BC MEND ML/ARD ANNUAL WORKSHOP

VERTEX

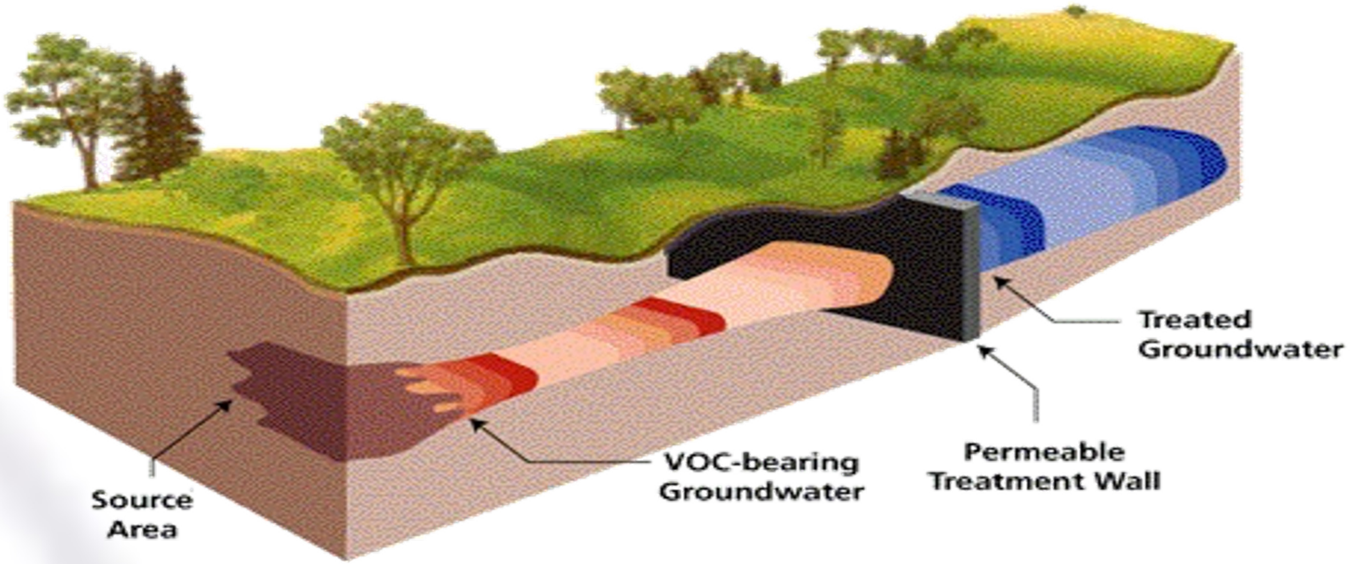
How the Design, Construction and Performance of Permeable Reactive Barriers Keeps Getting Better

BC MEND ML/ARD – Vancouver, BC

December 1, 2022

Kevin E. French, P.Eng.

Presentation Overview



- Introduction
- Overview of ML/ARD & PRBs
- Site Characterization Inputs
- Alignment Profiling
- Remedial Amendments
- Bench-Scale Testing
- Detailed Design & Sensitivity Analysis
- Installation Techniques
- QA/QC Testing
- Closing Thoughts

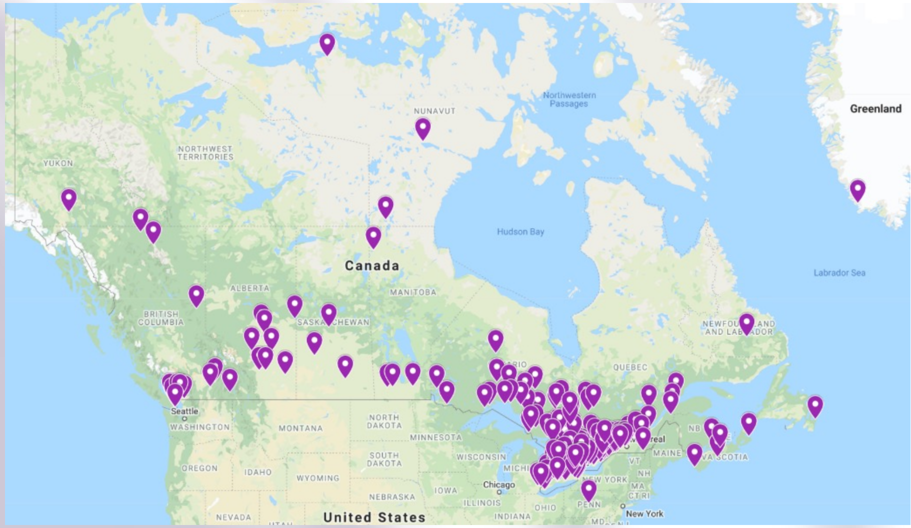
VERTEX

Introduction

Introduction – Presenter

Kevin French, P.Eng

- Vice President, Vertex Environmental
- B.A.Sc., Civil/Env. Eng., U. Waterloo
- Environmental engineering (consulting and remediation contracting) since 1988



Vertex Environmental Inc.

