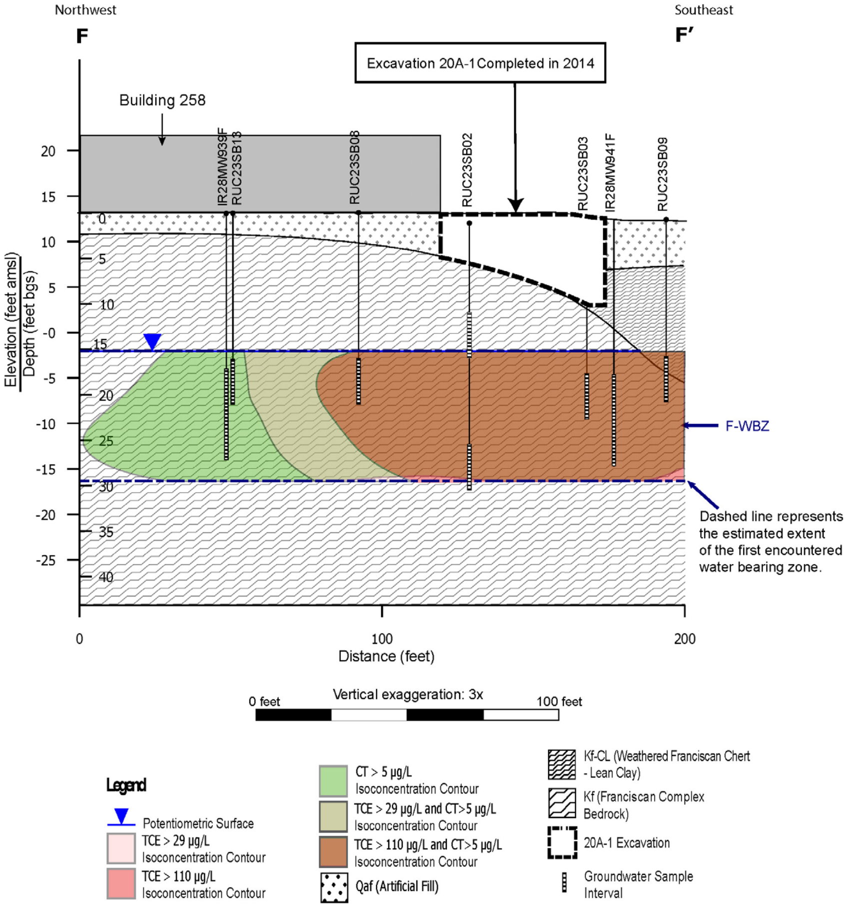
REMTEC & EMERGING CONTAMINANTS SUMMIT OCTOBER 3-5, 2023

Nature and Extent of COCs

COC	Concentration Range (µg/L)
TCE	30 – 7,800
CT	10 – 140
TCFM	0.26 J – 850



Geology and Hydrogeology



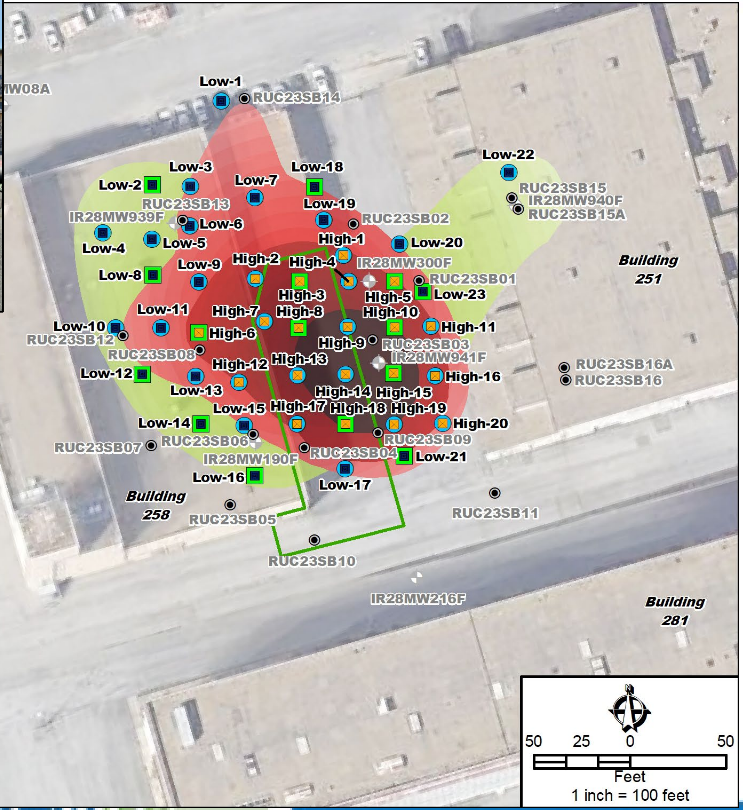
- Artificial fill
- Franciscan complex bedrock
- Complex weathered and fractured water-bearing zone
  - ~12-29 feet below ground surface

REMTEC & EMERGING CONTAMINANTS SUMMIT

OCTOBER 3-5, 2023

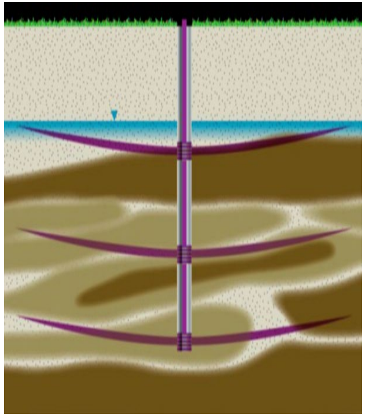
Adaptive Remedial Design

- 44 locations with 5 injection intervals
- High dose
  - TCE > 110 µg/L
  - 0.004 lb/lb mZVI
  - 25 feet radius
- Low dose
  - 29 < TCE < 110, or CT >5
  - 0.0025 lb/lb mZVI
  - 30 feet radius
- Emulsified vegetable oil (EVO): 2.5% in slurry
- Bioaugmentation cultures (50% locations)



ZVI / EVO Slurry Injection

- Sonic-drilled boreholes
- Use fluid (hydraulic) pumped under pressure (150-300 psi) to a soil/rock until failure i.e., injecting) occurs
- Amendment delivery to low permeability and rock matrices
- Solid (mZVI) and liquid (EVO) amendments
- Straddle packer focuses vertical interval



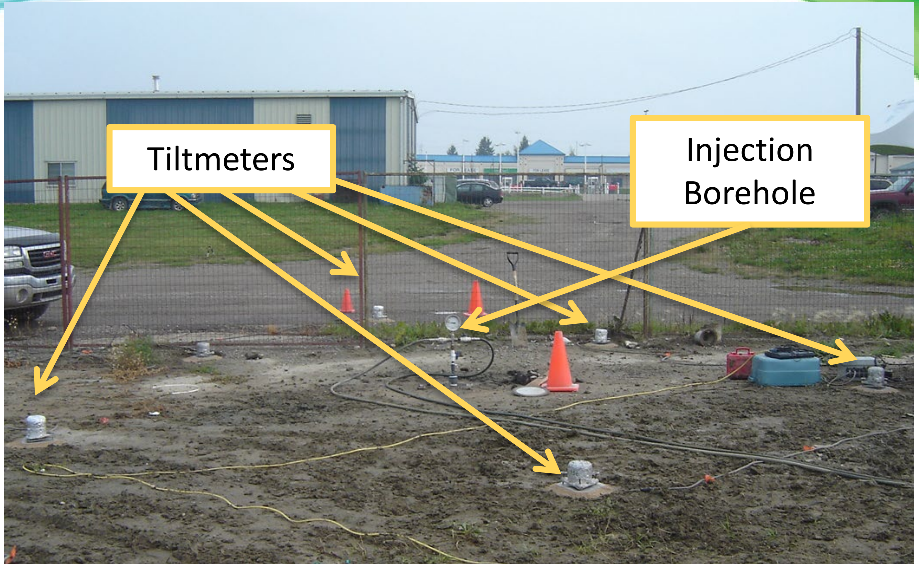
REMTEC & EMERGING CONTAMINANTS SUMMIT

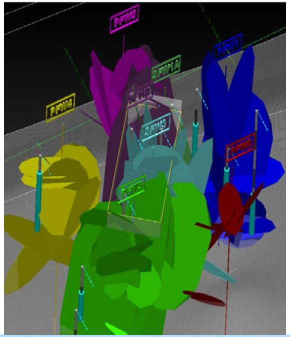
OCTOBER 3-5, 2023

Tiltmeter Geophysics

Tiltmeters Provide Estimate of:

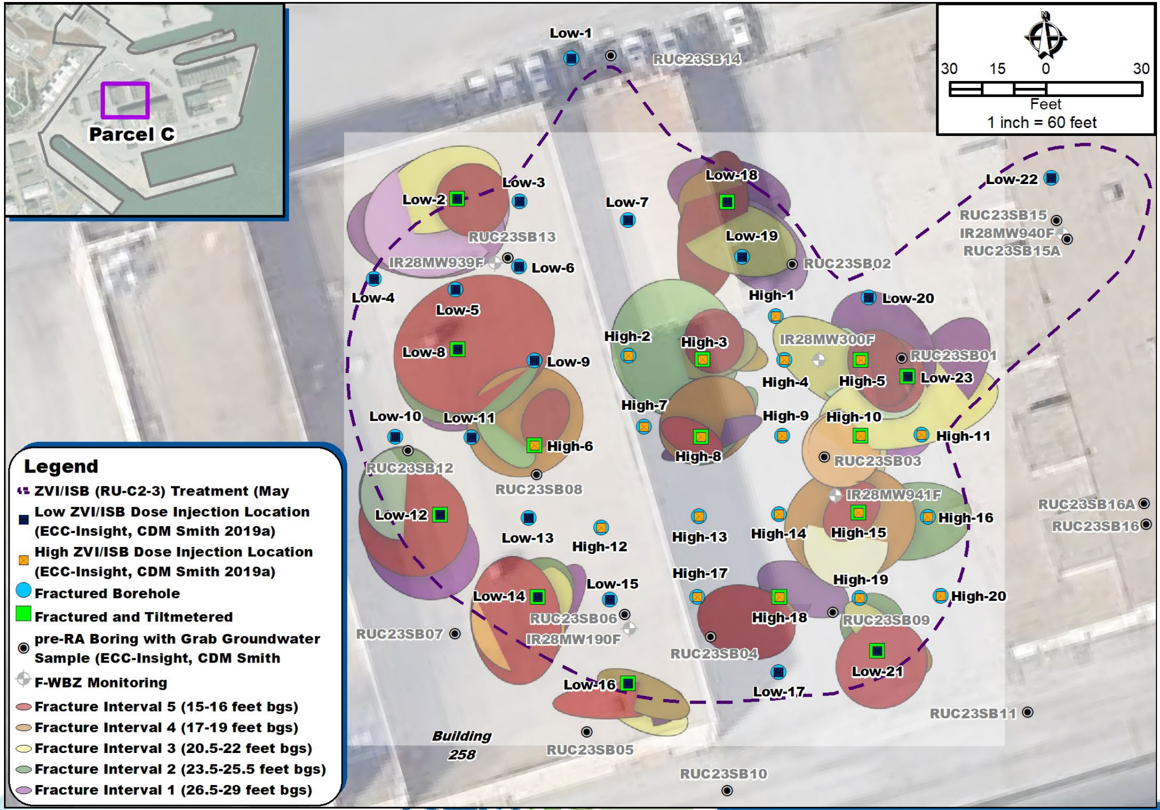
- Injection extent
- How distribution is centered to borehole
- How openings propagate





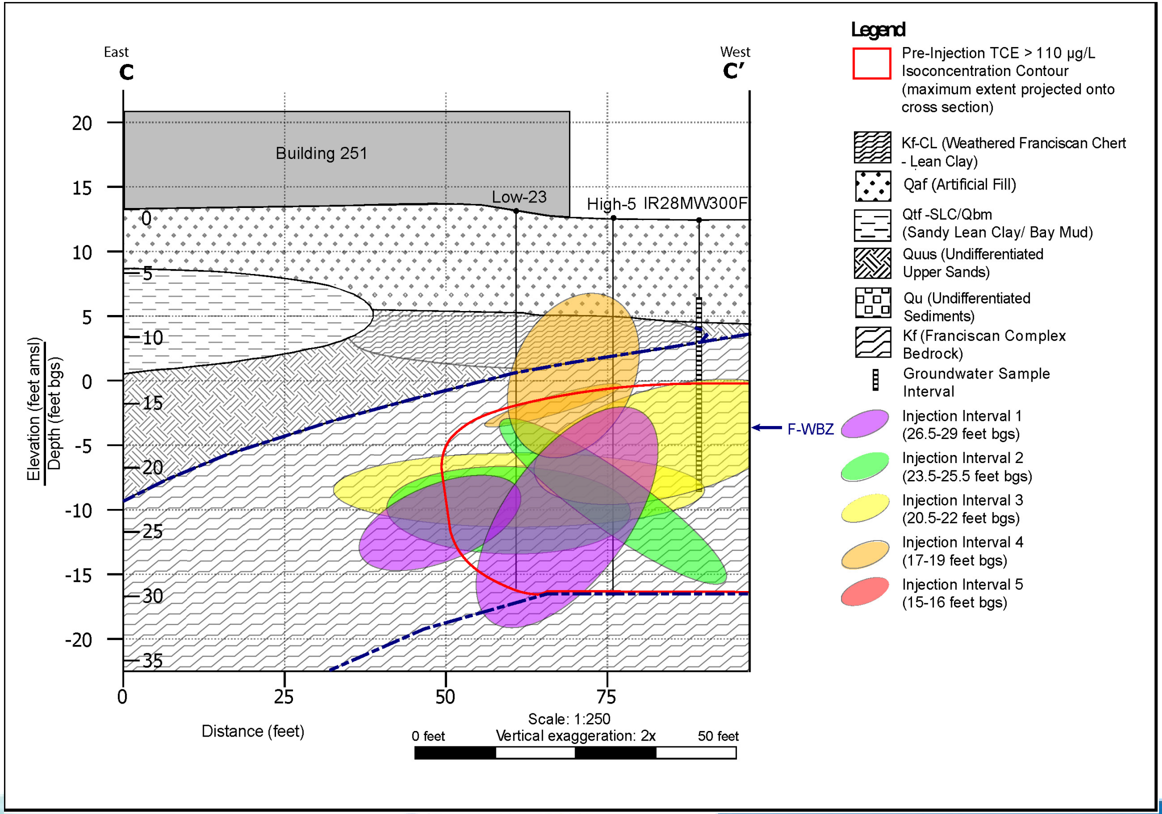
Amendment Distribution: Tiltmeter Data

- Tiltmetered locations
- Plan view representation
- Averages used to model other locations

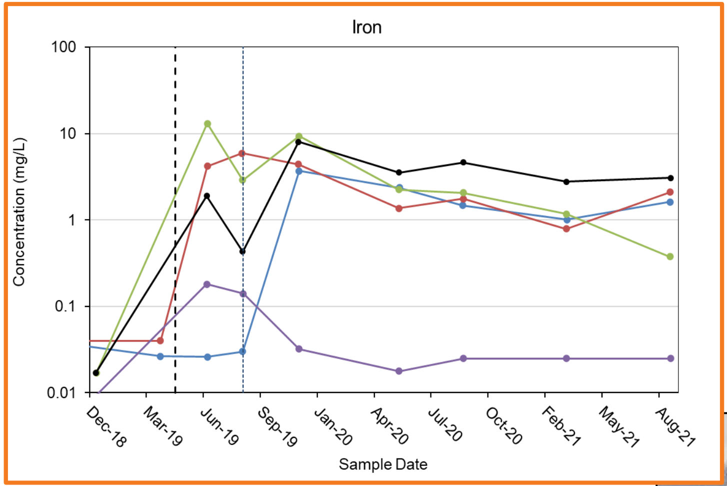


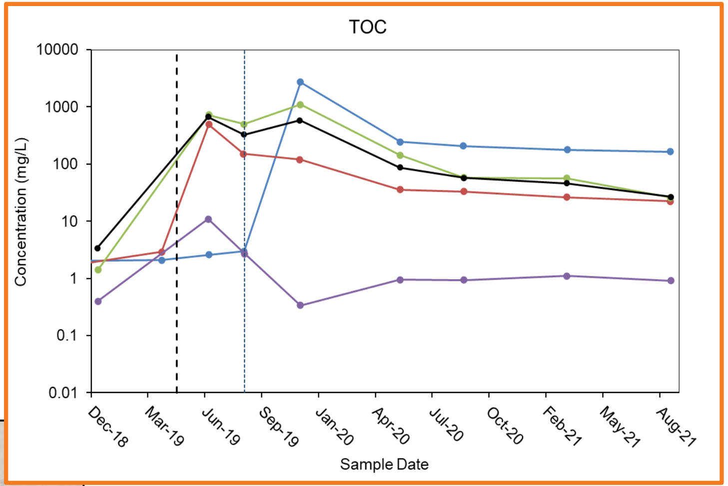
Amendment Distribution: Tiltmeter Data

- Example cross section
- 2 tiltmeter locations
- 5 vertical injection intervals

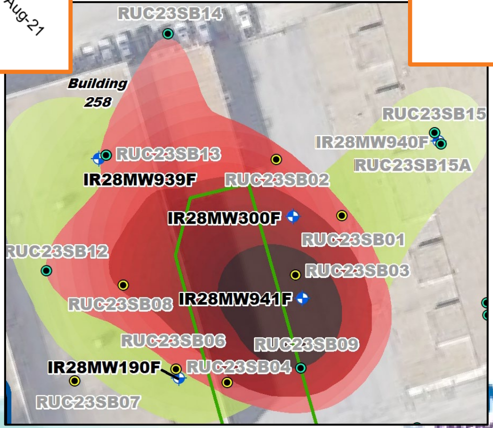


Amendment Delivery: Iron, TOC

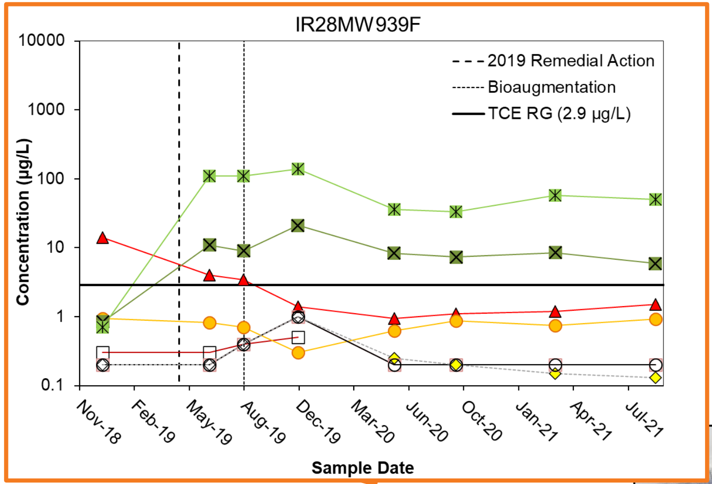


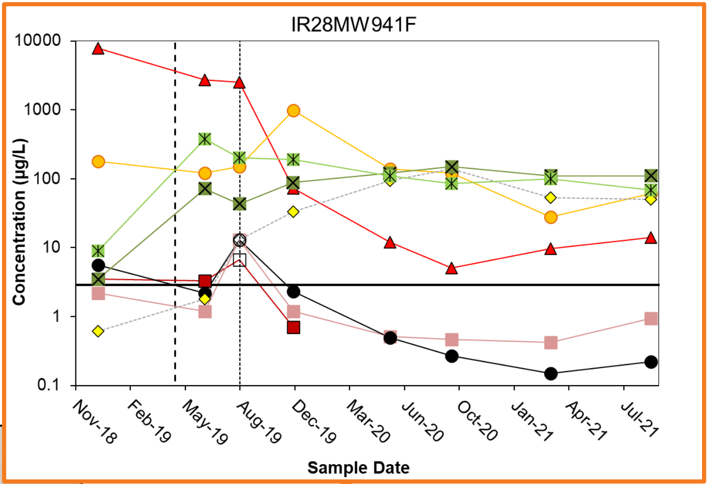


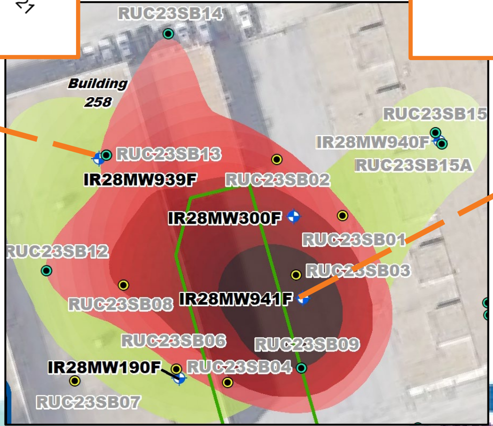
IR28MW190F
IR28MW300F
IR28MW939F
IR28MW940F
IR28MW941F
2019 Remedial Action
Bioaugmentation



Performance Monitoring: Chlorinated Ethenes





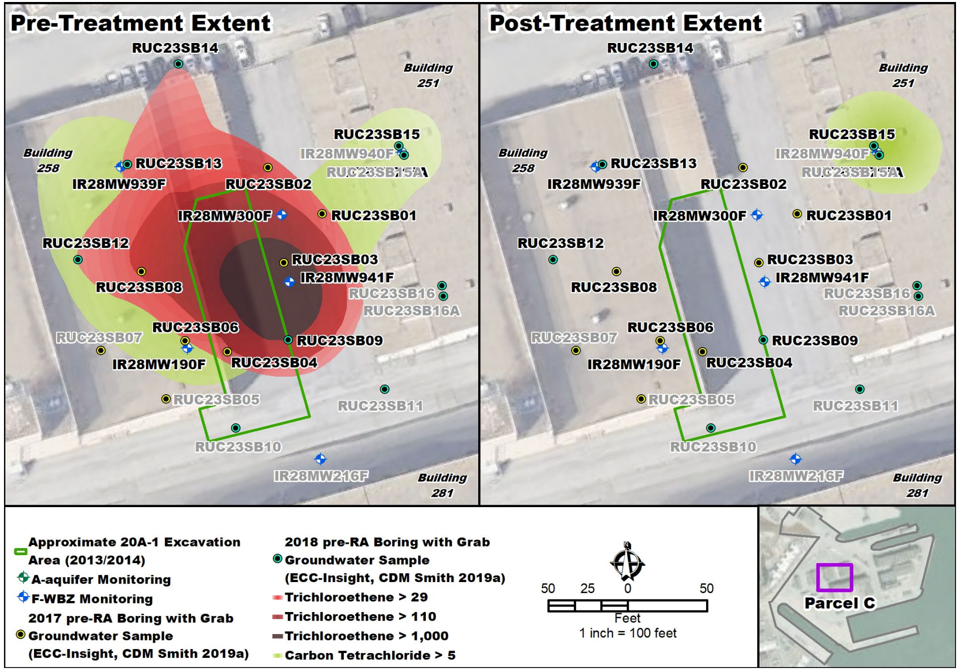


PCE
TCE
trans-1,2-DCE
cis-1,2-DCE
1,1-DCE
Vinyl Chloride
Ethene
Ethane

2019 Remedial Action
Bioaugmentation
TCE RG (2.9 µg/L)

RA Performance Assessment

- Successful amendment emplacement via slurry injections
  - Tiltmetering
  - TOC, Iron
- Successful treatment of COCs to below RGs*
  - Order of magnitude reductions in COCs
  - Anaerobic, reducing geochemistry
  - Microbial populations boosted
  - *IR28MW940F may need additional treatment; IR28MW941F still decreasing



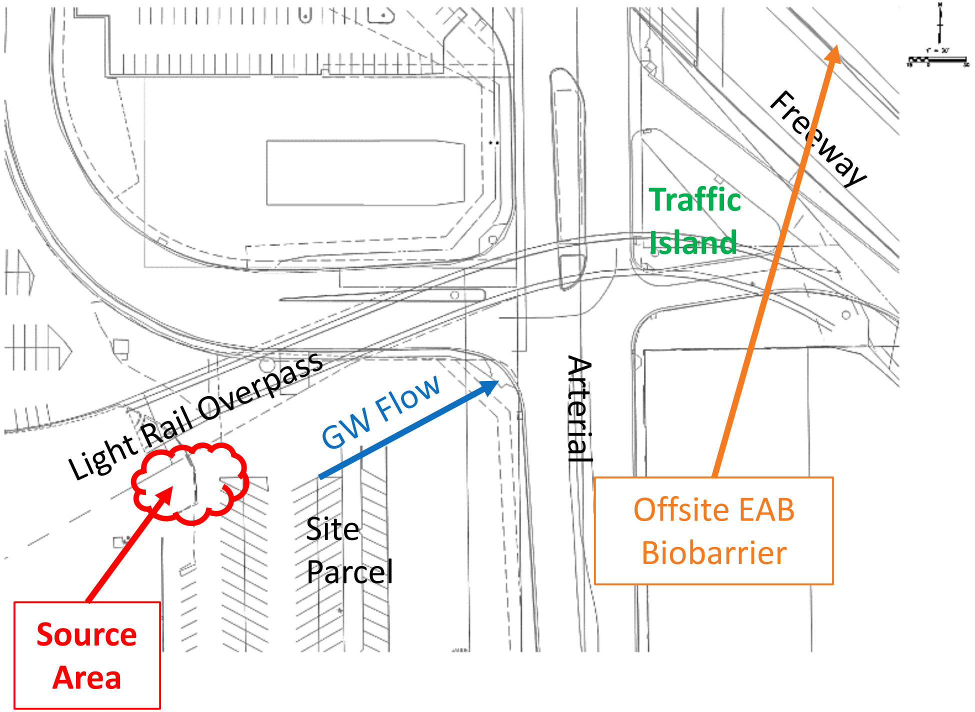
Lessons Learned

- Adaptive approach critical to success
- Potential challenges
  - Amendment surfacing
  - Destabilized boreholes
  - ZVI clogging
  - Packer damage (bedrock)
- Open boreholes not ideal for unconsolidated material

CASE STUDY #2
Biorecirculation with ZVI-Fractured Wells
Confidential Site
Denver, Colorado

Site Overview

- Former industrial site
- Major infrastructure
- CVOCs (TCE) in GW follow paleochannel to northeast
- Mobile DNAPL present onsite in bedrock wells
- Historical injections
  - Traffic island infrastructure
  - Offsite biobarrier



Site Geology

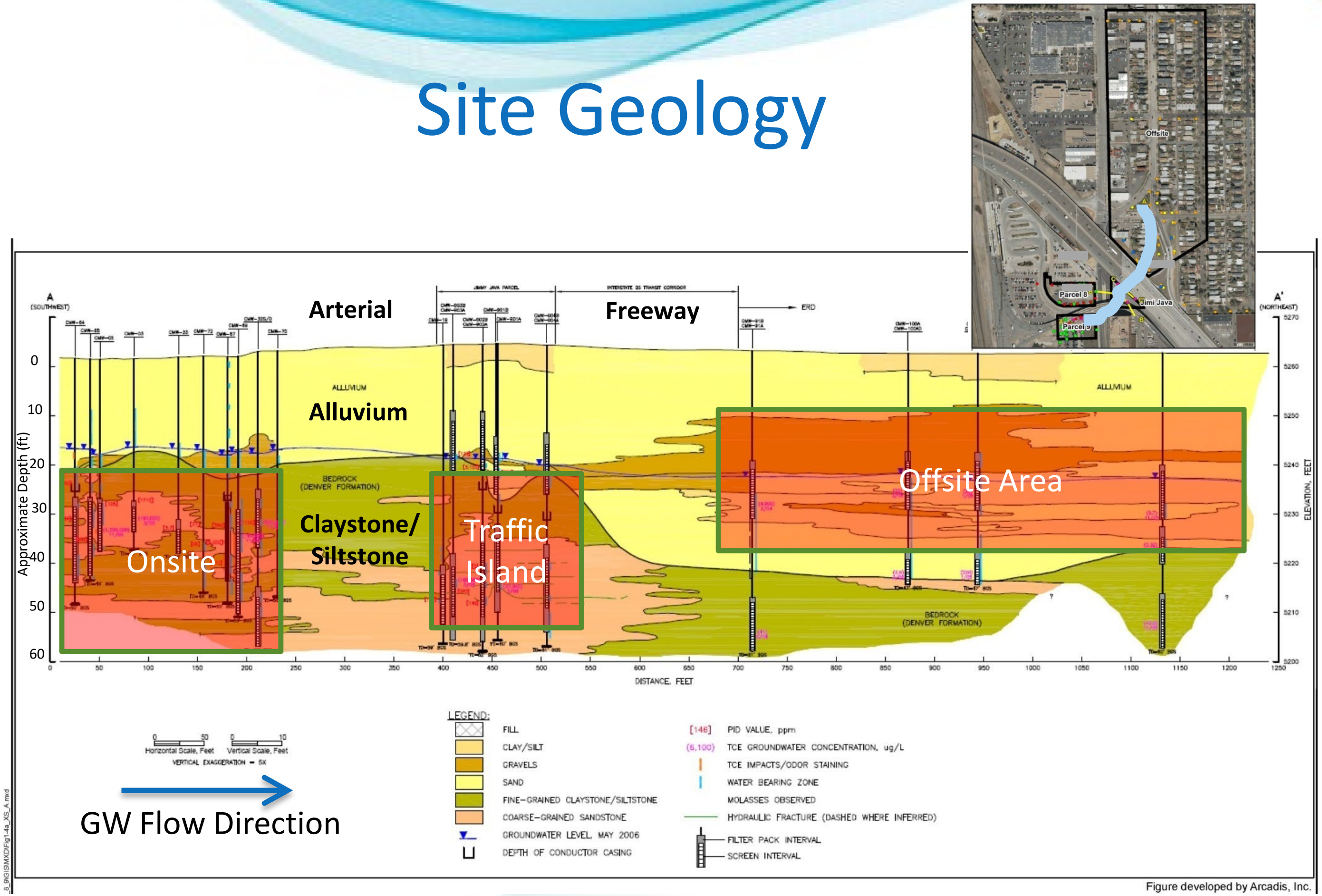
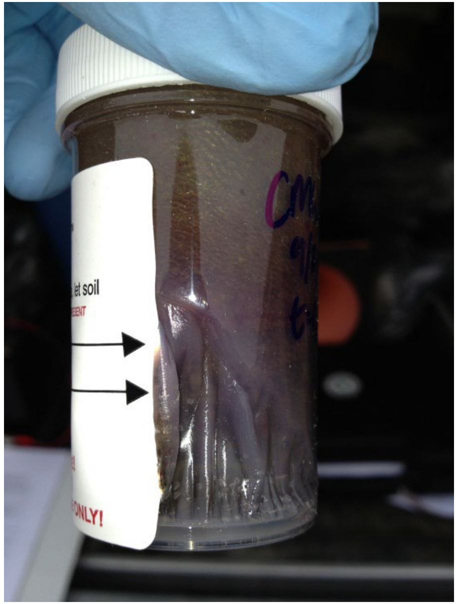


Figure developed by Arcadis, Inc.

REMTEC & EMERGING CONTAMINANTS SUMMIT
OCTOBER 3-5, 2023

Considerations and Constraints

- Existing infrastructure at traffic island
- Difficult hydrogeology / fractured bedrock
- Numerous access constraints (e.g,. streets, overpass)
- Significant VOC mass / DNAPL
- Large area (> 500 feet plume [TCE>1mg/L])
- High resolution characterization
  - FLUTe, geophysics, DNAPL delineation

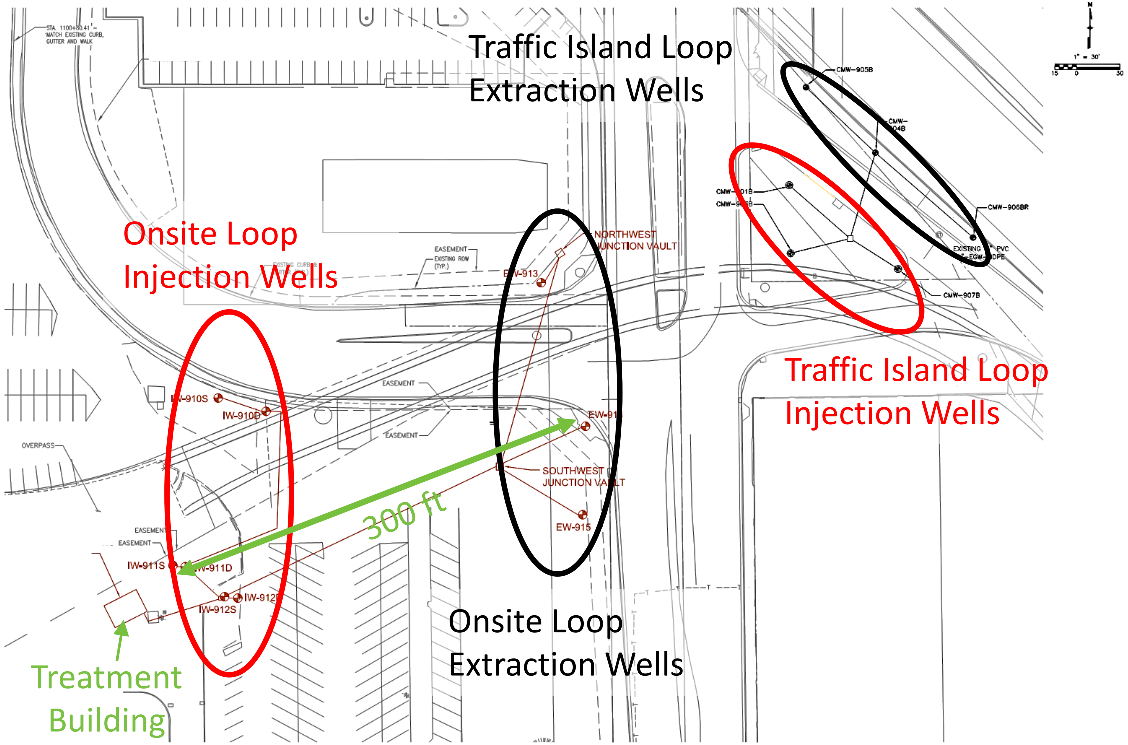


TCE-melted NAPL test kit

Remediation Approach – Two Loops

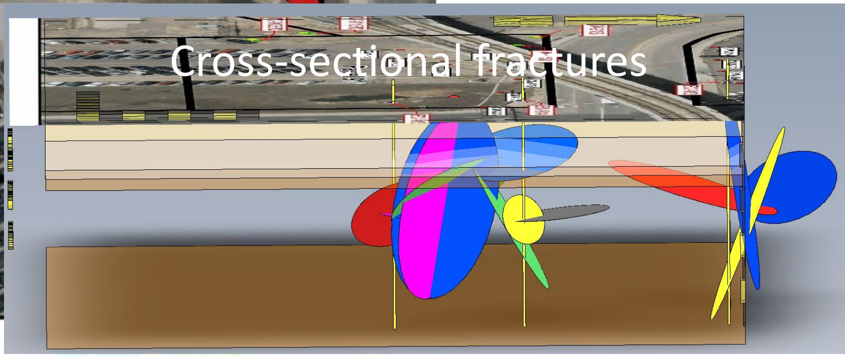
Onsite Loop

- 3 injection locations
- 3 extraction locations
- All wells fractured with
  - Micro-scale ZVI
  - Sand
- "Pulsed" amendment injections

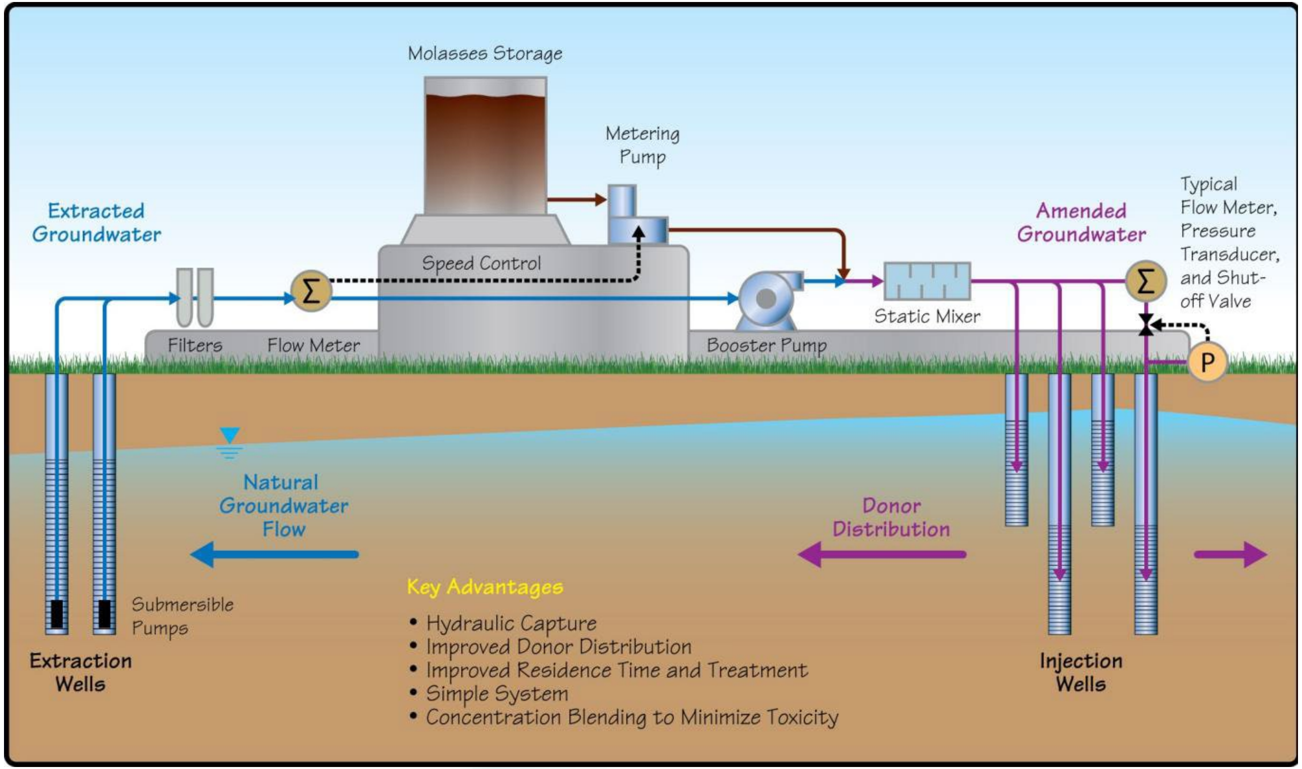


Step 1 - Environmental Fracturing

- 20 fractures (and 12 conjugate fractures) into 9 boreholes
- ~60,800 lbs of sand
- ~47,600 lbs of ZVI
- ZVI emplacement radius: 12 ft to 90 ft (40 avg)



Step 2 - Biorecirculation



Step 2 - Biorecirculation - Operational Data

ONSITE LOOP

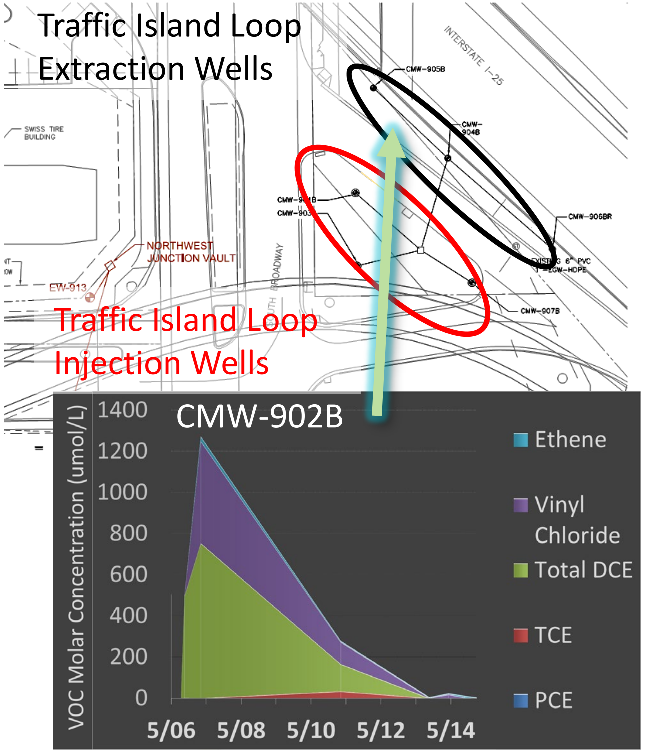
- 6 injection wells (3 shallow/deep pairs) (with ZVI)
- 3 extraction wells (with ZVI)
- 300 feet between INJ/EXT
- 63 weeks operation
- ~500,000 recirculated GW
- ~7,000 gallons amendment injected (molasses, sodium lactate)

TRAFFIC ISLAND LOOP

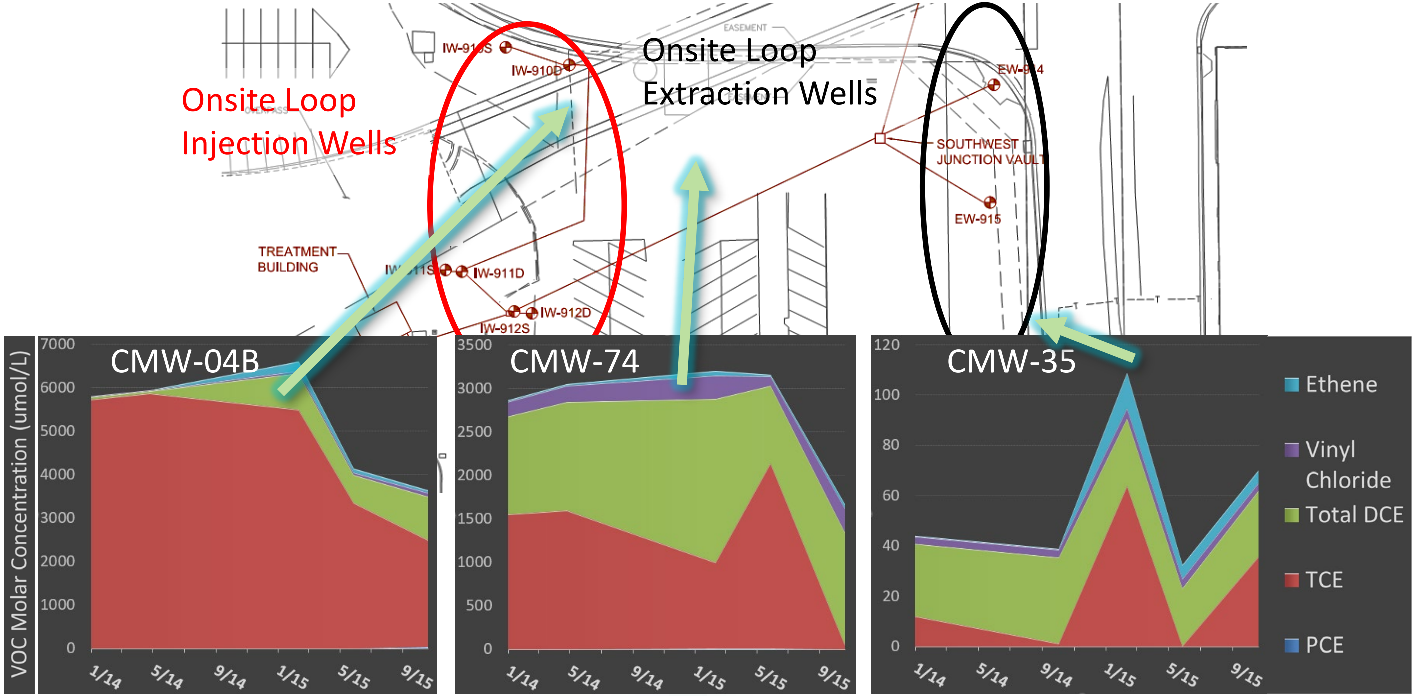
- 3 injection wells (no ZVI)
- 3 extraction wells (no ZVI)
- 50-100 feet between INJ/EXT
- 59 weeks operation
- ~600,000 recirculated GW
- ~2,000 gallons amendment injected (molasses)

Performance Data – Traffic Island Loop

- Wells fractured previously (w/o ZVI)
- Historical standard EAB injections (molasses)
- Biorecirculation operation since August 2012
- Intermittent operation
  - Based on TOC concentrations
  - Hydraulic control
- Limited monitoring network
- Complete dechlorination in all wells
- System shut off



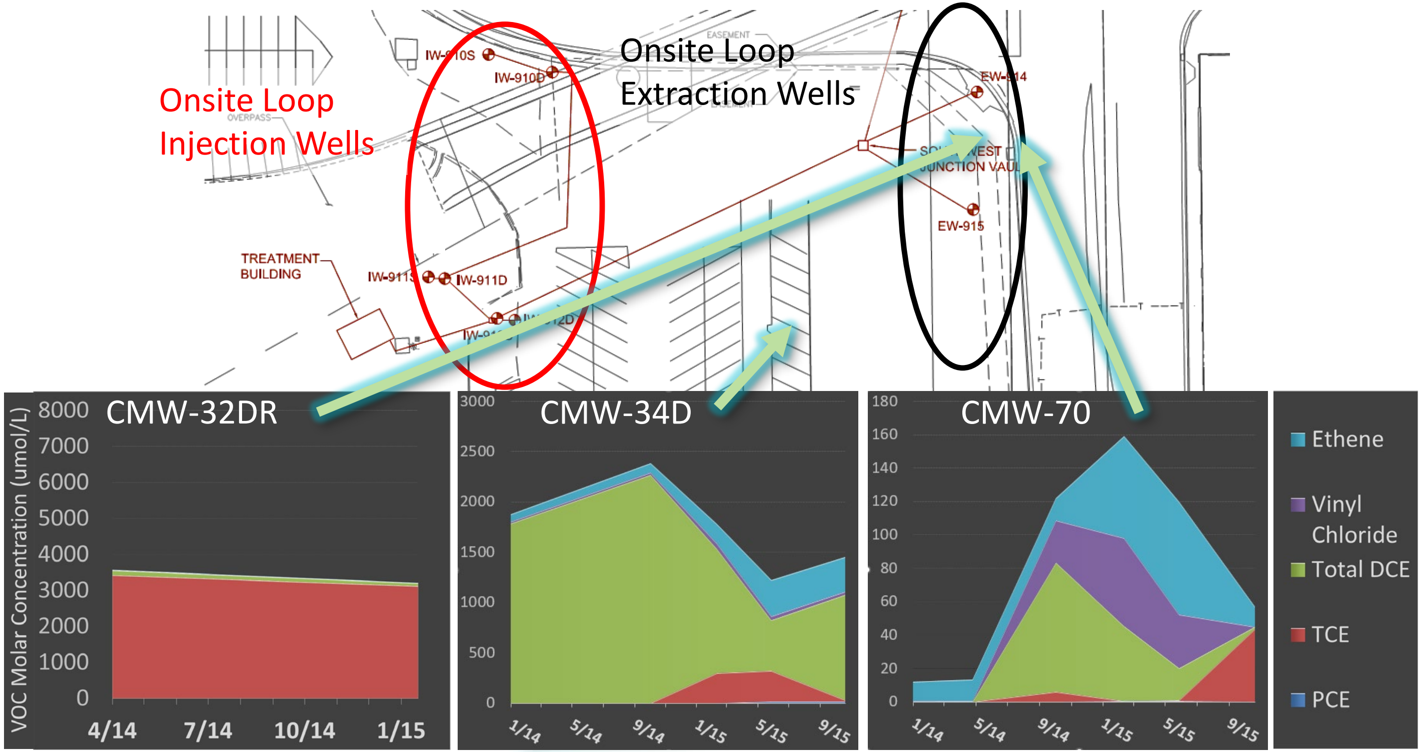
Performance Data – Onsite Loop (Shallow Bedrock)



REMTEC & EMERGING CONTAMINANTS SUMMIT

OCTOBER 3-5, 2023

Performance Data – Onsite Loop (Deep Bedrock)



Case Study #2 - Lessons Learned

- Experience in similar geology
- Environmental fracturing expertise and equipment
- Pre-design characterization
- Injection well control strategy
- Dynamic water flushing strategy
- Intermittent operation
- Adaptive management

Overall - Lessons Learned

- CSM / Pre-design characterization
- Utilize Resources to Plan
  - ITRC, AFCEC, NAVFAC, Conferences
- Utilize vendors / contractors during design
  - Two-sided discussion important
  - Get multiple perspectives
- Design for adaptability
- Do set realistic remedial goals
- Don’t overestimate technology applications

Acknowledgements

CDM Smith

- Tamzen Macbeth
- Emma Ehret
- Charles Schaefer
- Kimberly Myers
- Neil Smith
- Zoom Nguyen
- Matt Gamache
- Tom Cook
- Jeff Bamer

SERDP/ESTCP US EPA

- Rene Fuentes (Region 10)
- Kira Lynch (Region 10)
- Chris Cora (Region 10)

United States Army Corps of Engineers

- Travis Shaw
- Karl Kunas
- Maleena Lemiere
- Veronica Henzi

Lucas Hellerich, PhD, PE, LEP

Optimization of a Combined Active and Passive In Situ Remediation Approach for High Concentration Metals in Groundwater

Woodard & Curran, Inc.