- Founded in 2003
- Specialized Environmental Remediation Contracting (in-situ, ex-situ, systems, HRSC)
- Provides services across Canada

VERTEX

Background on ML/ARD and PRBs

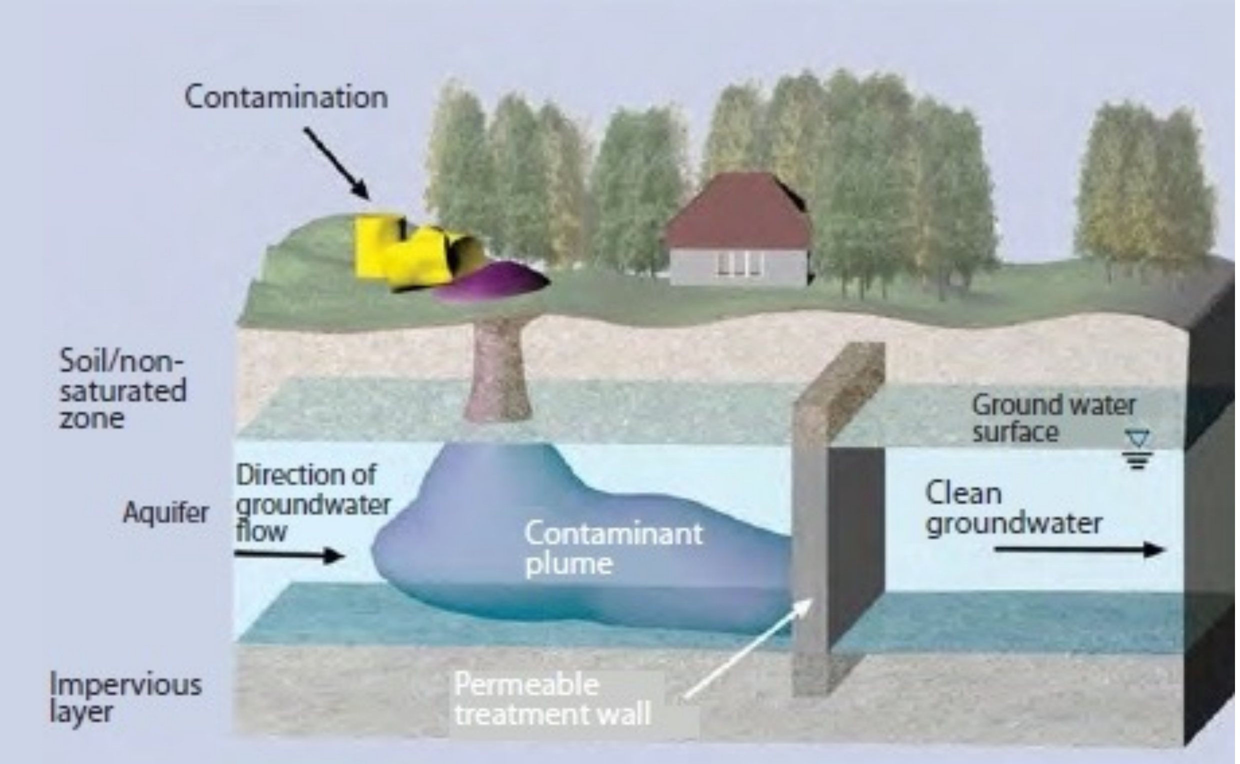
Background on ML/ARD

- Metal leachate (ML) and acid rock drainage (ARD) are common issues at mine sites where the rock contains reactive sulfide minerals
- Dissolved-phase heavy metal plumes are also common at other industrial sites
- When exposed to air and water, oxidation of the sulfides generates acidity
- The resulting leachate typically has a low pH and high concentrations of soluble heavy metals
- The long-term generation of ML/ARD requires an effective and equally long-term and ideally passive and sustainable solution

VERTEX

Background on PRBs

- Intercept and passively treat contaminated groundwater plumes
- Allow groundwater to flow through unimpeded
- Can be excavated, soil mixed or injected, etc.
- Long-lasting and sustainable (no energy use to operate)
- Contain plumes and prevent off-site migration
- Protect sensitive receptors
- Mitigate regulatory and/or third party liability



How to Design and Install a PRB – Old School

- Use generic assumptions / rules of thumb
- Dig a trench
- Mix up some ZVI and sand
- Maybe do some mag. separation testing
- Backfill the trench
- Hope for the best…
  - Under-design = Failure
  - Over-design = Wasted $$
- But what if there is something unusual about your site?
- Is there a better way?

VERTEX

Designing and Installing a PRB – A Better Way

Drivers & objectives for the PRB

Data evaluation & gaps identification

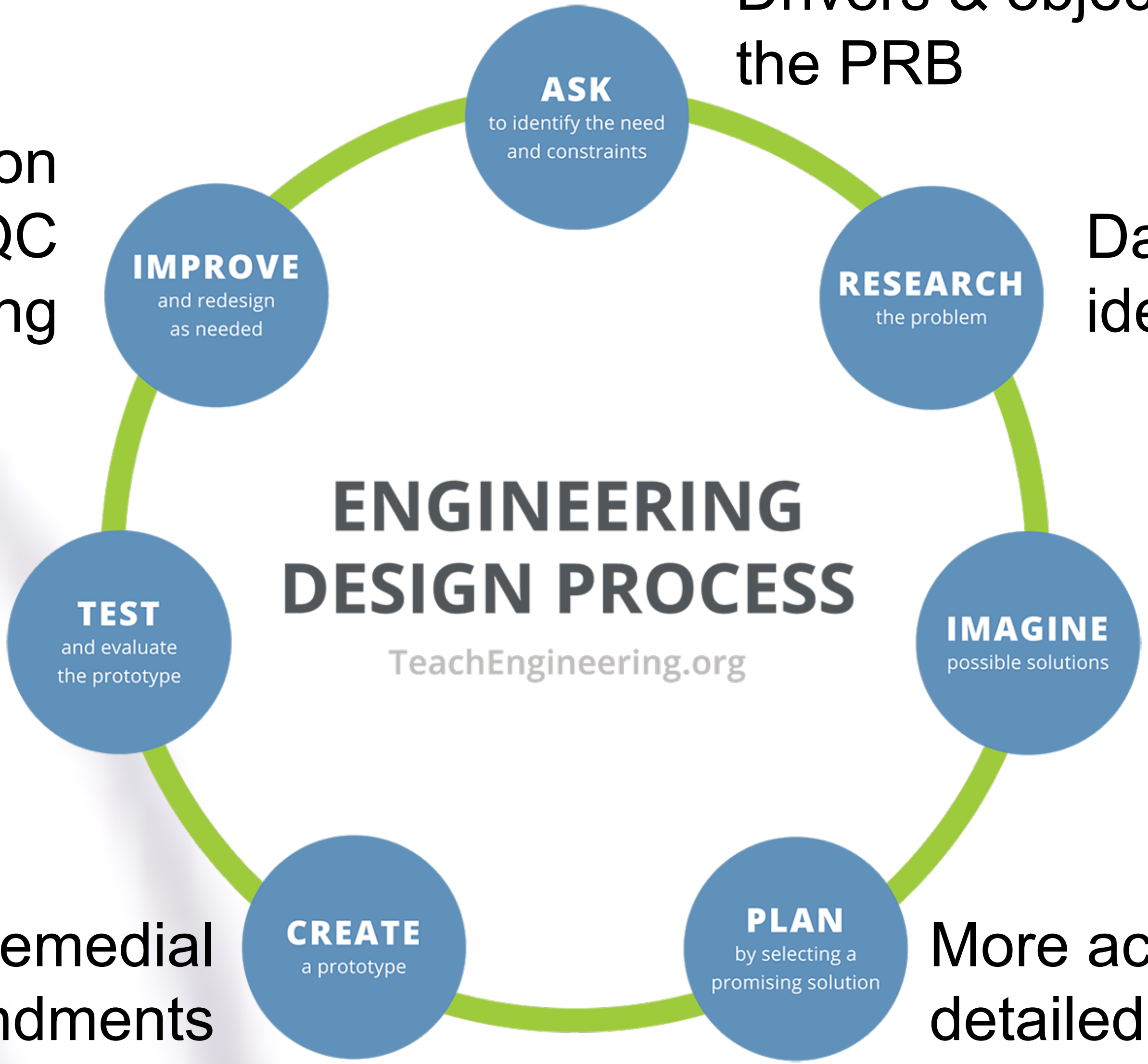