Co-Authors

Ramin Ansari, Lanxess, USA

Nick Hastings, PG, LEP, Woodard & Curran

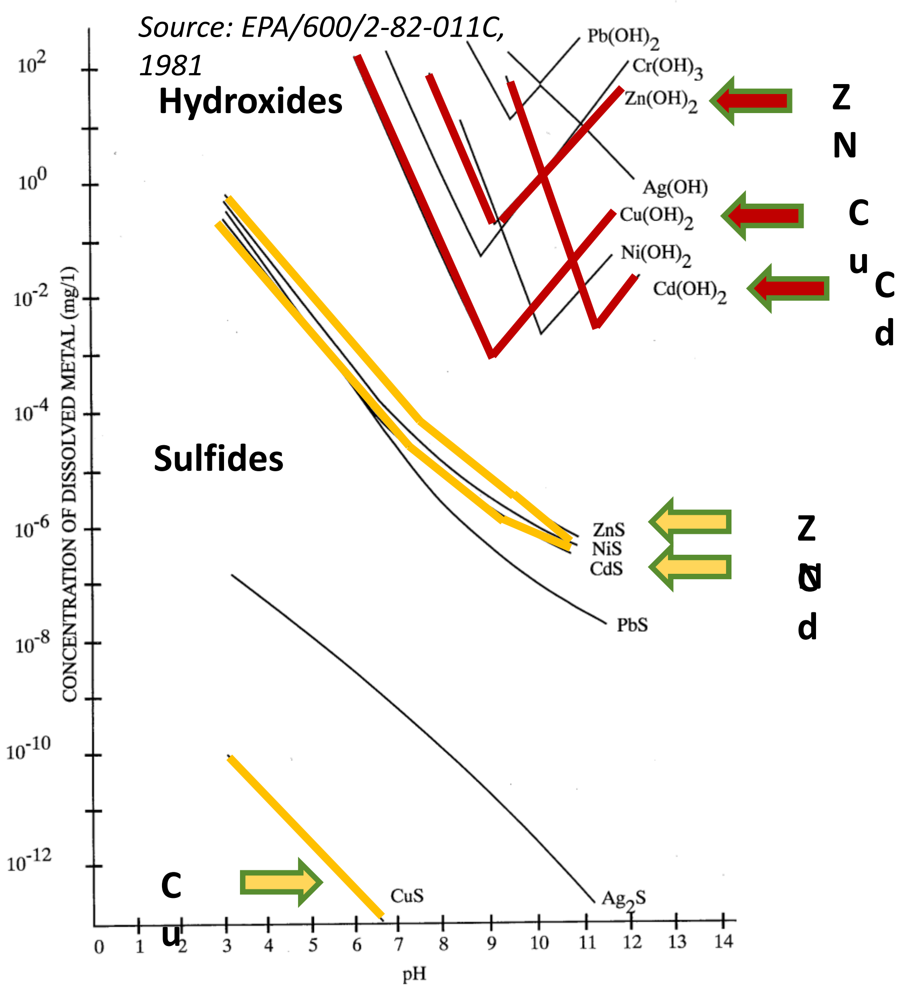
Samantha Olney, PG, Woodard & Curran

Trevor King, PE, Woodard & Curran

Dan Brockmeyer, LEP, Woodard & Curran

Forming low solubility metal precipitates can be an effective remediation strategy

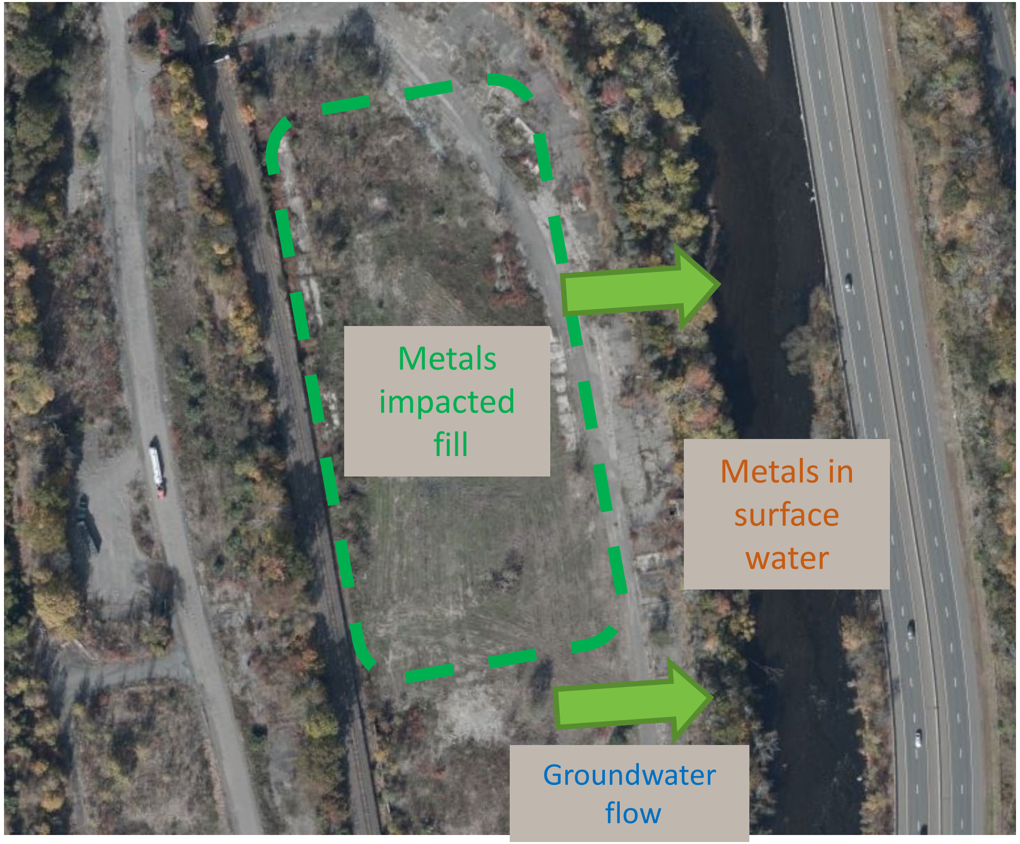
Decreasing solubility



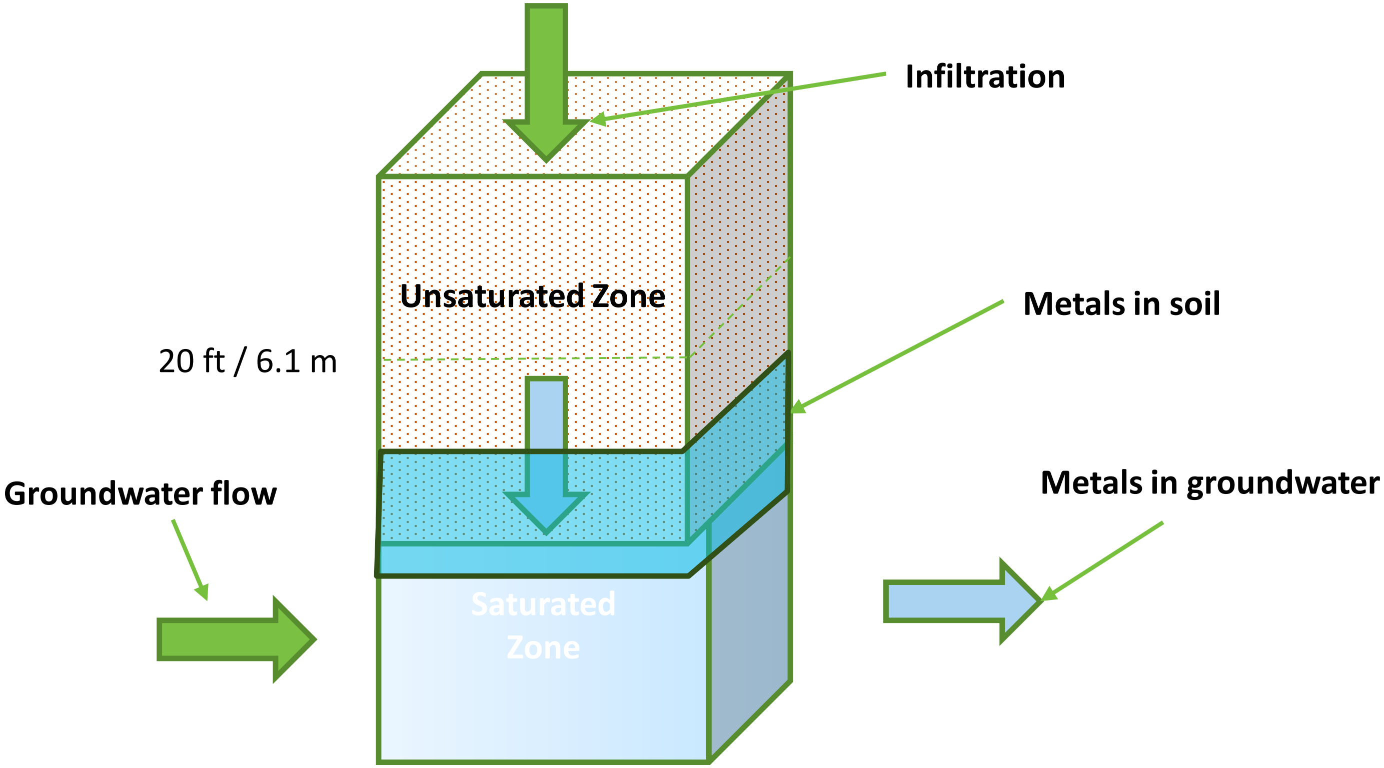
Agenda

- Conceptual site model
- Technology evaluation and selection
- Pilot test implementation and results

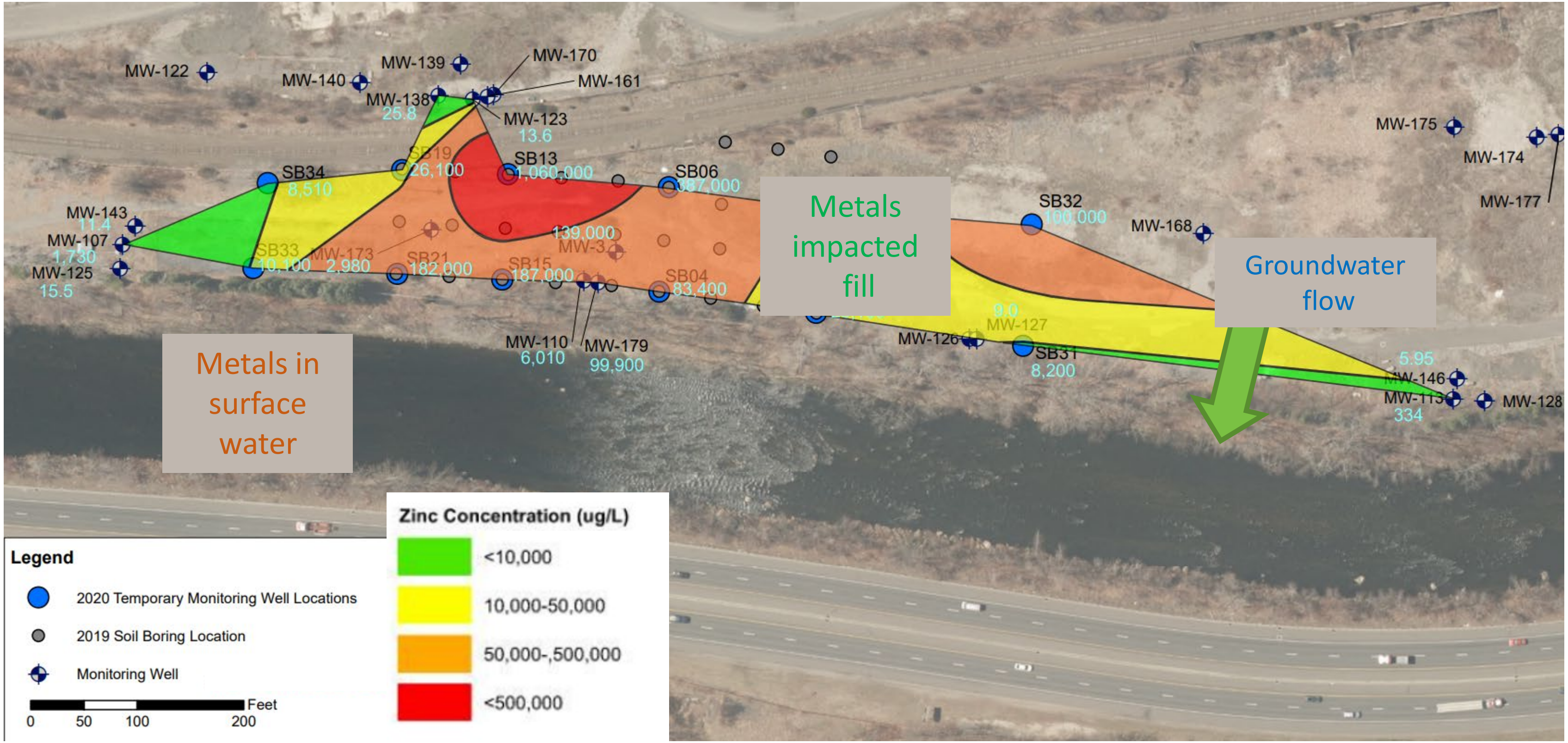
Cadmium, copper, and zinc in groundwater are discharging to surface water above criteria



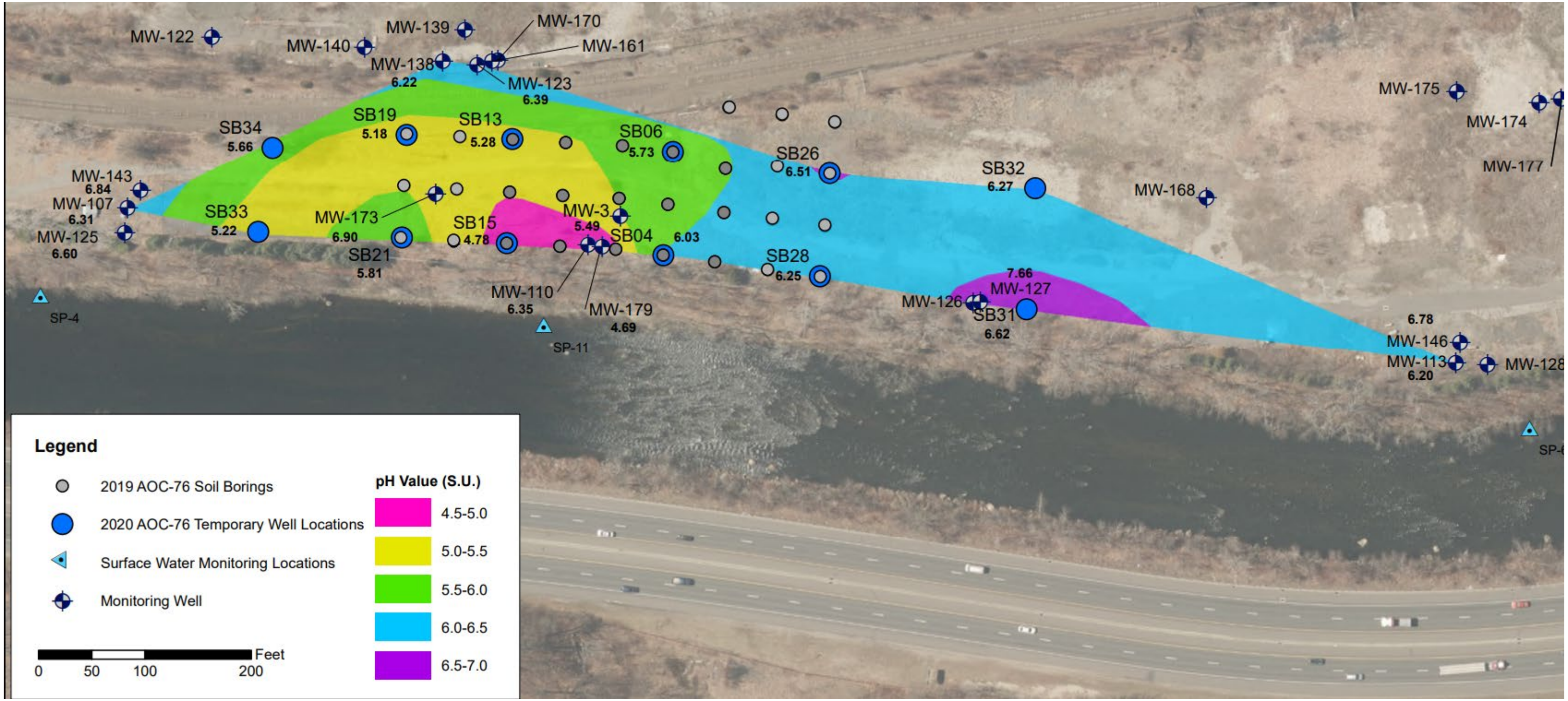
CSM for metals leaching and migration



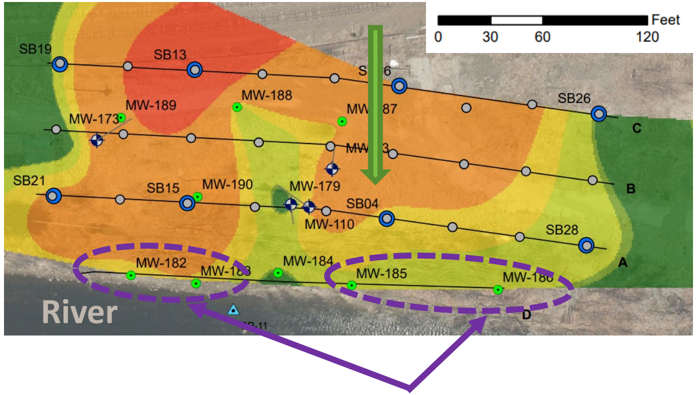
Metals solubilize in groundwater and discharge into surface water

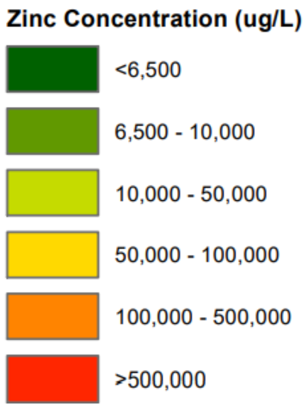


Acidic pH increases solubility of metals



Metals concentrations exceed criteria at the river by approximately 10X - 15X





Surface Water Protection Criteria (SWPC) exceedances

SWPC

Cd = 12.5 ug/L
Cu = 480 ug/L
Zn = 6,500 ug/L

Site conditions constrain remediation options

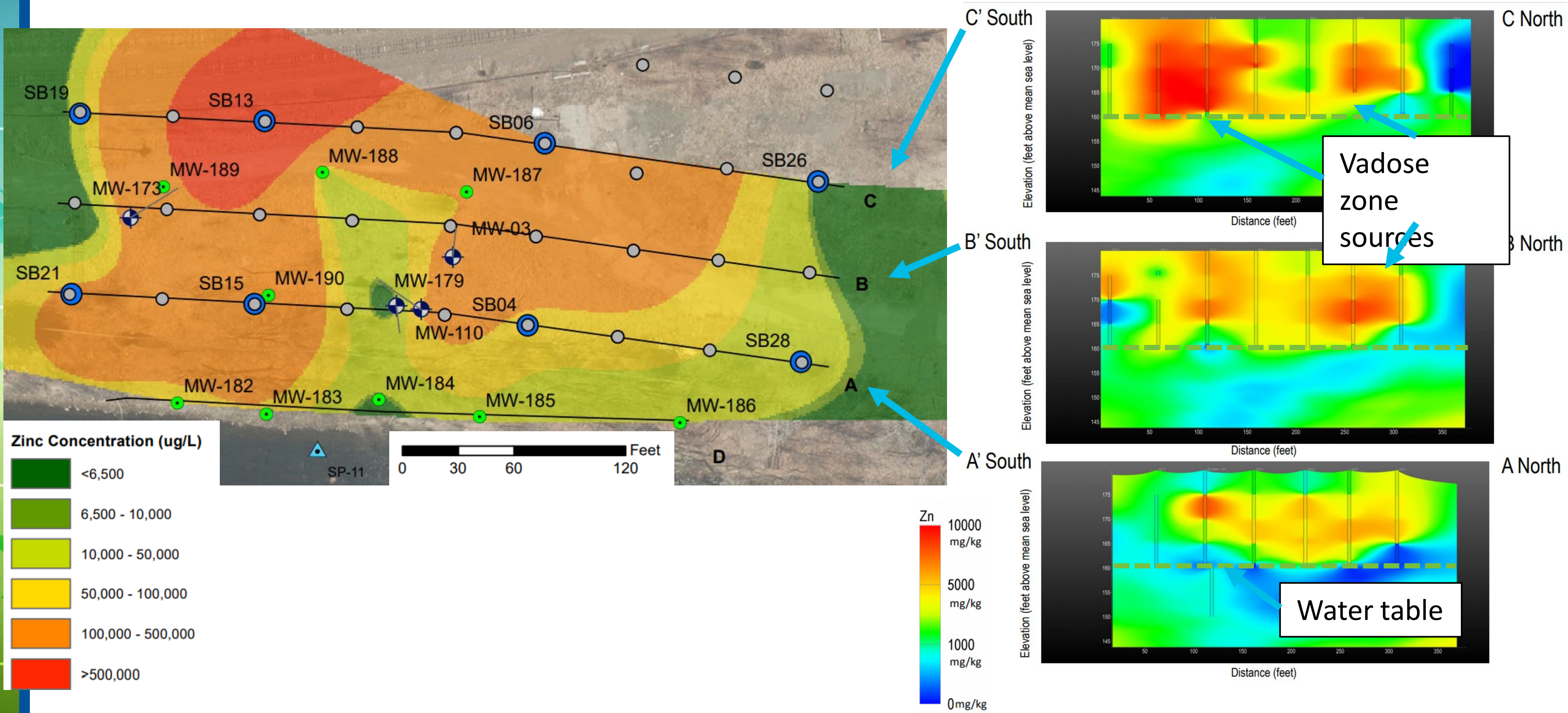
Near river

Plume area

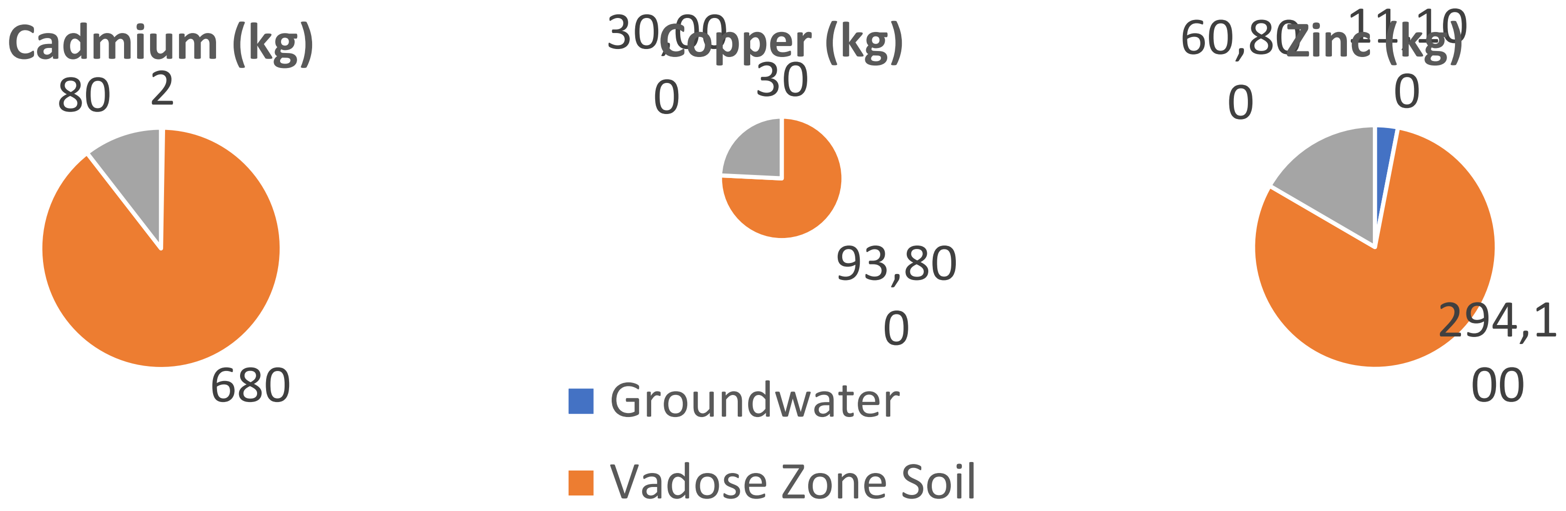
Source area

Extensive sub-grade rock layer is present at the base of the vadose zone source materials

HRSC, 3-D modeling and data visualization used to identify vadose and saturated zone source areas



Majority of the metals mass is in the vadose zone and at the groundwater "smear" zone



Agenda

Conceptual site model

Technology evaluation and selection

Pilot test implementation and results

Multi-phase treatability study was conducted

Site media

- Groundwater
- Unsaturated (vadose) zone soil
- Saturated zone soil

Unsaturated zone

- Soil + “rainwater”
- Reduction of concentrations and leachability from soil
- Reagents (different doses)
- Portland cement
- Ferrous iron

- Soil +
- Conce
- Reage
  - Port
  - Ferr
  - Calc

Treatability testing for the saturated and unsaturated zones showed that calcium polysulfide (CPS), iron sulfide, and Portland Cement performed best

Saturated zone

Saturated 1 (SB-13)	Dose (% Weight)	Cd	Cu	Zn
Portland Cement	5	Green	Green	Green
Portland Cement (3%) + Metafix 1 (2%)	5	Green	Green	Green
Metafix 1	3	Red	Yellow	Red
MetaFix 1 (3%) + FerroBlack-H (1%)	4	Green	Green	Red
Metafix 1	7	Green	Green	Yellow
Metafix 1 Modified	5	Green	Green	Red
FerroBlack-H	3	Red	Yellow	Red
FerroBlack-H	8	Green	Green	Yellow
Provect-IRM (3%) + FerroBlack-H (1%)	4	Red	Yellow	Red
Calcium polysulfide	8	Green	Green	Green
Calcium polysulfide	12	Green	Green	Green

Unsaturated (vadose) zone

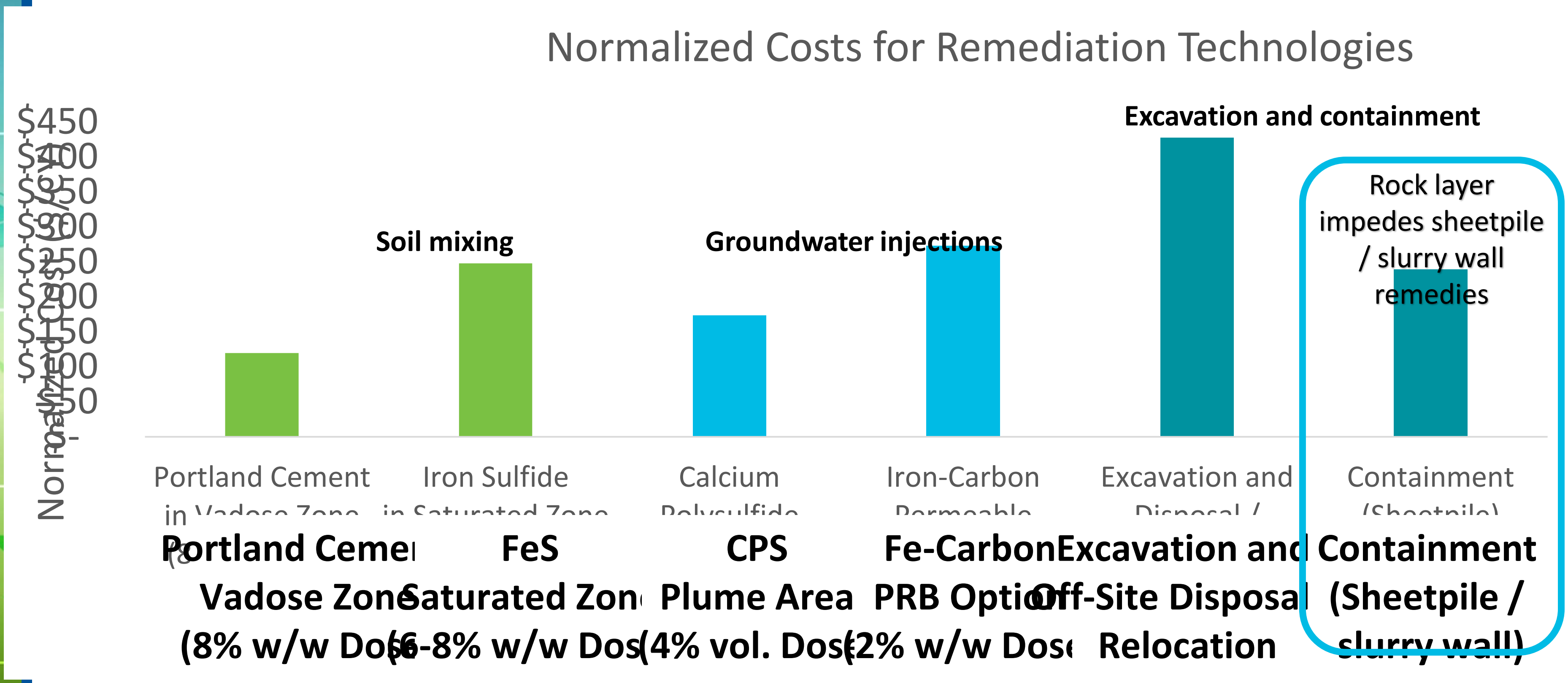
Vadose 2 (SB-15)	Dose (% Weight)	Cd	Cu	Zn	SPLP Cd	SPLP Cu	SPLP Zn
Portland Cement	5	Green	Yellow	Green	Yellow	Yellow	Green
Portland Cement (5%) + Metafix 1 (2%)	7	Green	Yellow	Green	Yellow	Yellow	Green
Metafix 1	1	Red	Red	Red	Red	Red	Red
Metafix 1	3	Yellow	Yellow	Yellow	Red	Yellow	Red
Metafix 1 Modified	3	Yellow	Yellow	Yellow	Red	Yellow	Red
Metafix 1 (3%) + FerroBlack-H (1%)	4	Green	Green	Green	Yellow	Green	Yellow
FerroBlack-H	3	Yellow	Yellow	Red	Red	Yellow	Red
FerroBlack-H	8	Green	Green	Green	Red	Green	Red
Provect-IRM (3%) + FerroBlack-H (1%)	4	Red	Yellow	Red	Red	Yellow	Red

Green: > 99 % concentration reduction

Yellow: < 99% and > 80% concentration reduction

Red: < 80% concentration reduction

Site-specific in situ remediation costs are significantly less than excavation and off-site disposal



Agenda

- Conceptual site model
- Technology evaluation and selection
- Pilot test implementation and results

Remedy steps and metrics

Complete the pilot study construction → Geotechnical metrics: UCS = 50 - 100 psi; $K = 10^{-6}$ cm/s

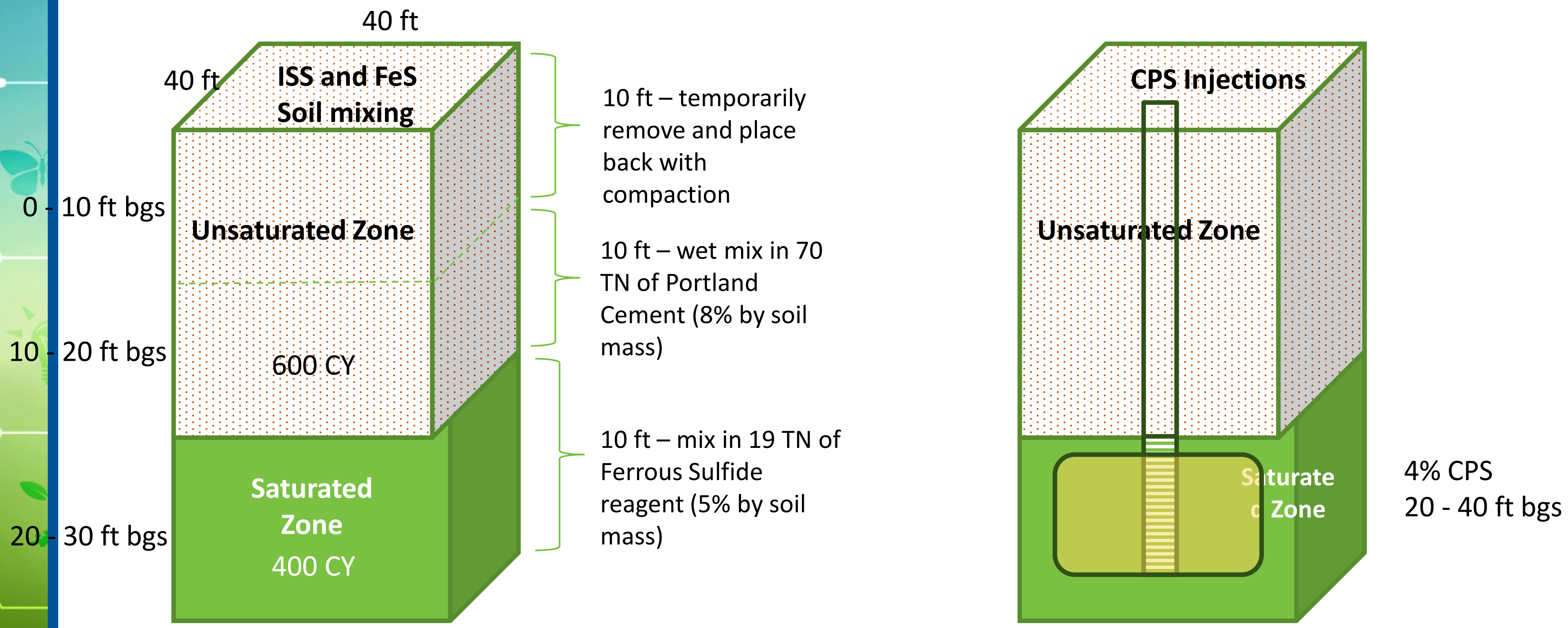
↓

Collect performance monitoring data → Groundwater metals concentrations decrease by 90% and pH increases to 6 – 8.5

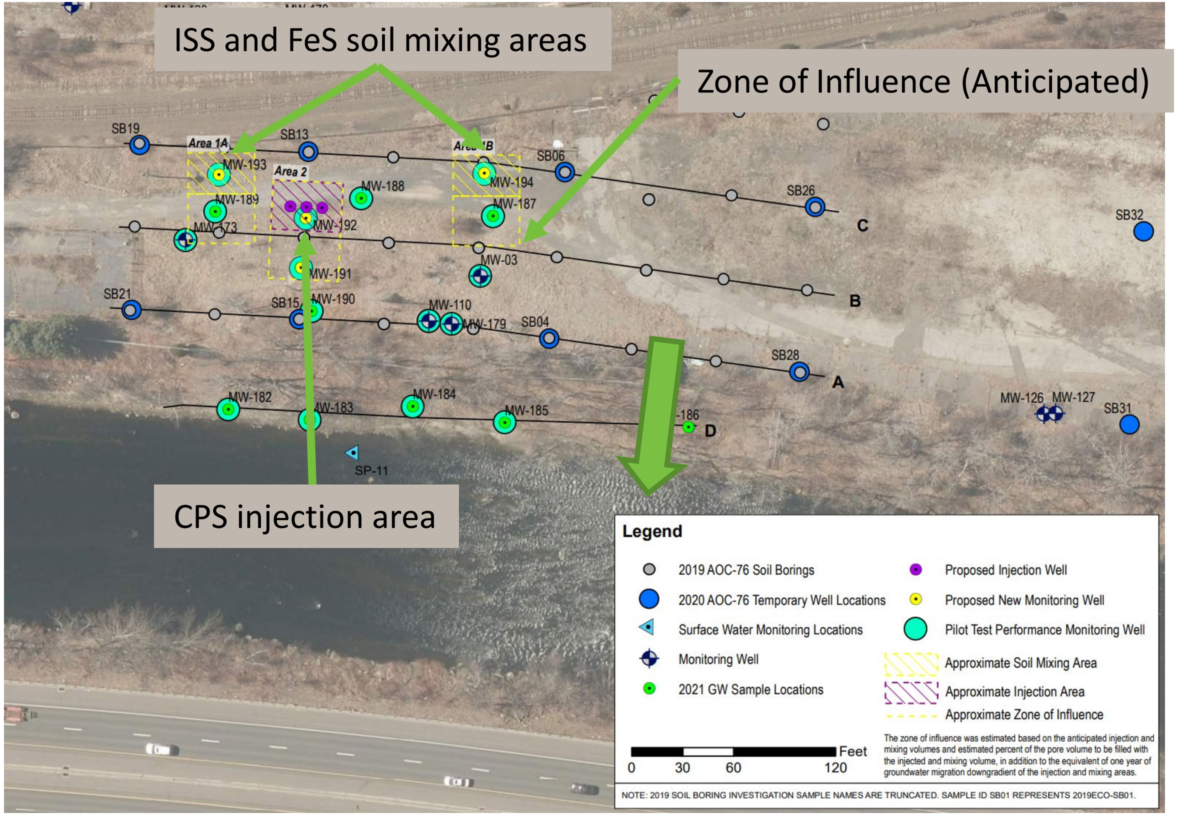
↓

Design and construct the full-scale remediation

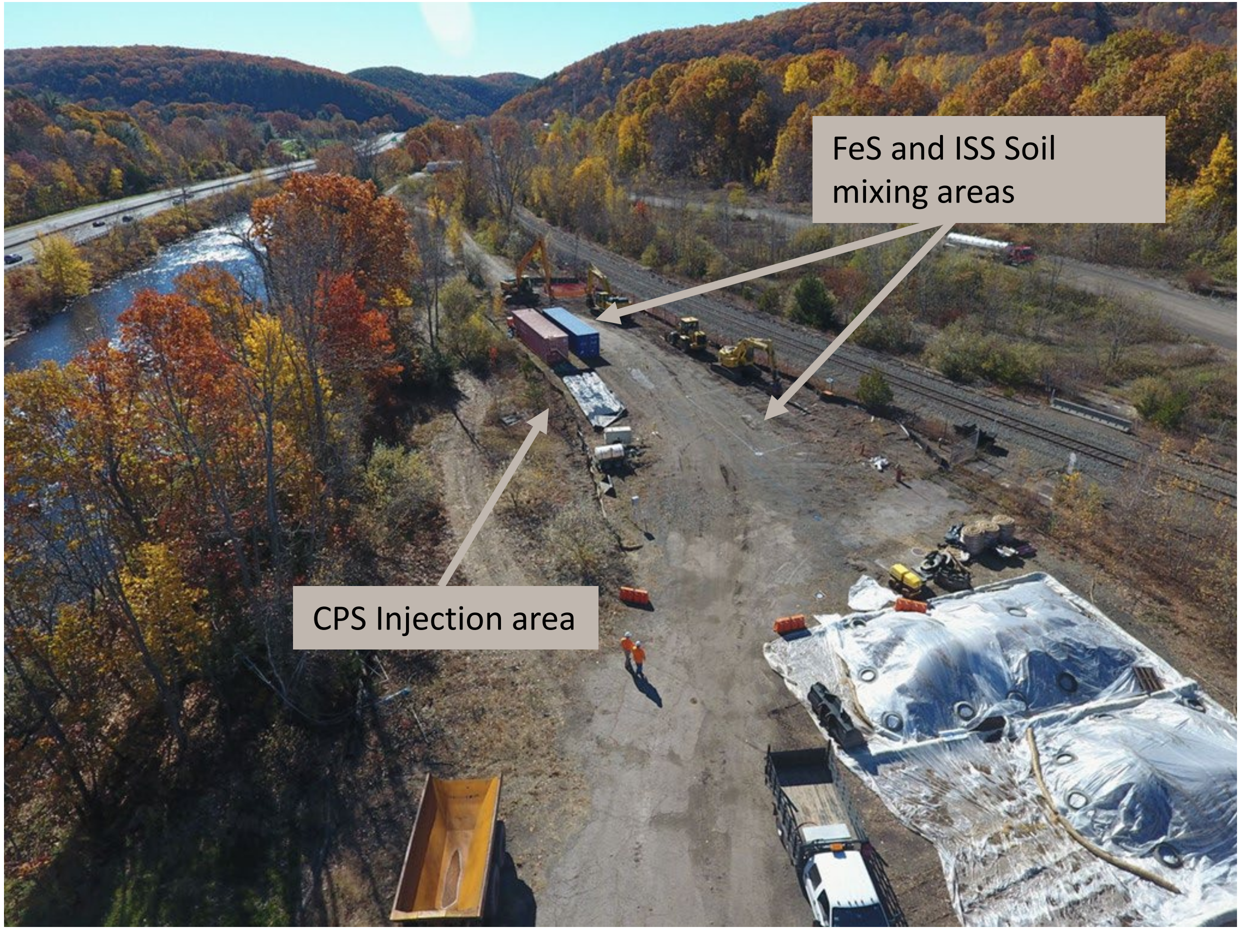
Field pilot test – in situ solidification and stabilization (ISS) of soil and geochemical precipitation in groundwater



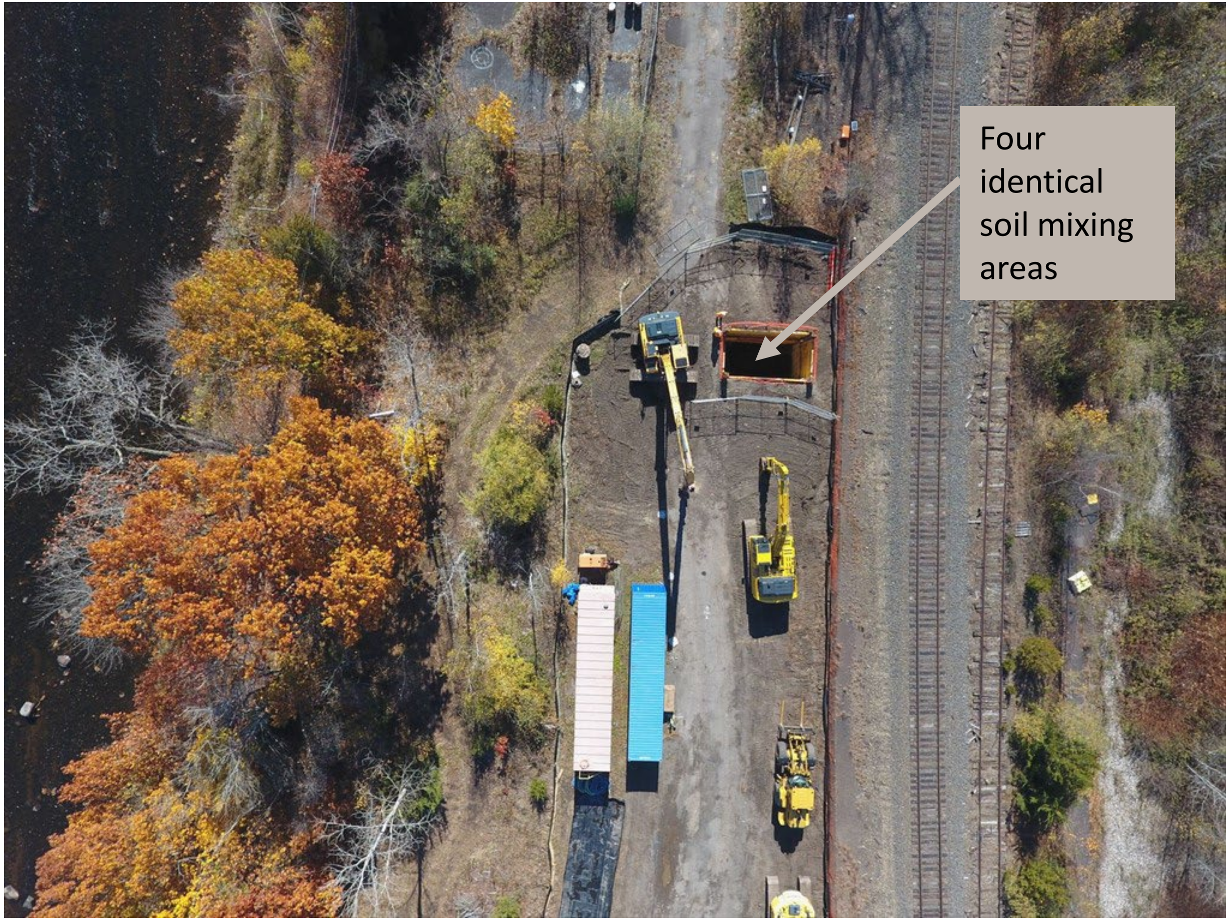
Pilot testing layout



Pilot test remediation area



Pilot test remediation area



Pilot test remediation soil mixing

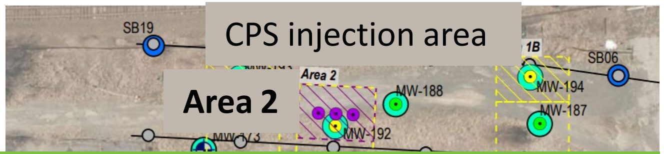
Rocks ranging in size from approximately 0.5 ft to 5 ft