Preliminary design options

More accurate & detailed site information

Better remedial amendments

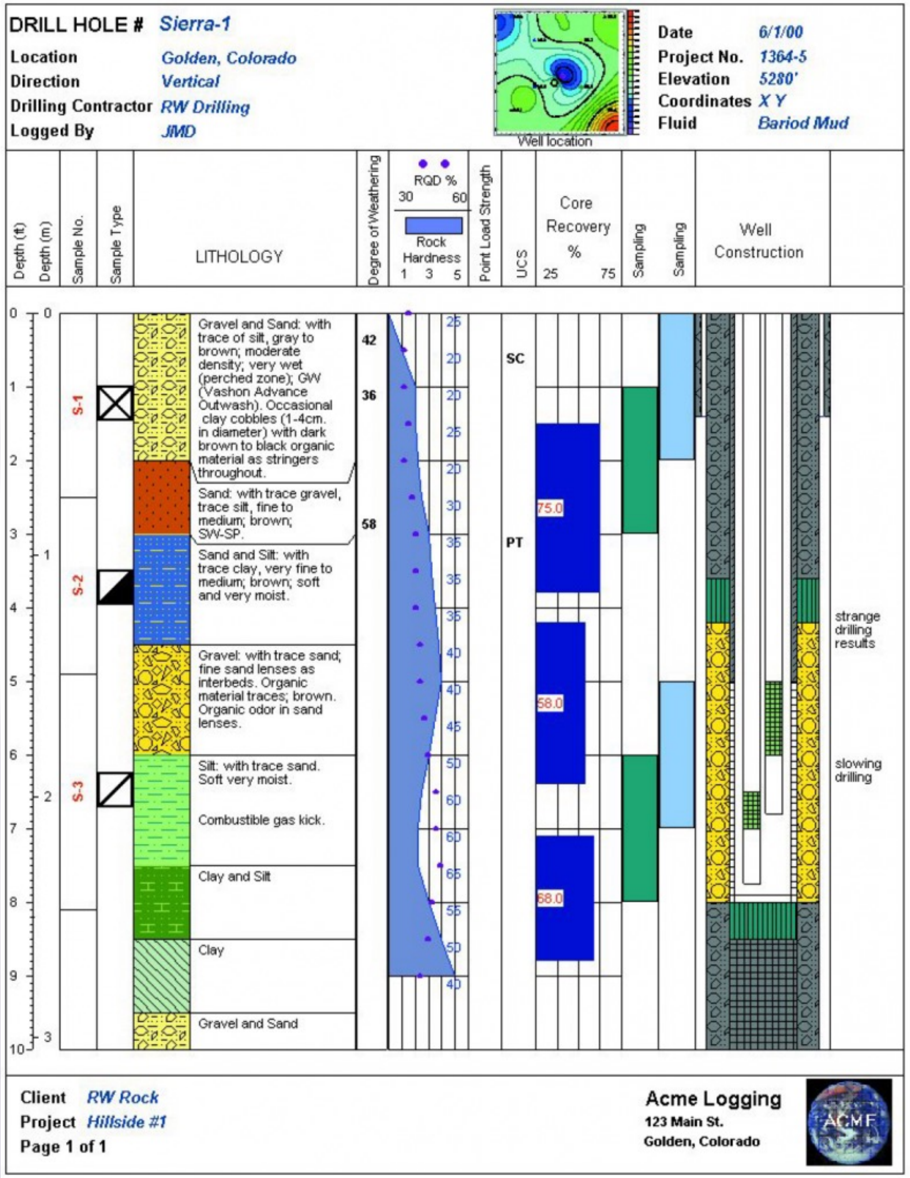
Bench-scale feasibility & design testing