Soil mixing – Reductant mixing and ISS

FeS from 18 – 25 ft bgs (mostly shallower due to rock layer)

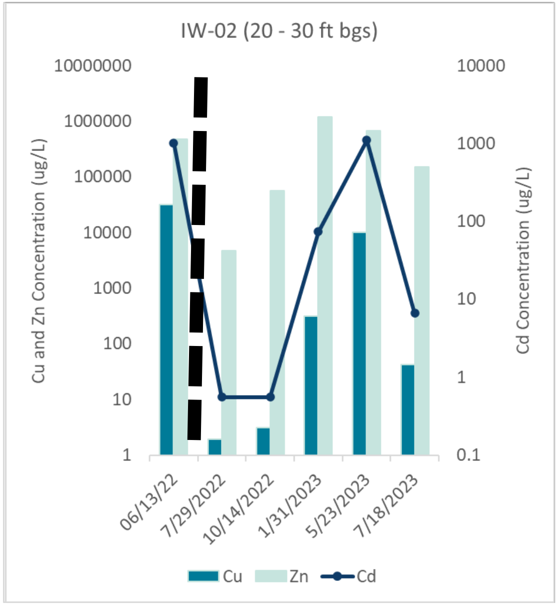
Portland Cement from 8 – 18 ft bgs

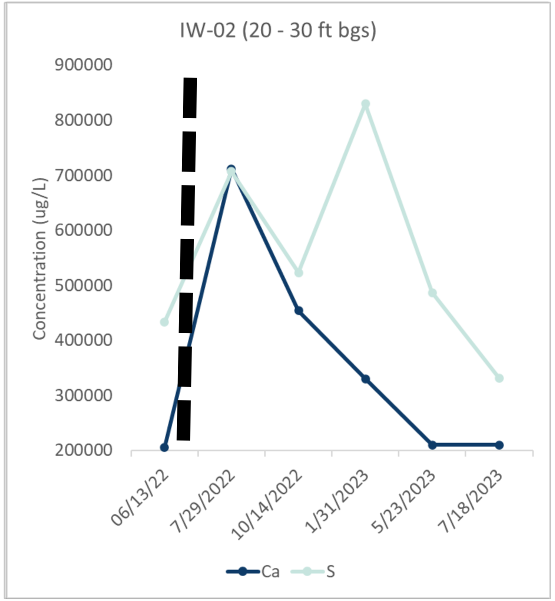
Calcium polysulfide results
(20 – 30 ft bgs)

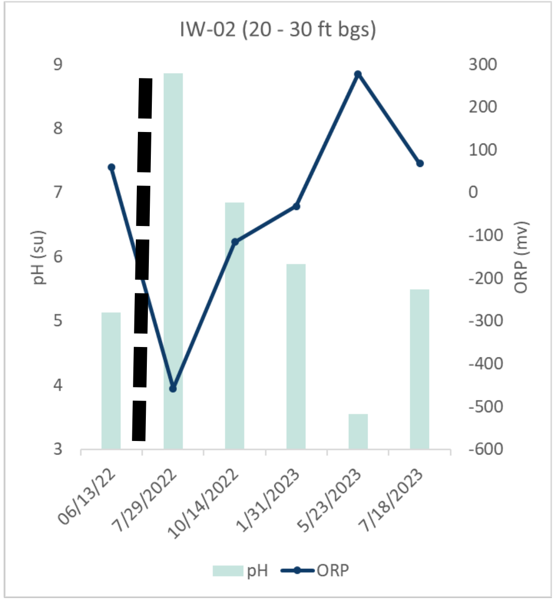


CPS provided about six months of treatment in shallow groundwater

Area 2

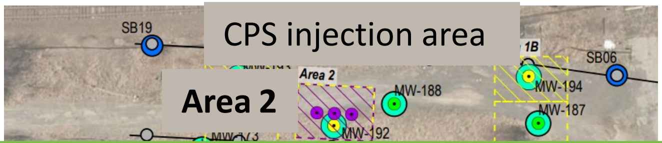






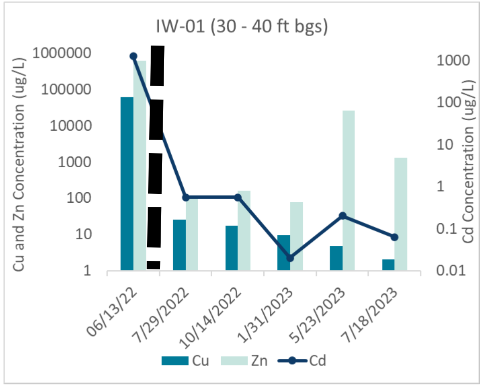
Injection event

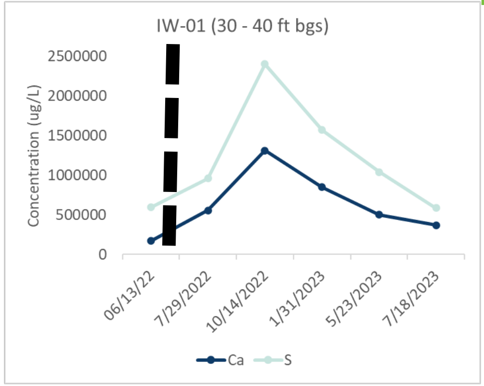
Calcium polysulfide results
(30 – 40 ft bgs)

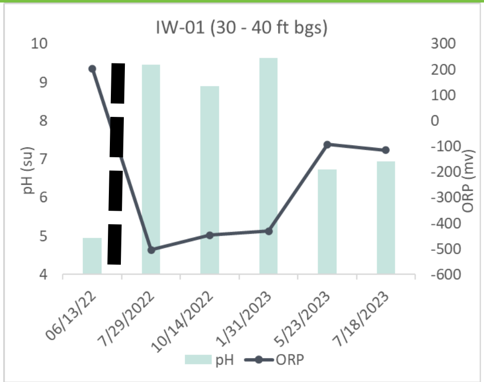


CPS provided at least one year of treatment in shallow groundwater

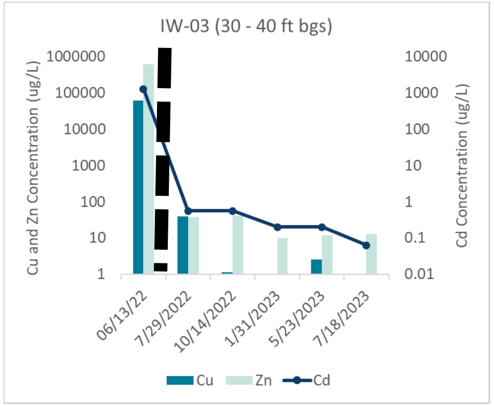
Area 2

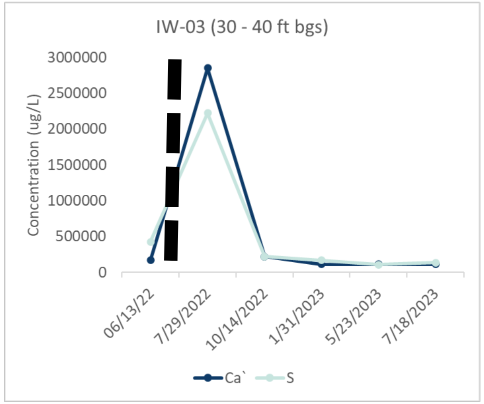


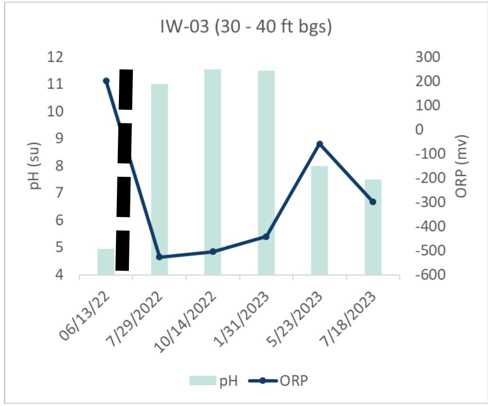




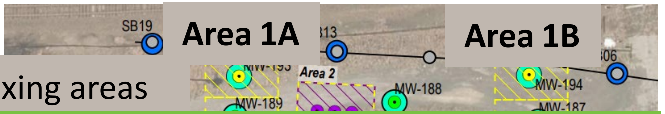
Injection event





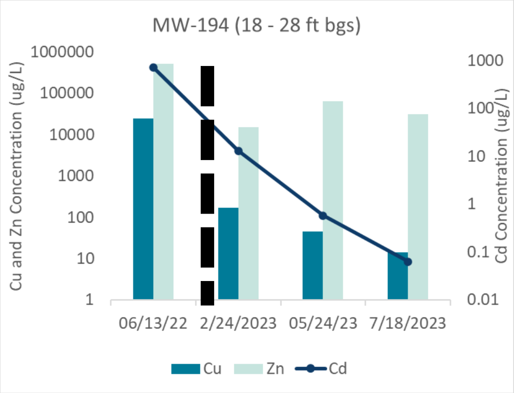


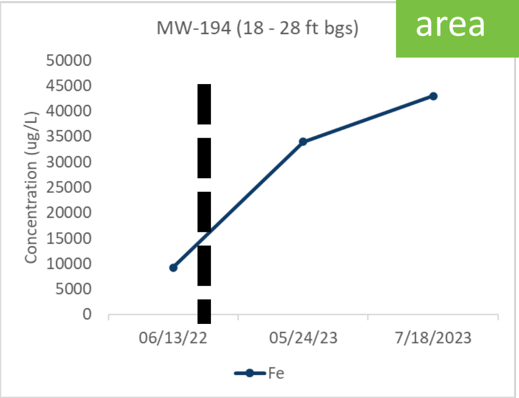
FeS and ISS soil mixing results (18-28 ft bgs)

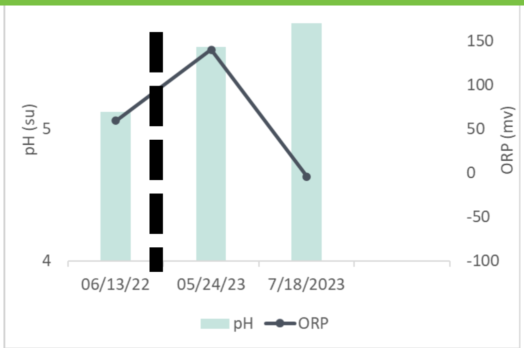


Fe-S and ISS provided at least one year (and counting) of treatment within the source area

Area 1A

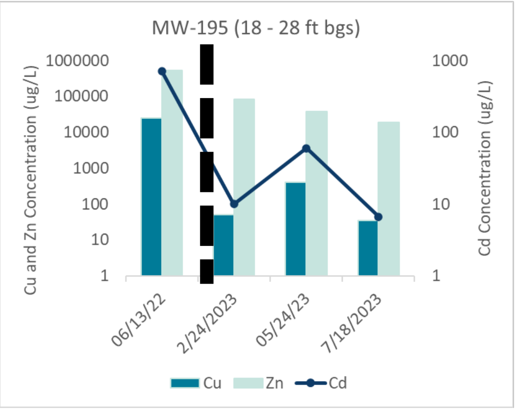


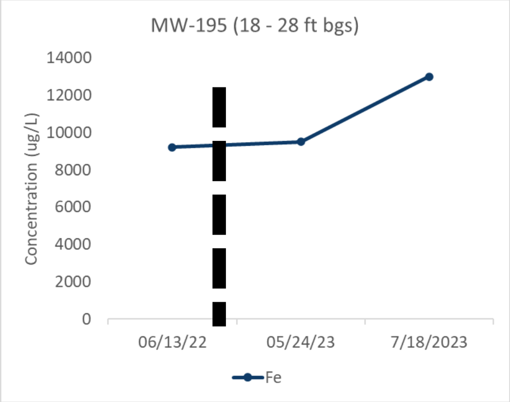


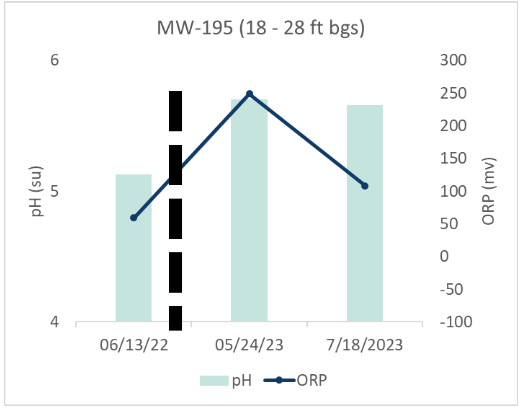


Soil mixing

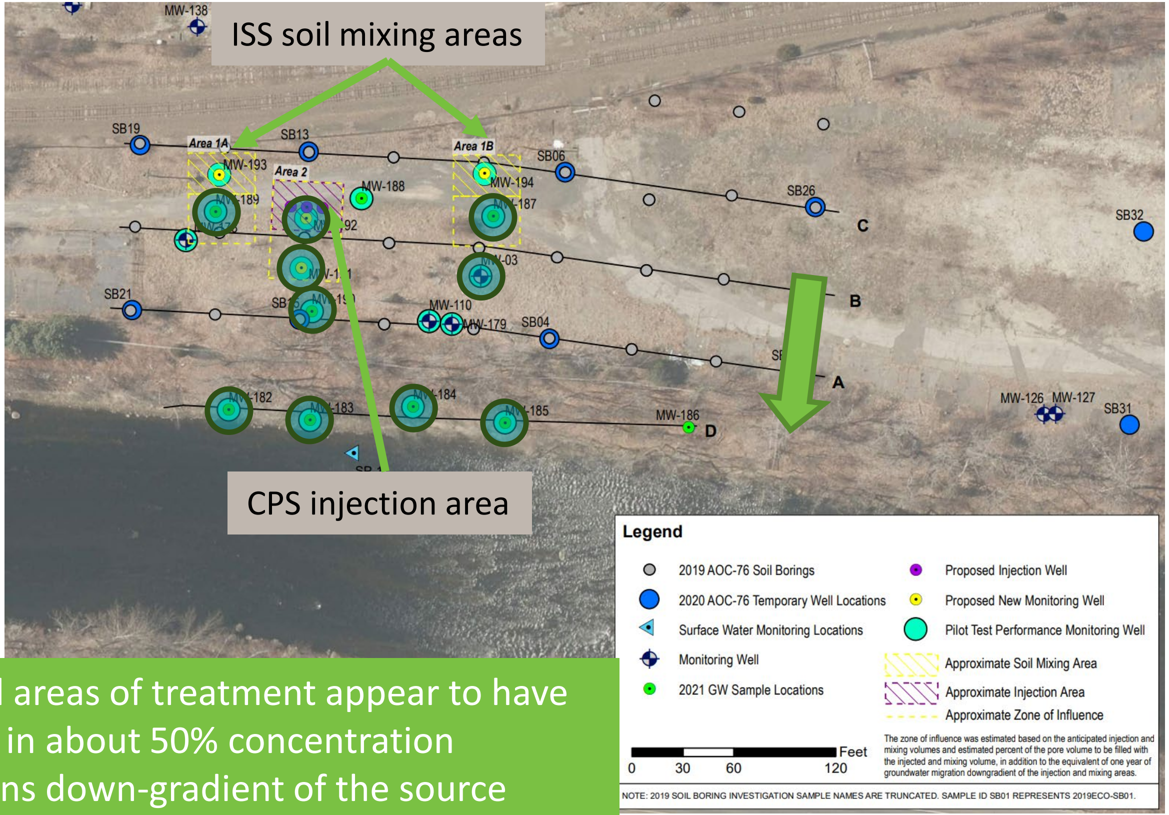
Area 1B







Zone of influence of treatment areas



Targeted areas of treatment appear to have resulted in about 50% concentration reductions down-gradient of the source areas

Reduced concentrations of Cd, Cu, and Zn

Moderation of pH and/or reduction of ORP not observed outside of treatment areas

Lessons learned – full-scale design considerations

- ISS formulation (8% w/w cement; 8% w/w FeS) in Area 1A achieved treatment goals
  - Groundwater Cd, Cu, and Zn concentrations substantially reduced
  - UCS > 50 psi
  - $K < 10^{-6}$ cm/s
- Extensive rock layer impeded soil mixing – larger excavation cells would improve ability to mix rock
- CPS injection rates of 2 – 4 gpm per well (10 gpm for three wells) achieved
- Current CPS dose (4% w/w) is adequate for 30-40 ft bgs
- Higher CPS dose is required for 20-30 ft bgs

Full-scale considerations for the combined full-scale remedy

- Further focusing of soil mixing at water table interface and performing in larger cells
  - Highest flux zones
  - Where highest concentrations intersect water table
- Adaptively injecting CPS outside of source areas
  - Flexible application
  - Cost effective delivery of reductant
- Incorporation of a low permeability liner to further reduce costs
  - Can cost-effectively address pollutant mobility criteria exceedances and leachable metals in vadose zone
  - Can readily be integrated into development

Q & A

Thank you!

Lucas Hellerich

lhellerich@woodardcurran.com

Reducing Time of Remediation at Clay and Fractured Rock Sites:

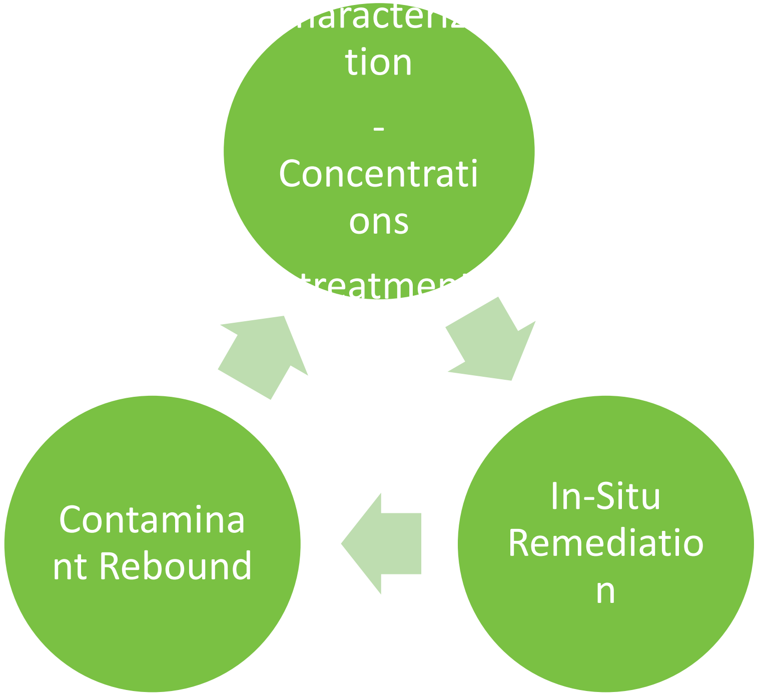
Marrying Permeability Enhancement with Remediation Chemistry

Lowell Kessel

President

CERES Remediation Products

Typical Remediation Process



Assess feasibility of reagents to targe
contaminants and select most viable
reduction chemistry.

Inject in the source area and/or plu
traditional injection methods.

Observe rebound after 6-18 month
repeat injections. Sometimes 3-4 ev
over a 10 year period. Everyone is f

Residual Mass >>> Diffusion Constraints

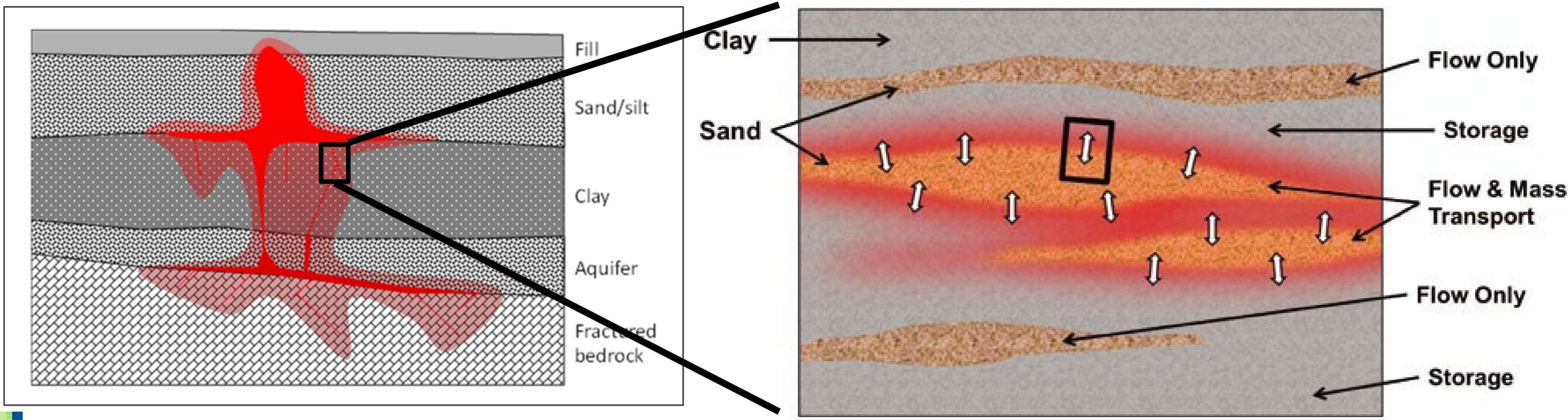
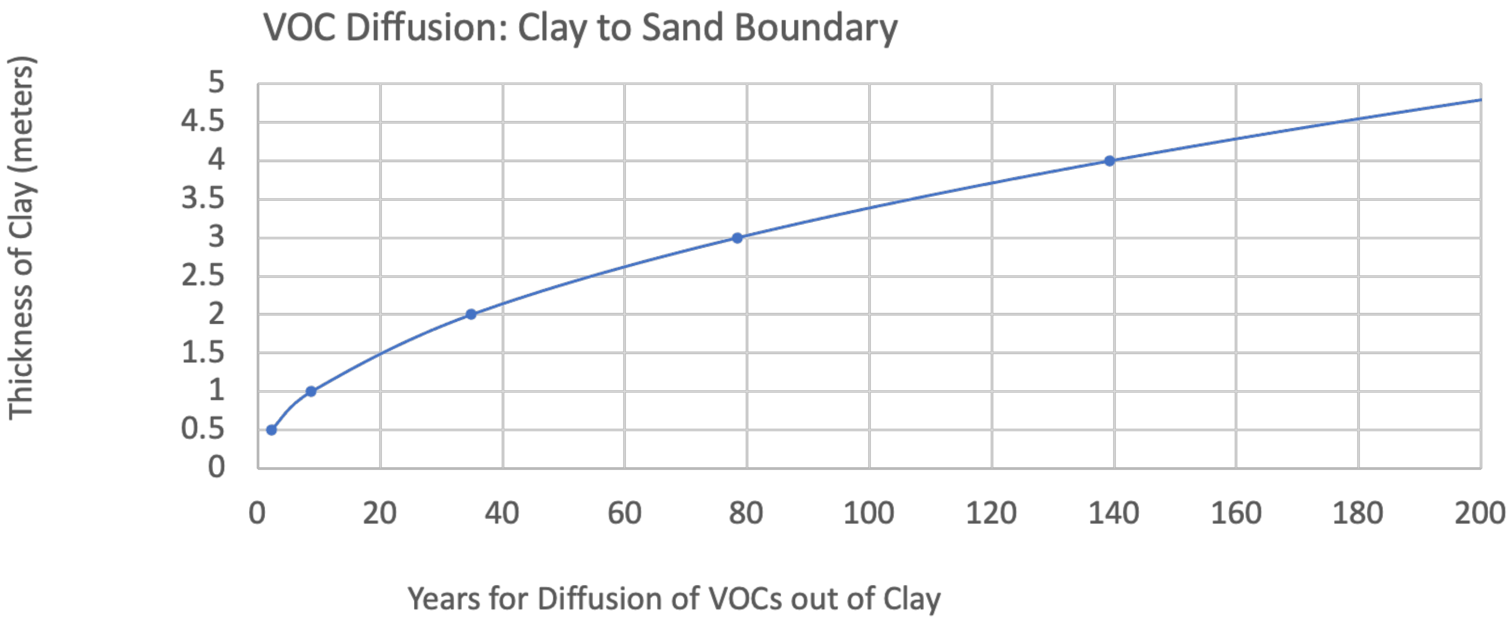
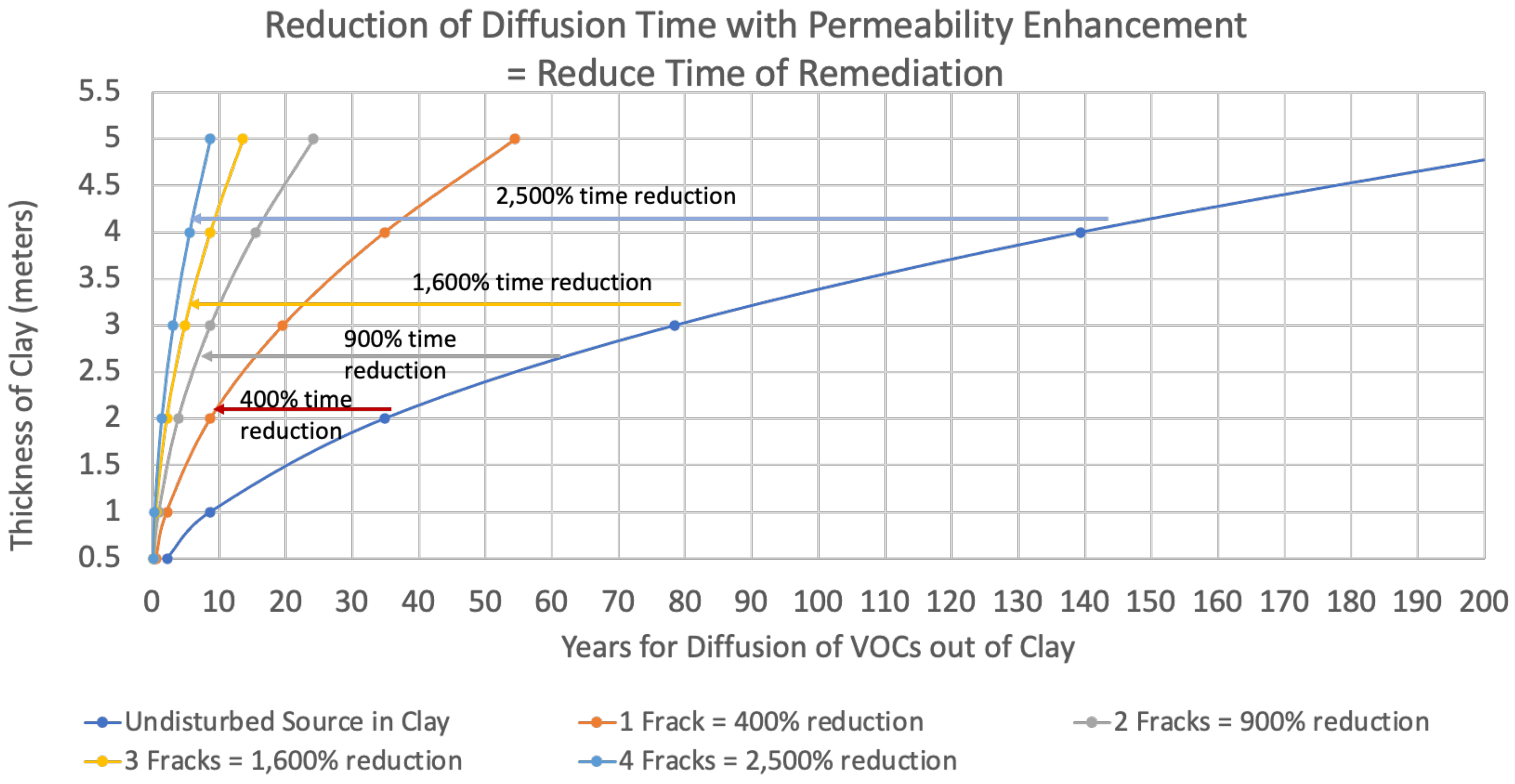


Figure 4. Suthersan, *GWMR* 2013

Diffusion Controls the **Time of Remediation-** Not the chemistry




Reduction of Diffusion Time with Permeability Enhancement
= Reduce Time of Remediation
Thickness of Clay (meters)
Years for Diffusion of VOCs out of Clay
2,500% time reduction
1,600% time reduction
900% time reduction
400% time reduction
Undisturbed Source in Clay
1 Frack = 400% reduction
2 Fracks = 900% reduction
3 Fracks = 1,600% reduction
4 Fracks = 2,500% reduction

Reagents for Permeability Enhanced Remediation

MTS®
Metals Treatment Solution

Long Duration (Decade to centuries)
Reduction and Sequestration Reagents

IPAC
INJECTABLE POWDER ACTIVATED CARBON

Frac Sand

ZVI
Zero Valent Iron

Key Factors to Successful Use of Reagents with Proppants

Come by the poster or Booth to learn more

CERES REMEDIATION PRODUCTS

Lucas Hellerich, PhD, PE, LEP

Optimization of a Combined Active and Passive In Situ Remediation Approach for High Concentration Metals in Groundwater

Woodard & Curran, Inc.

Co-Authors

Ramin Ansari, Lanxess, USA

Nick Hastings, PG, LEP, Woodard & Curran

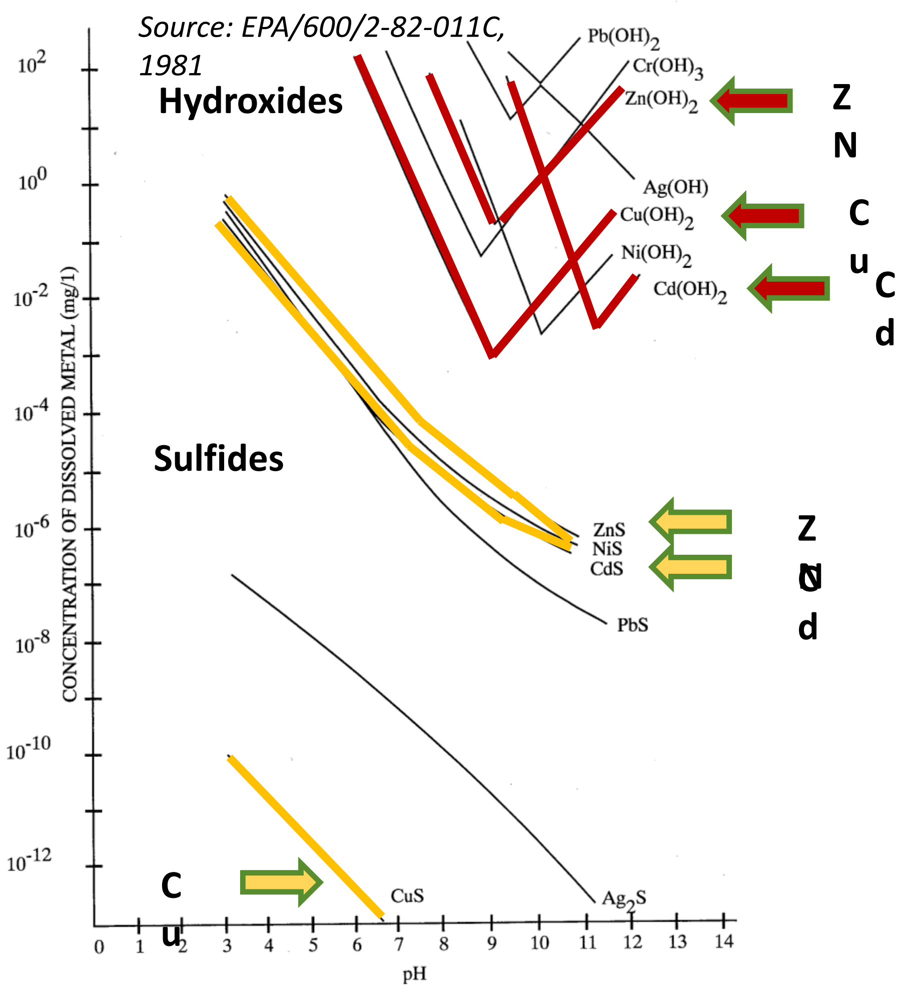
Samantha Olney, PG, Woodard & Curran

Trevor King, PE, Woodard & Curran

Dan Brockmeyer, LEP, Woodard & Curran

Forming low solubility metal precipitates can be an effective remediation strategy

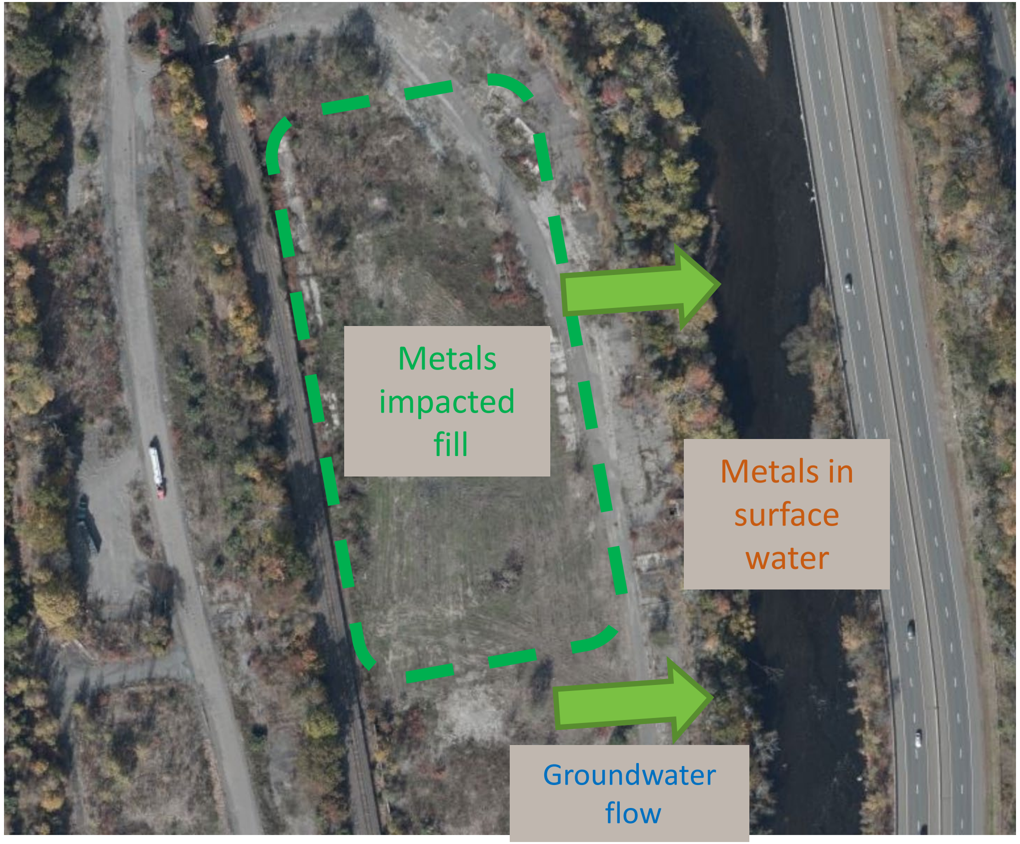
Decreasing solubility



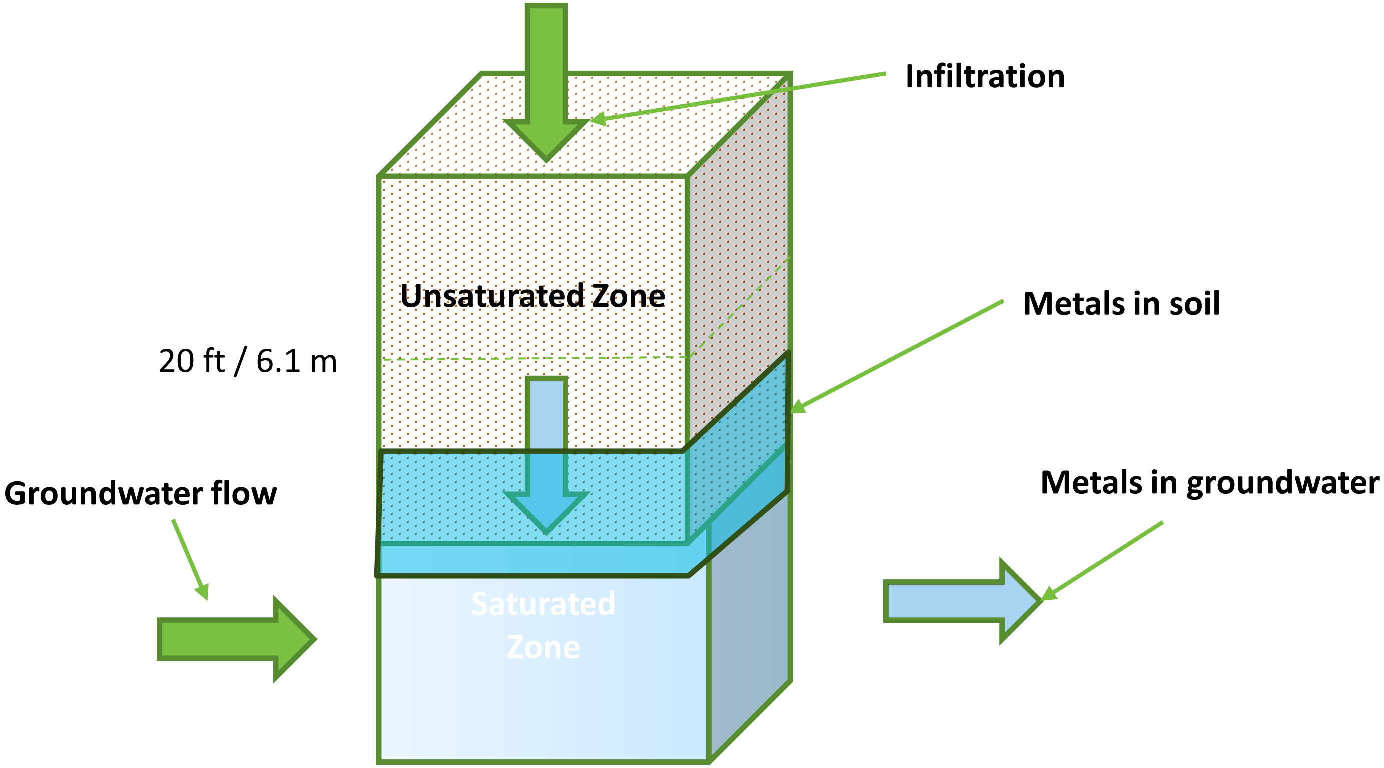
Agenda

- Conceptual site model
- Technology evaluation and selection
- Pilot test implementation and results

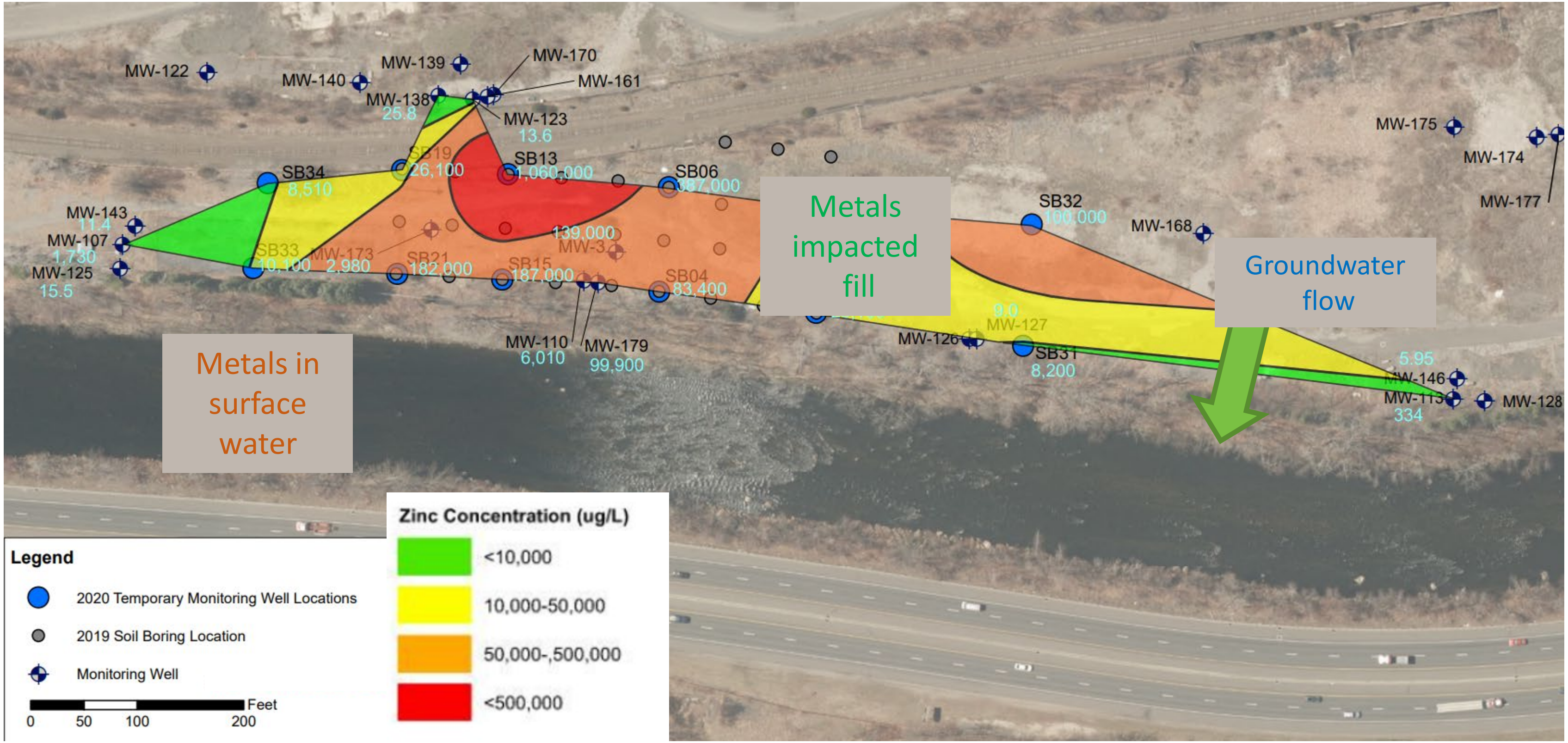
Cadmium, copper, and zinc in groundwater are discharging to surface water above criteria



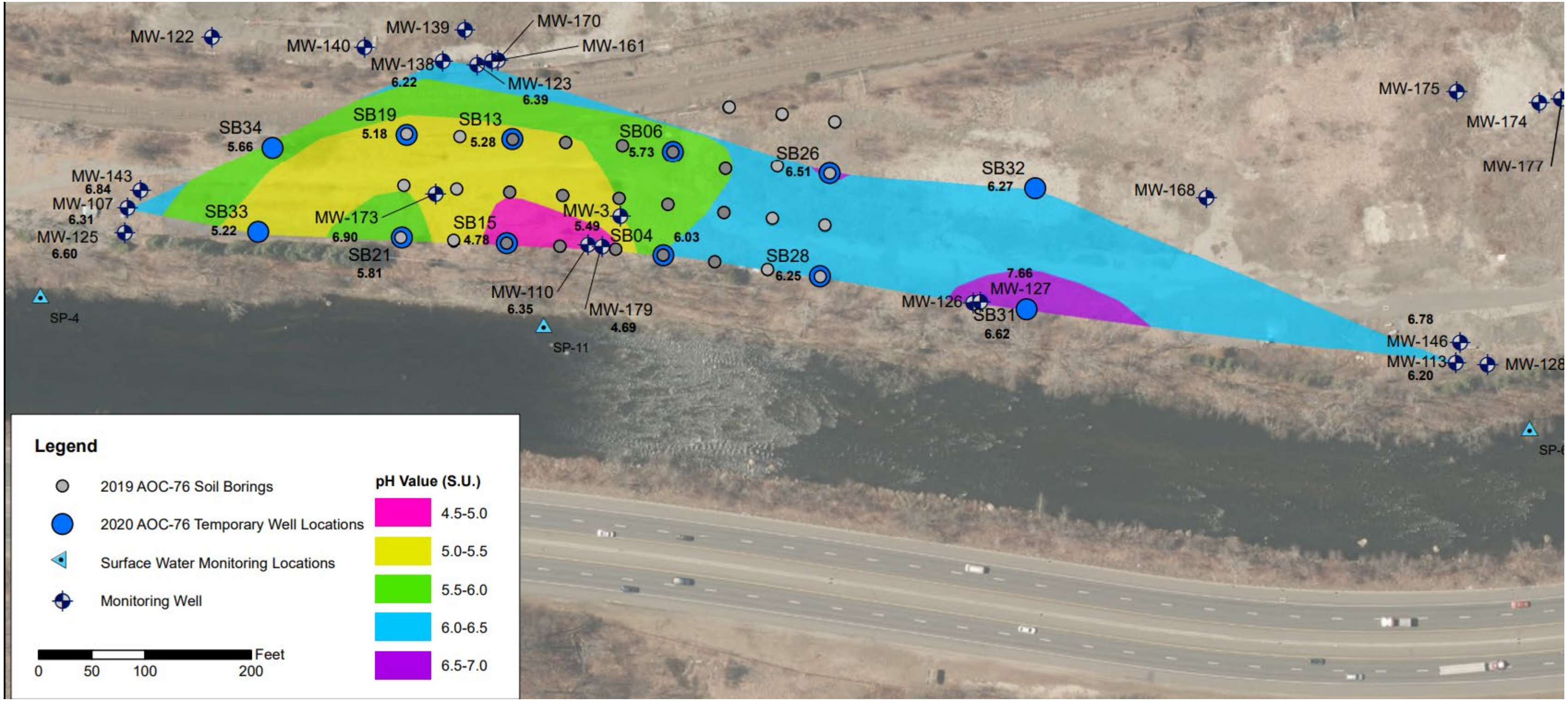
CSM for metals leaching and migration



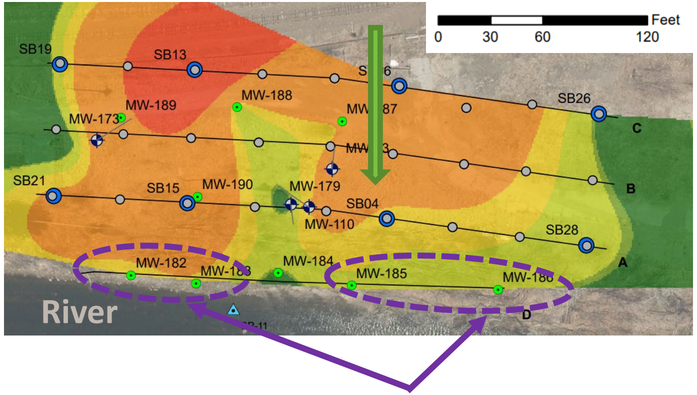
Metals solubilize in groundwater and discharge into surface water