Better installation methods & QA/QC testing



Site Characterization Inputs

Site Characterization Inputs



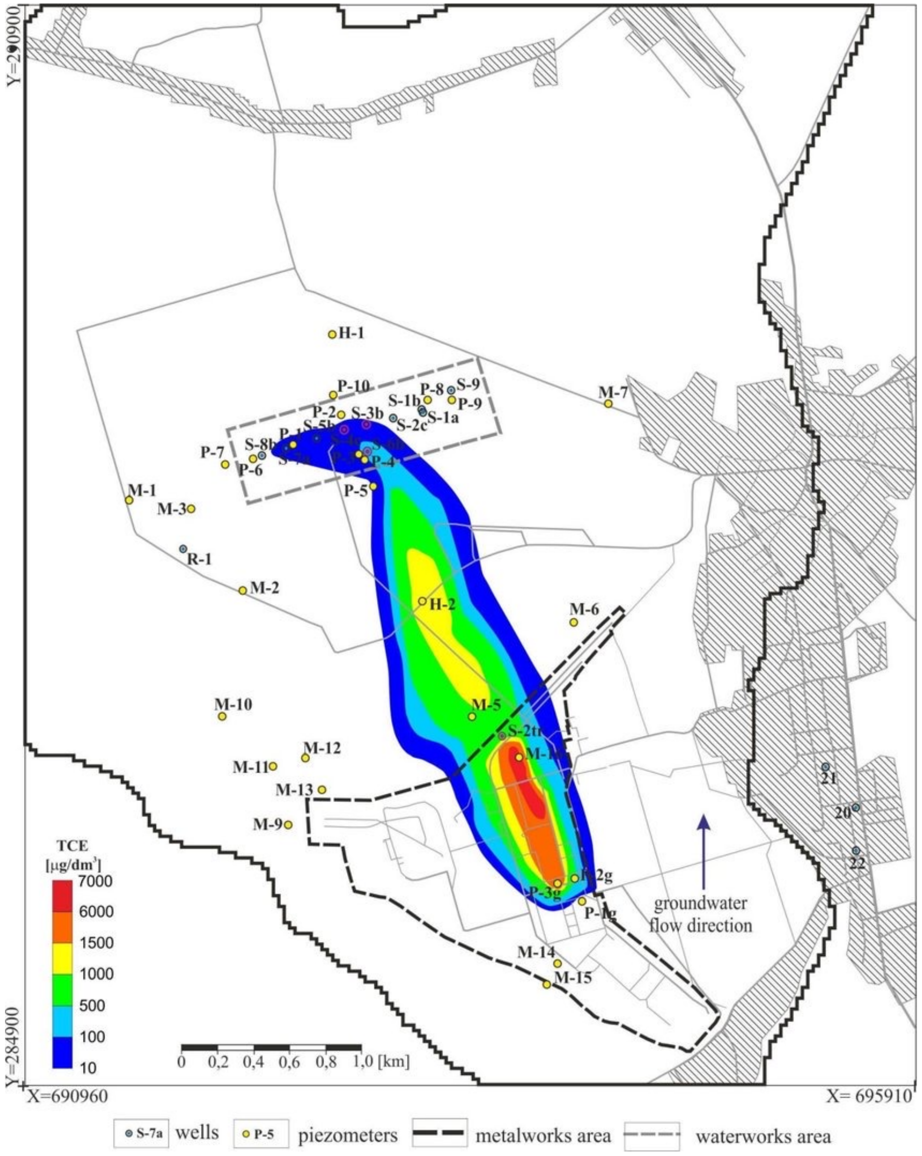
Basic Requirements (data package):

- Remedial objectives
- Contaminant types & concentrations
- Groundwater field readings
- Plume configuration / dimensions
- Groundwater depth / flow direction
- Groundwater flow velocity estimate
- Stratigraphy / BH logs
- Confining layer / base of plume
- Site access / installation restrictions

Site Characterization Inputs

Added Benefit (detailed CSM):

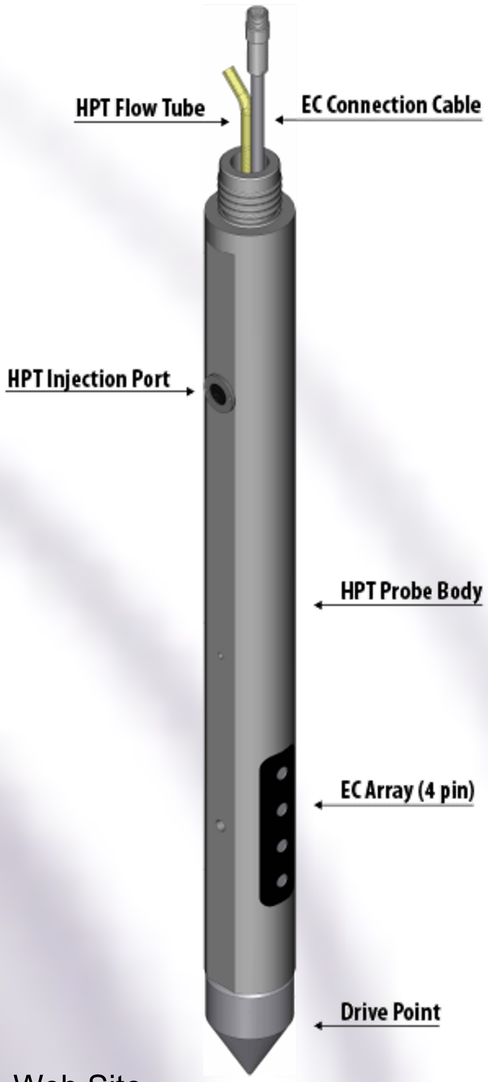
- 3D contaminant distribution
- Increasing / decreasing / steady state plume
- Seasonal variabilities
- Heterogeneities
- Hydraulic conductivity measurements
- Hydraulic gradients
- Fracture porosity (if bedrock)
- Detailed geochemistry
- Contaminant mass flux estimate