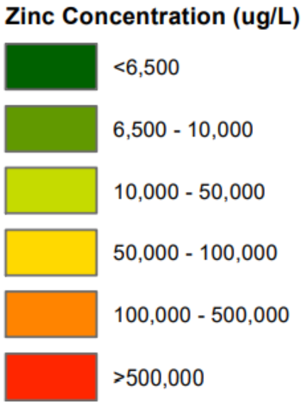


Acidic pH increases solubility of metals



Metals concentrations exceed criteria at the river by approximately 10X - 15X





Surface Water Protection Criteria (SWPC) exceedances

SWPC

Cd = 12.5 ug/L
Cu = 480 ug/L
Zn = 6,500 ug/L

Site conditions constrain remediation options

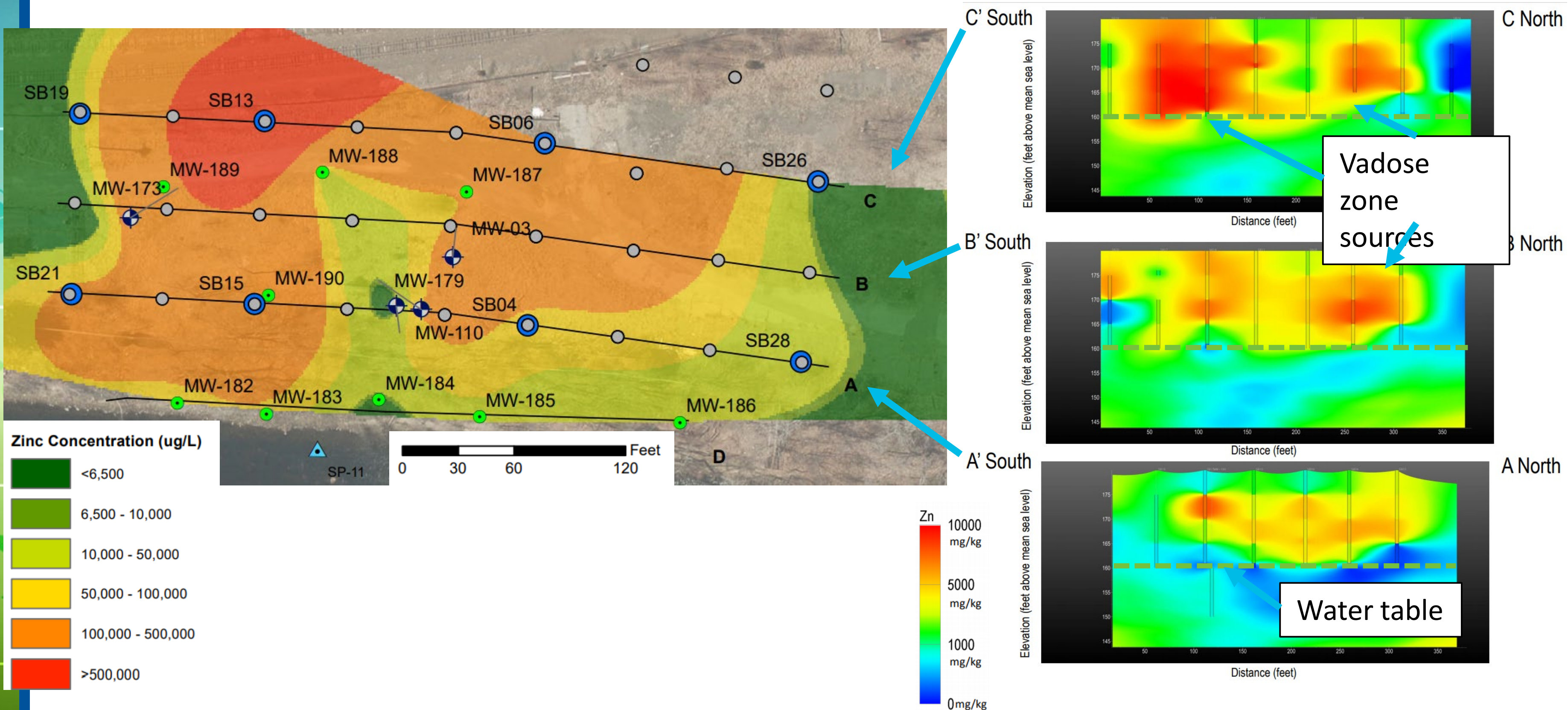
Near river

Plume area

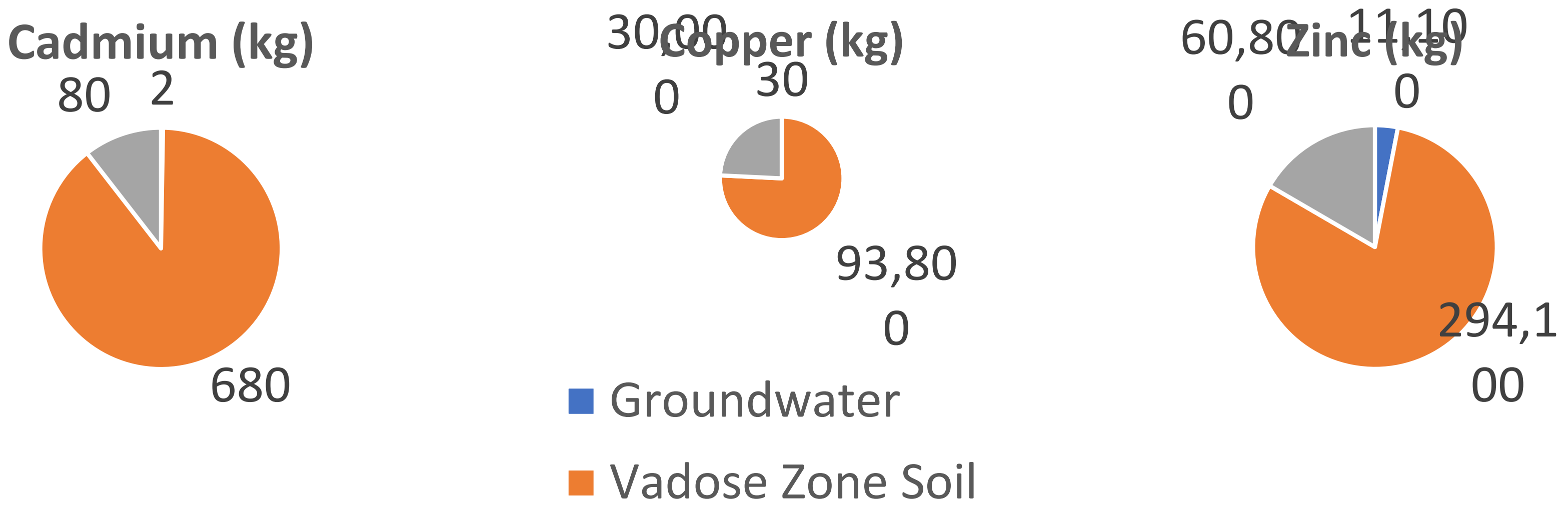
Source area

Extensive sub-grade rock layer is present at the base of the vadose zone source materials

HRSC, 3-D modeling and data visualization used to identify vadose and saturated zone source areas



Majority of the metals mass is in the vadose zone and at the groundwater "smear" zone



Agenda

Conceptual site model

Technology evaluation and selection

Pilot test implementation and results

Multi-phase treatability study was conducted

Site media

- Groundwater
- Unsaturated (vadose) zone soil
- Saturated zone soil

Unsaturated zone

- Soil + "rainwater"
- Reduction of concentrations and leachability from soil
- Reagents (different doses)
- Portland cement
- Ferrous iron

Saturated zone

- Soil + groundwater
- Concentration reduction
- Reagents (different doses)
  - Portland cement
  - Ferrous iron
  - Calcium polysulfide

Treatability testing for the saturated and unsaturated zones showed that calcium polysulfide (CPS), iron sulfide, and Portland Cement performed best

Saturated zone

Saturated 1 (SB-13)	Dose (% Weight)	Cd	Cu	Zn
Portland Cement	5	Green	Green	Green
Portland Cement (3%) + Metafix 1 (2%)	5	Green	Green	Green
Metafix 1	3	Red	Yellow	Red
MetaFix 1 (3%) + FerroBlack-H (1%)	4	Green	Green	Red
Metafix 1	7	Green	Green	Yellow
Metafix 1 Modified	5	Green	Green	Red
FerroBlack-H	3	Red	Yellow	Red
FerroBlack-H	8	Green	Green	Yellow
Provect-IRM (3%) + FerroBlack-H (1%)	4	Red	Yellow	Red
Calcium polysulfide	8	Green	Green	Green
Calcium polysulfide	12	Green	Green	Green

Unsaturated (vadose) zone

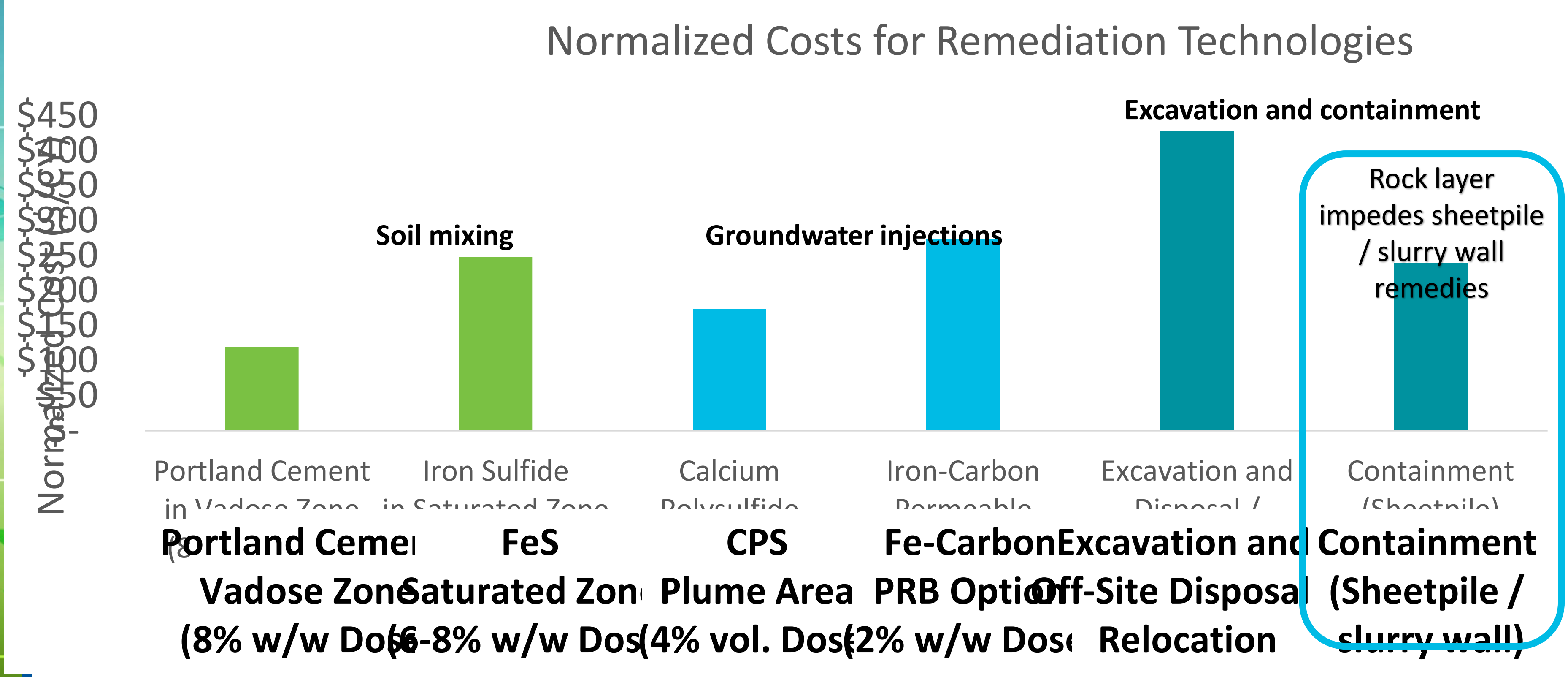
Vadose 2 (SB-15)	Dose (% Weight)	Cd	Cu	Zn	SPLP Cd	SPLP Cu	SPLP Zn
Portland Cement	5	Green	Yellow	Green	Yellow	Yellow	Green
Portland Cement (5%) + Metafix 1 (2%)	7	Green	Yellow	Green	Yellow	Yellow	Green
Metafix 1	1	Red	Red	Red	Red	Red	Red
Metafix 1	3	Yellow	Yellow	Yellow	Red	Yellow	Red
Metafix 1 Modified	3	Yellow	Yellow	Yellow	Red	Yellow	Red
Metafix 1 (3%) + FerroBlack-H (1%)	4	Green	Green	Green	Yellow	Green	Yellow
FerroBlack-H	3	Yellow	Yellow	Red	Red	Yellow	Red
FerroBlack-H	8	Green	Green	Green	Red	Green	Red
Provect-IRM (3%) + FerroBlack-H (1%)	4	Red	Yellow	Red	Red	Yellow	Red

> 99 % concentration reduction (Green)

< 99% and > 80% concentration reduction (Yellow)

< 80% concentration reduction (Red)

Site-specific in situ remediation costs are significantly less than excavation and off-site disposal



Agenda

- Conceptual site model
- Technology evaluation and selection
- Pilot test implementation and results

Remedy steps and metrics

Complete the pilot study construction → Geotechnical metrics
UCS = 50 - 100 psi
$K = 10^{-6}$ cm/s

↓

Collect performance monitoring data → Groundwater metals concentrations decrease by 90% and pH increases to 6 – 8.5

↓

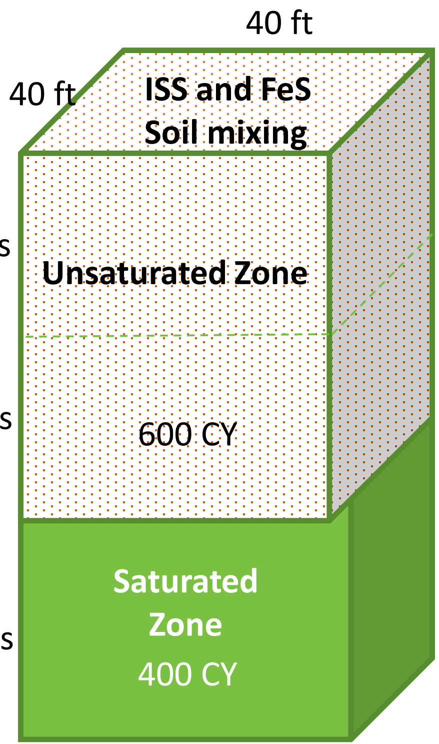
Design and construct the full-scale remediation

Field pilot test – in situ solidification and stabilization (ISS) of soil and geochemical precipitation in groundwater

0 - 10 ft bgs

10 - 20 ft bgs

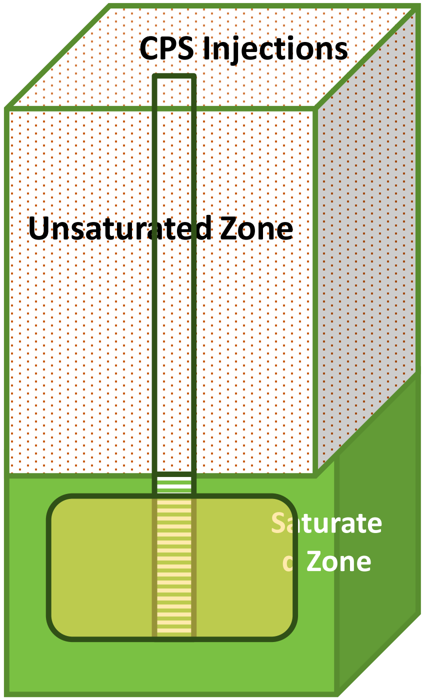
20 - 30 ft bgs



10 ft – temporarily remove and place back with compaction

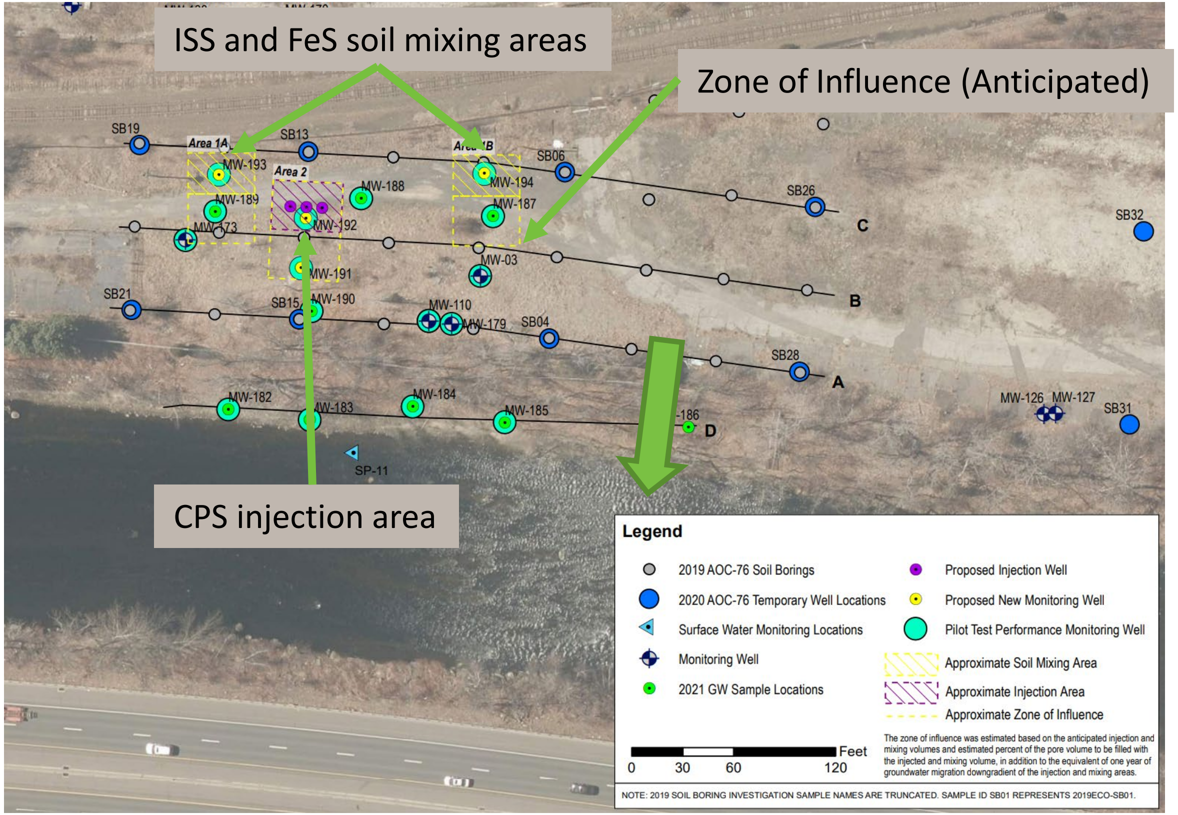
10 ft – wet mix in 70 TN of Portland Cement (8% by soil mass)

10 ft – mix in 19 TN of Ferrous Sulfide reagent (5% by soil mass)

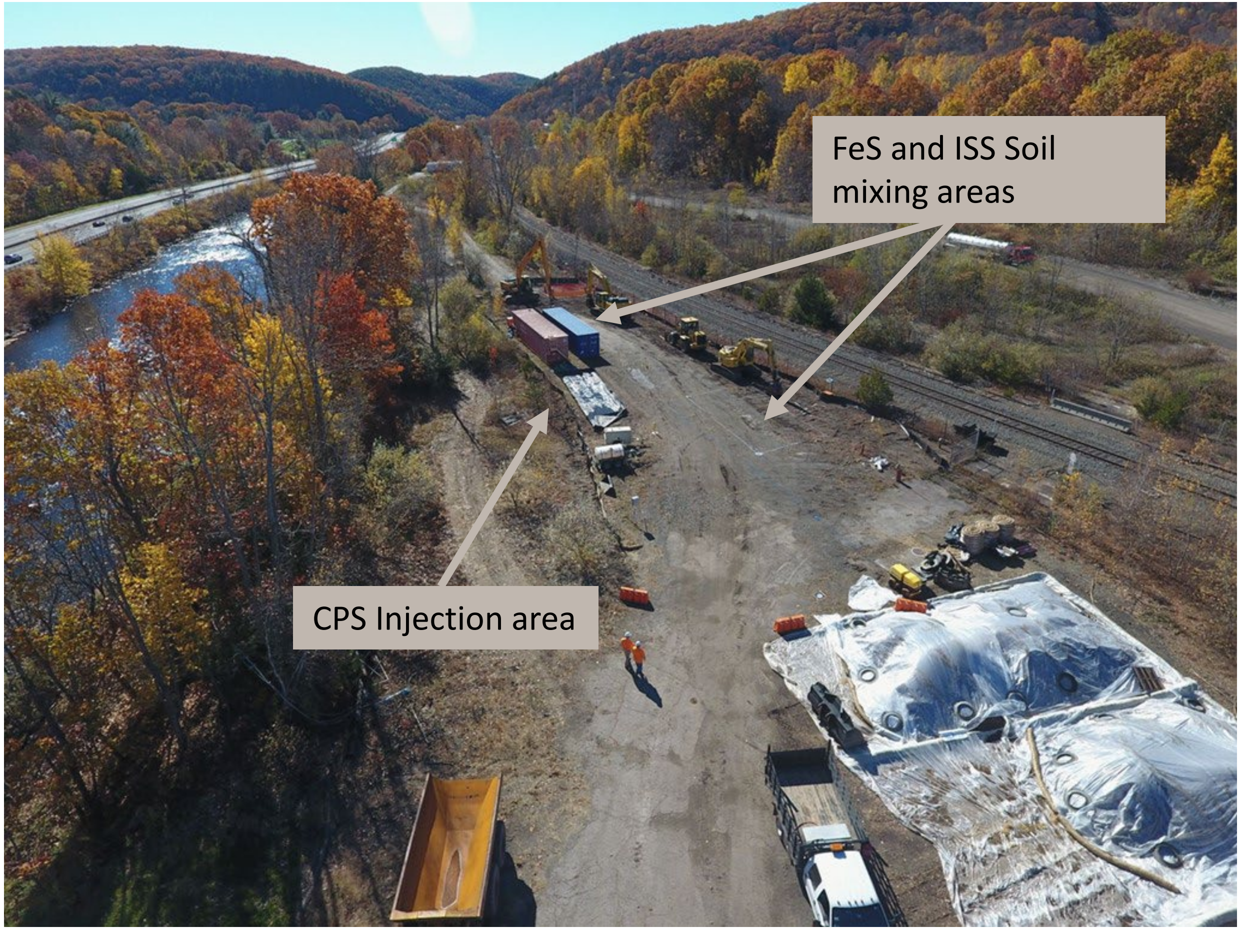


4% CPS
20 - 40 ft bgs

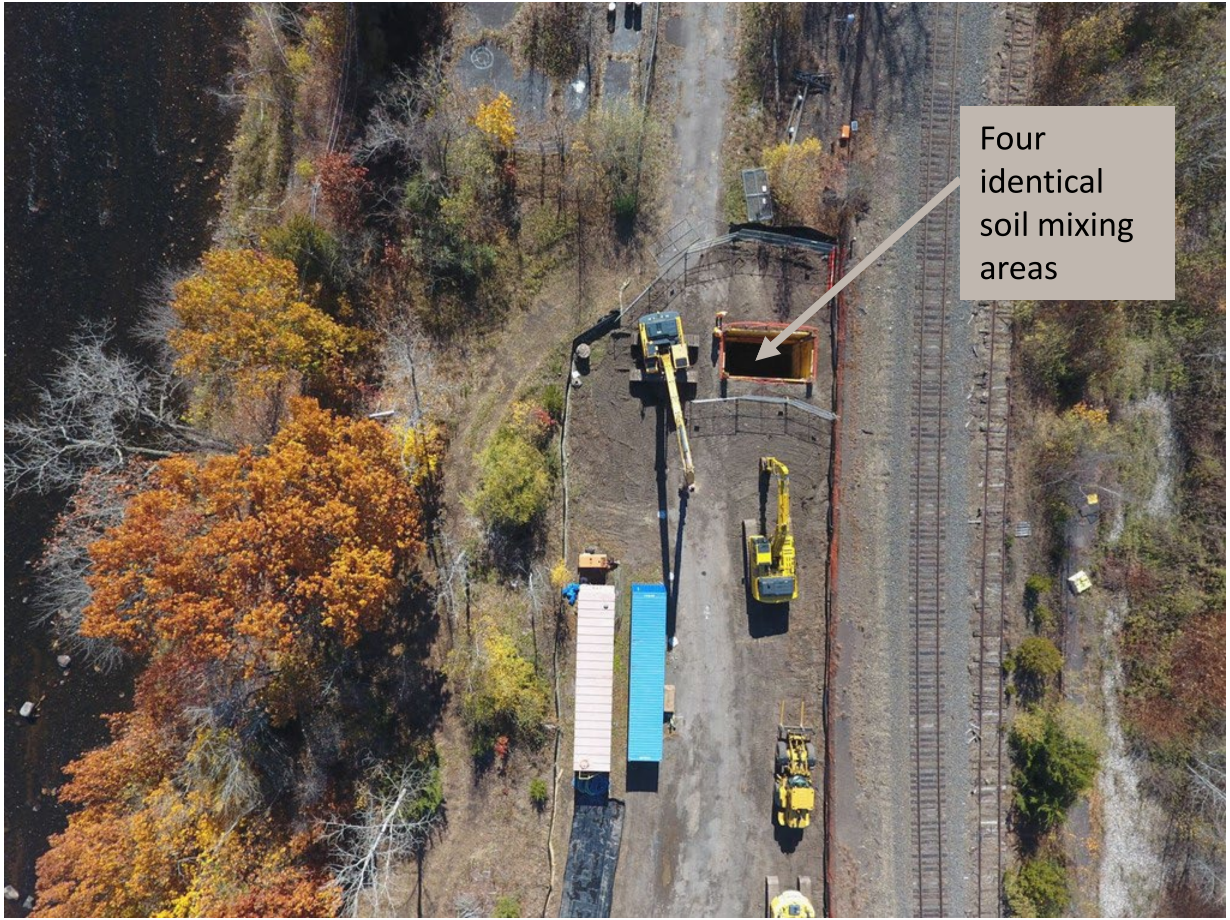
Pilot testing layout



Pilot test remediation area



Pilot test remediation area



Pilot test remediation soil mixing

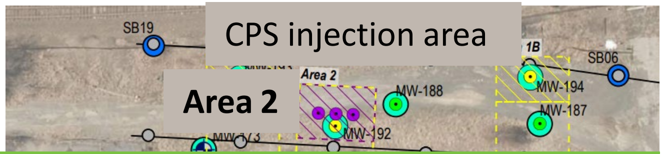
Rocks ranging in size from approximately 0.5 ft to 5 ft

Soil mixing – Reductant mixing and ISS

FeS from 18 – 25 ft bgs (mostly shallower due to rock layer)

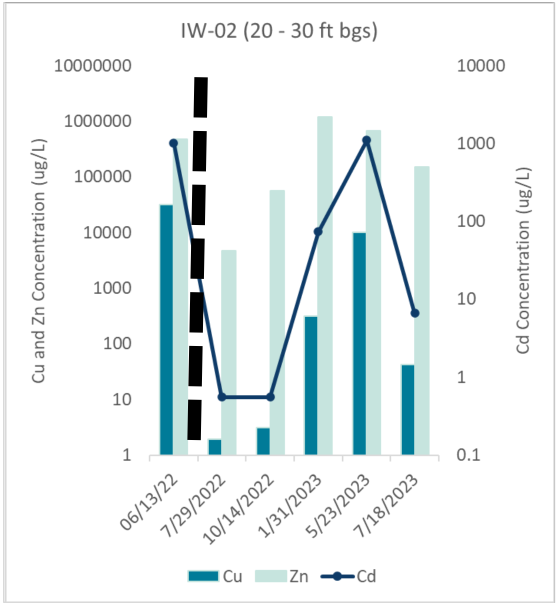
Portland Cement from 8 – 18 ft bgs

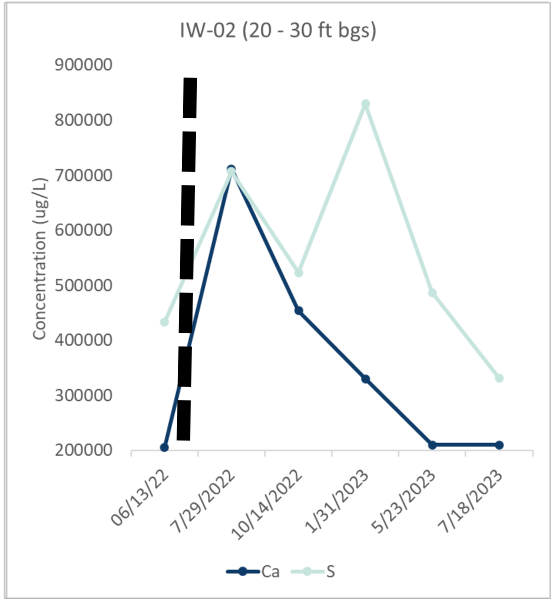
Calcium polysulfide results
(20 – 30 ft bgs)

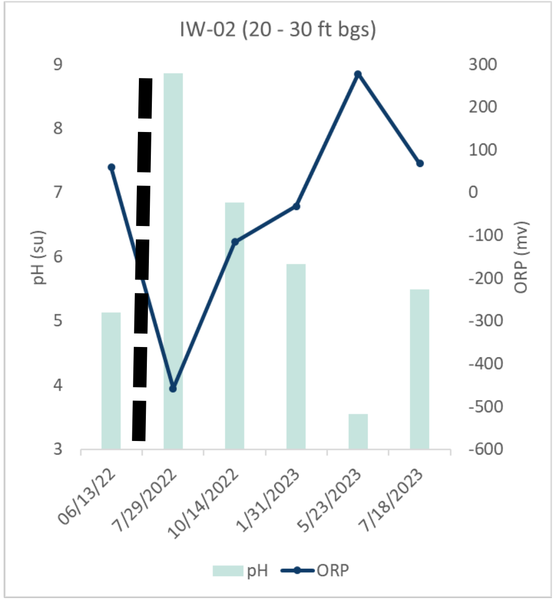


CPS provided about six months of treatment in shallow groundwater

Area 2

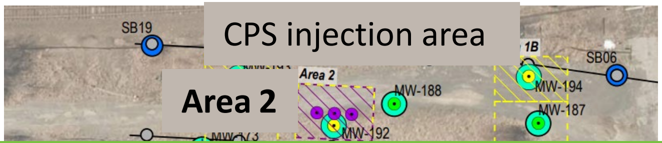






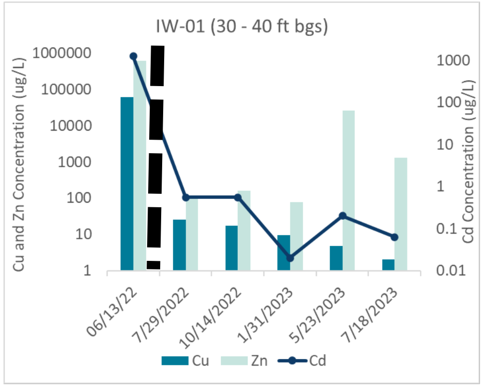
Injection event

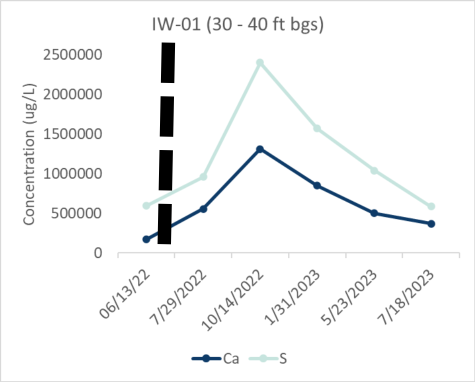
Calcium polysulfide results
(30 – 40 ft bgs)

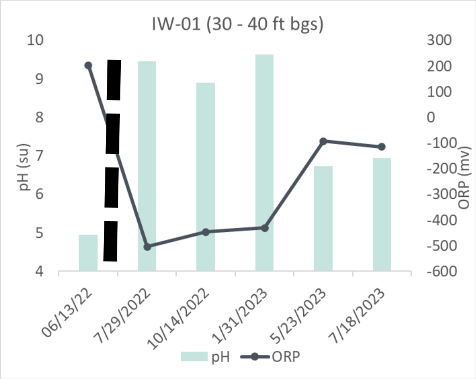


CPS provided at least one year of treatment in shallow groundwater

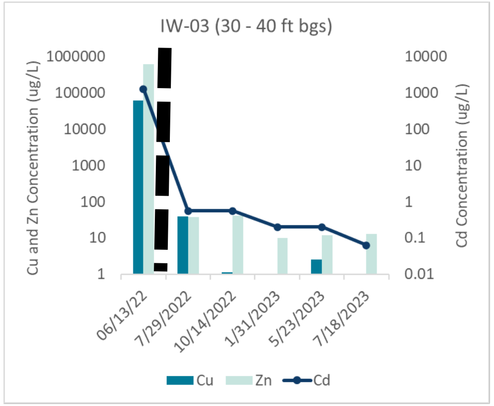
Area 2

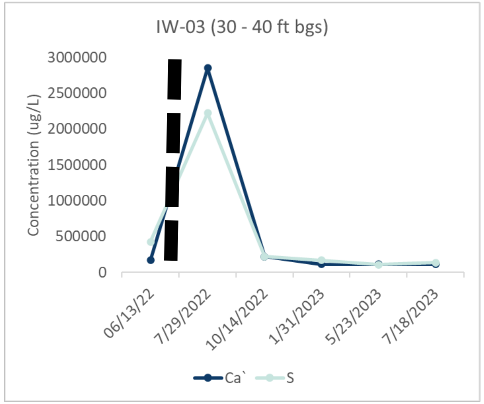


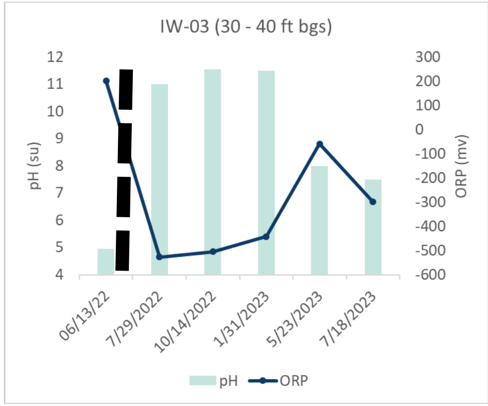




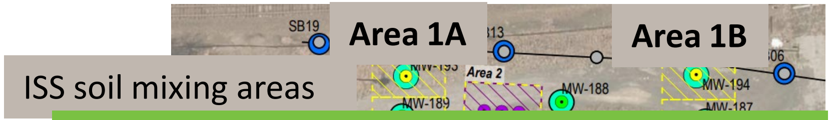
Injection event





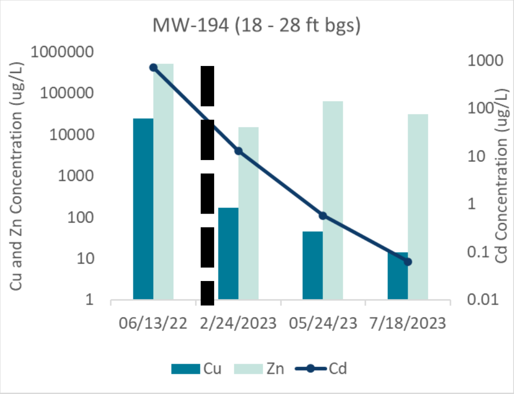


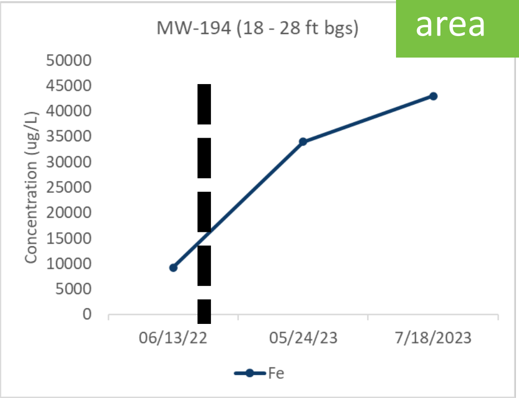
FeS and ISS soil mixing results (18-28 ft bgs)

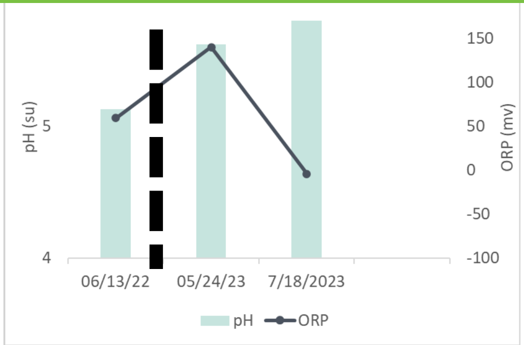


Fe-S and ISS provided at least one year (and counting) of treatment within the source area

Area 1A

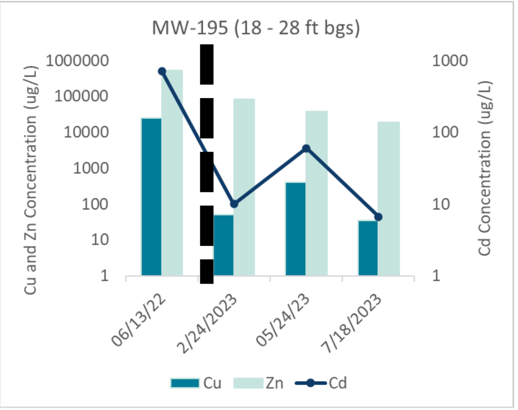


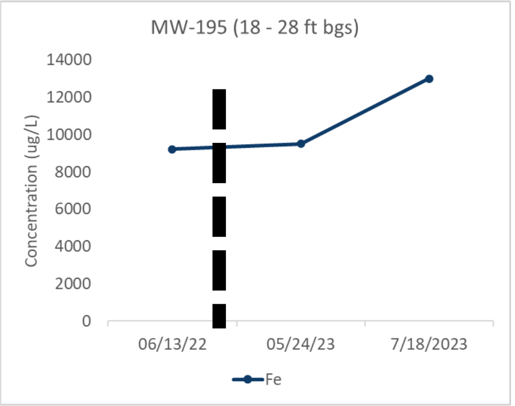


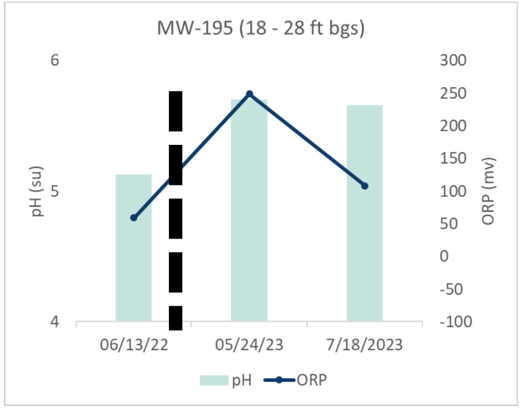


Soil mixing

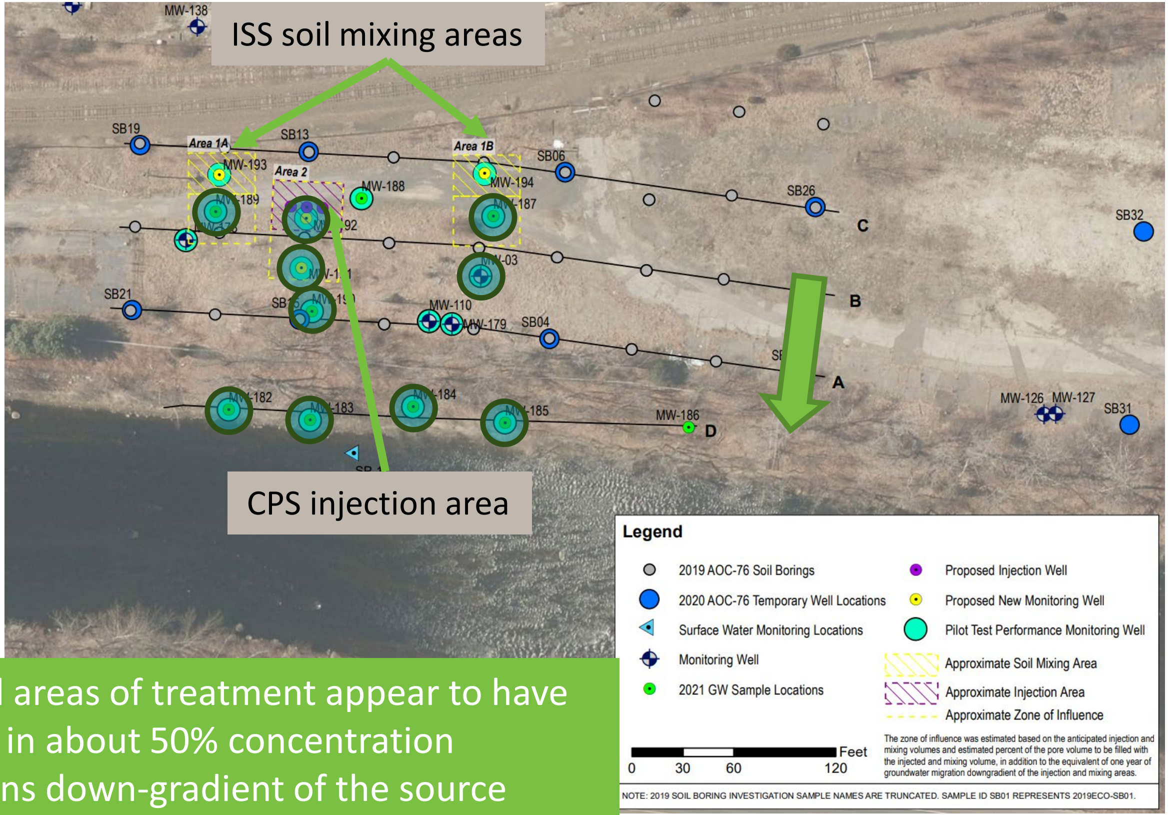
Area 1B







Zone of influence of treatment areas



Reduced concentrations of Cd, Cu, and Zn

Moderation of pH and/or reduction of ORP not observed outside of treatment areas

Targeted areas of treatment appear to have resulted in about 50% concentration reductions down-gradient of the source areas

Lessons learned – full-scale design considerations

- ISS formulation (8% w/w cement; 8% w/w FeS) in Area 1A achieved treatment goals
  - Groundwater Cd, Cu, and Zn concentrations substantially reduced
  - UCS > 50 psi
  - K < 10^{-6} cm/s
- Extensive rock layer impeded soil mixing – larger excavation cells would improve ability to mix rock
- CPS injection rates of 2 – 4 gpm per well (10 gpm for three wells) achieved
- Current CPS dose (4% w/w) is adequate for 30-40 ft bgs
- Higher CPS dose is required for 20-30 ft bgs

Full-scale considerations for the combined full-scale remedy

- Further focusing of soil mixing at water table interface and performing in larger cells
  - Highest flux zones
  - Where highest concentrations intersect water table
- Adaptively injecting CPS outside of source areas
  - Flexible application
  - Cost effective delivery of reductant
- Incorporation of a low permeability liner to further reduce costs
  - Can cost-effectively address pollutant mobility criteria exceedances and leachable metals in vadose zone
  - Can readily be integrated into development

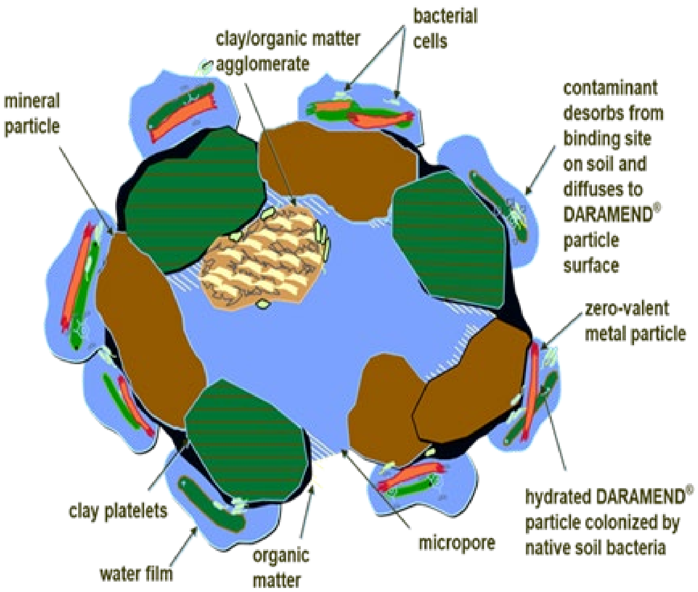
Q & A

Thank you!

Lucas Hellerich

lhellerich@woodardcurran.com

Biochemical Destruction of Chlorinated Pesticides and Organic Explosive Compounds with Sustainable ZVI/Organic Carbon Reagents



Stacey Telesz, Fayaz Lakhwala and Alan Seech
Evonik Corp.

- Daramend has been applied for more than 20 years on large-scale soil remediation projects in North America, South America, Asia and Europe.

- Contaminants treated include chlorinated pesticides such as DDT, Toxaphene, and Lindane, most CVOCs, and organic explosive compounds including TNT, RDX, and HMX.

- Sustainability is an integral part of the Daramend approach to soil remediation in both the composition of the reagents and they ways they are applied during remediation.

- Daramend reagents are formulated with zero valent iron manufactured through recycling of scrap iron and food grade plant fiber that is a byproduct of grain milling.

- Our most common approaches to soil remediation with Daramend reagents are in-situ treatment of surface soil and on-site treatment of soil after excavation.

- Both methods are considered sustainable since they eliminate transportation and off-site disposal.