VERTEX

Alignment Profiling

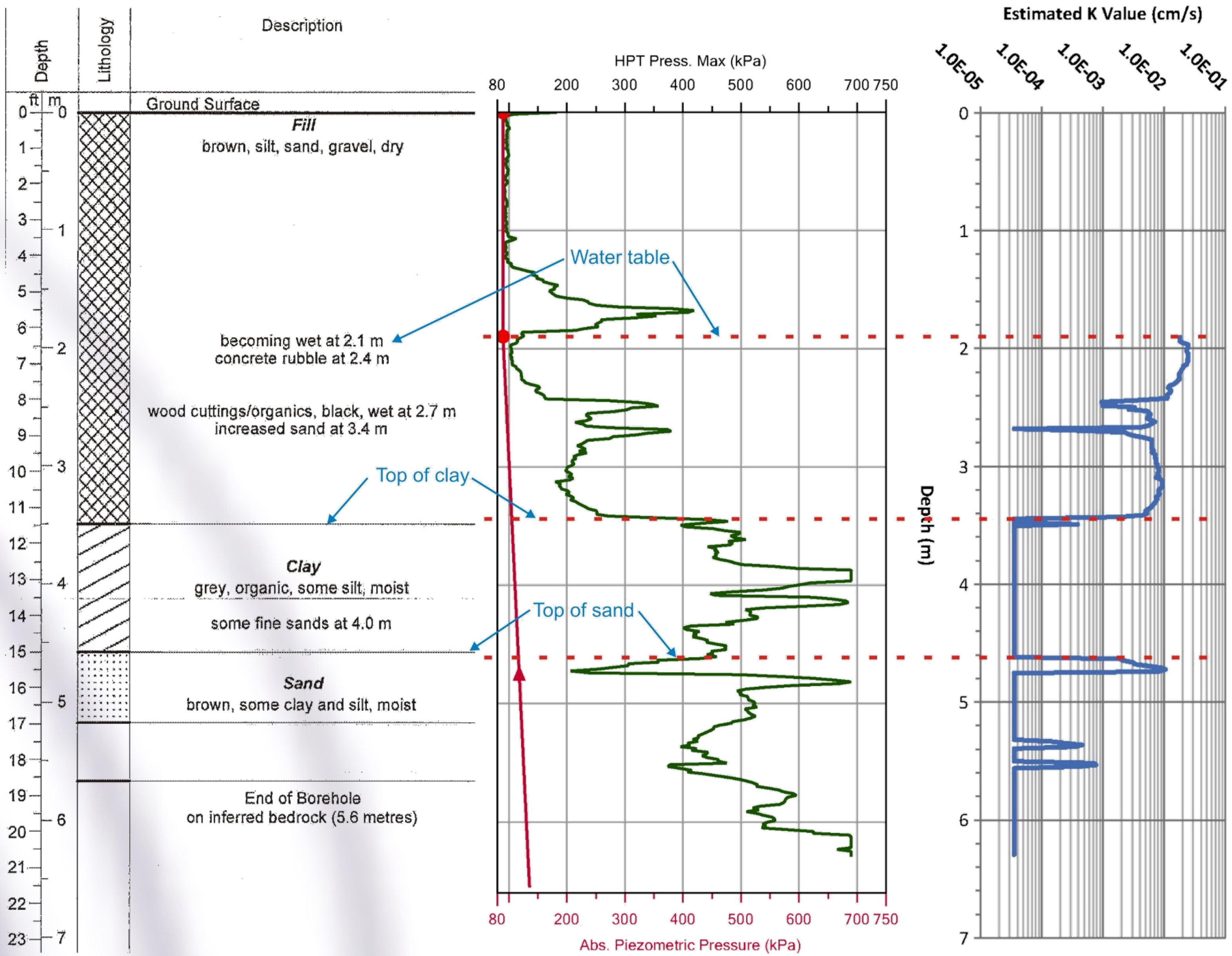
High-Resolution Site Characterization



Source:
Geoprobe Web Site

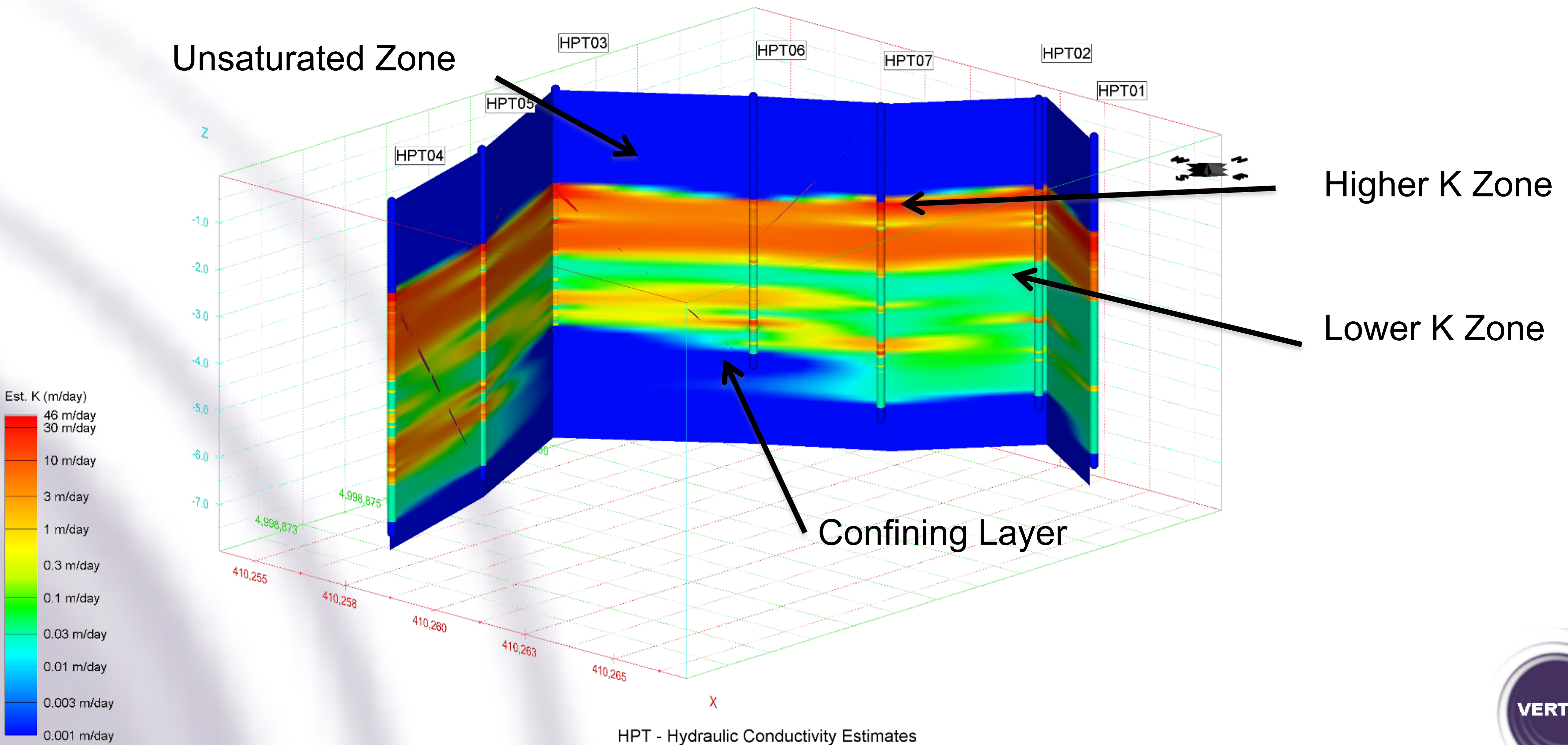
- Used to better understand subsurface conditions in fine detail
- HRSC tools can detect:
  - Permeability – Hydraulic Profiling Tool (HPT)
  - Electrical Conductivity
  - Other tools can detect LNAPL, PHCs, VOCs
- Available in Canada since 2011
- HRSC has been used at 100s of sites across Canada with 10s of km in depth probed

HRSC Results – HPT vs BH



VERTEX

HRSC Results – Data Visualization



HPT - Hydraulic Conductivity Estimates

Remedial Amendments

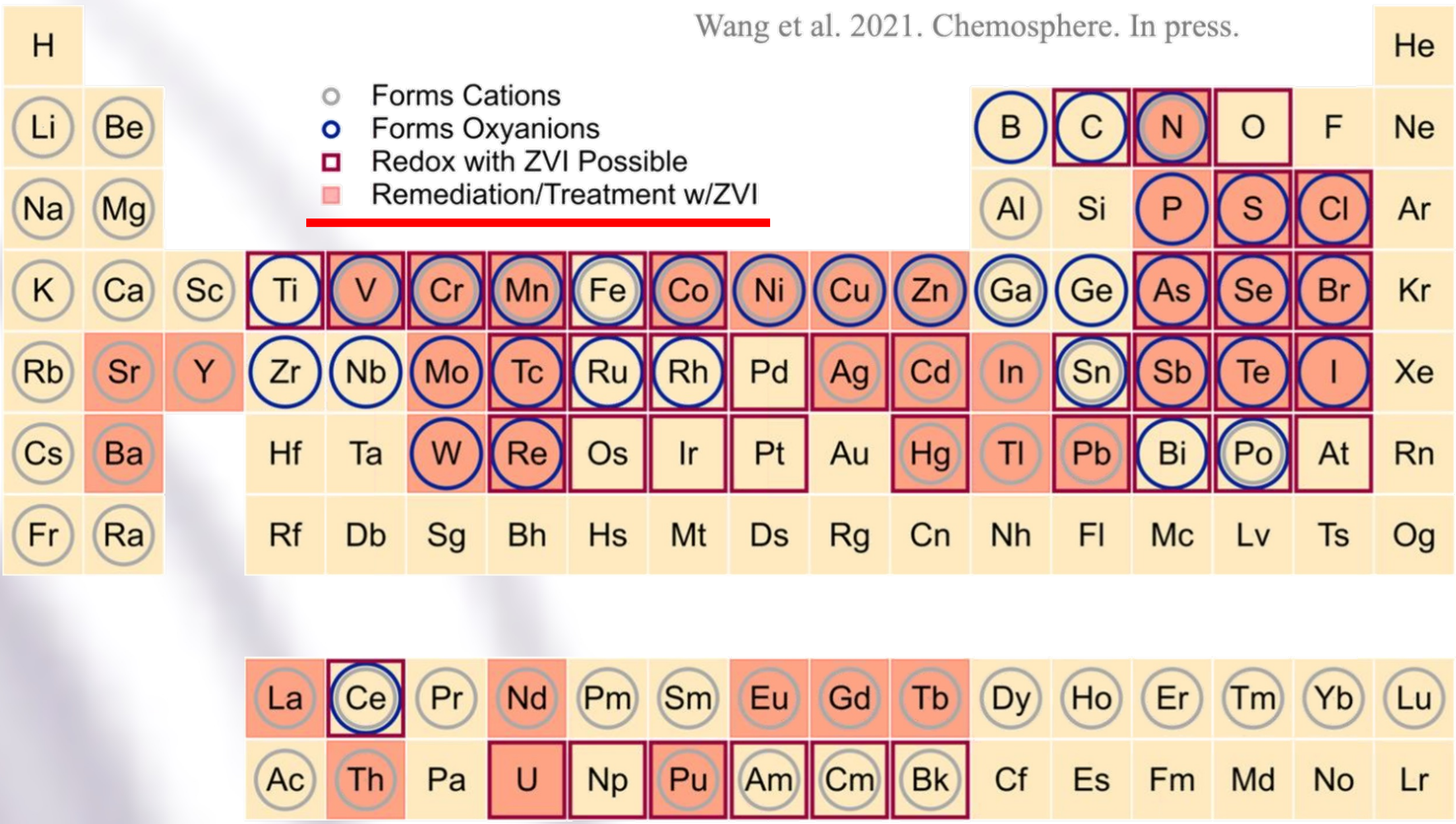
Zero-Valent Iron (ZVI) Background

- Elemental iron (Fe^0)
- Discovered in 1980s; first PRBs installed in 1990s
- Main uses were and remain heavy metals and chlorinated ethylenes
- Mechanisms: chemical reduction, complexation, (co-)precipitation of heavy metals
- Particulate solid: not mobile; will not migrate
- Multiple application techniques
- Inexpensive and readily available
- Well established, long-lasting technology
- Many of these original ZVI PRBs are still active and effective today (proven 20+ years longevity)

VERTEX

ZVI – Metals Treated

Contaminant Removal: Metals and Metalloids (Overview)



Common Metals Treated:

Most multi-valent cations: As, Cd, Co, Cr, Cu, Hg, Mn, Mo, Ni, Pb, Sb, Zn and more

Acidity Buffering Amendments

- Typically carbonate rock (limestone, dolostone, etc.) that is less soluble than CaO or $Ca(OH)_2$
- Main purpose is to assist in buffering pH and increasing alkalinity
- Not all created equal: different hardness and ABA (Sobek) values (especially pH and NNP)
- Some can also contain other trace metals!
- Must consider particle size, surface area, fines (porosity & buffering capacity over time)
- Particulate solid: not mobile; will not migrate
- More limited application techniques
- Inexpensive and readily available

Bench-Scale Testing

Types of Bench-Scale Tests

Static Batch Reactor Testing:

- Small quantities of waste, soil or groundwater from a site or spiked samples
- Physical, chemical, biological or combinations of testing possible
- Aerobic or anaerobic conditions
- Testing for inorganic or organic contaminants
- Relatively quick, easy and inexpensive to complete

Types of Bench-Scale Tests

Flow-Through Column Reactor Testing:

- Larger quantities of groundwater from a site or spiked samples
- Physical, chemical, biological or combinations of testing possible
- Aerobic or anaerobic conditions
- Testing of inorganic or organic contaminants
- Slightly more complicated and expensive to complete
- Usually takes more time

VERTEX

Case Study
Part 1 – Bench-Scale Testing

Approach: Static Batch and
Flow-Through Column Reactors

Objective: Evaluate the feasibility of
removing various heavy metals from ARD
and other impacted groundwaters

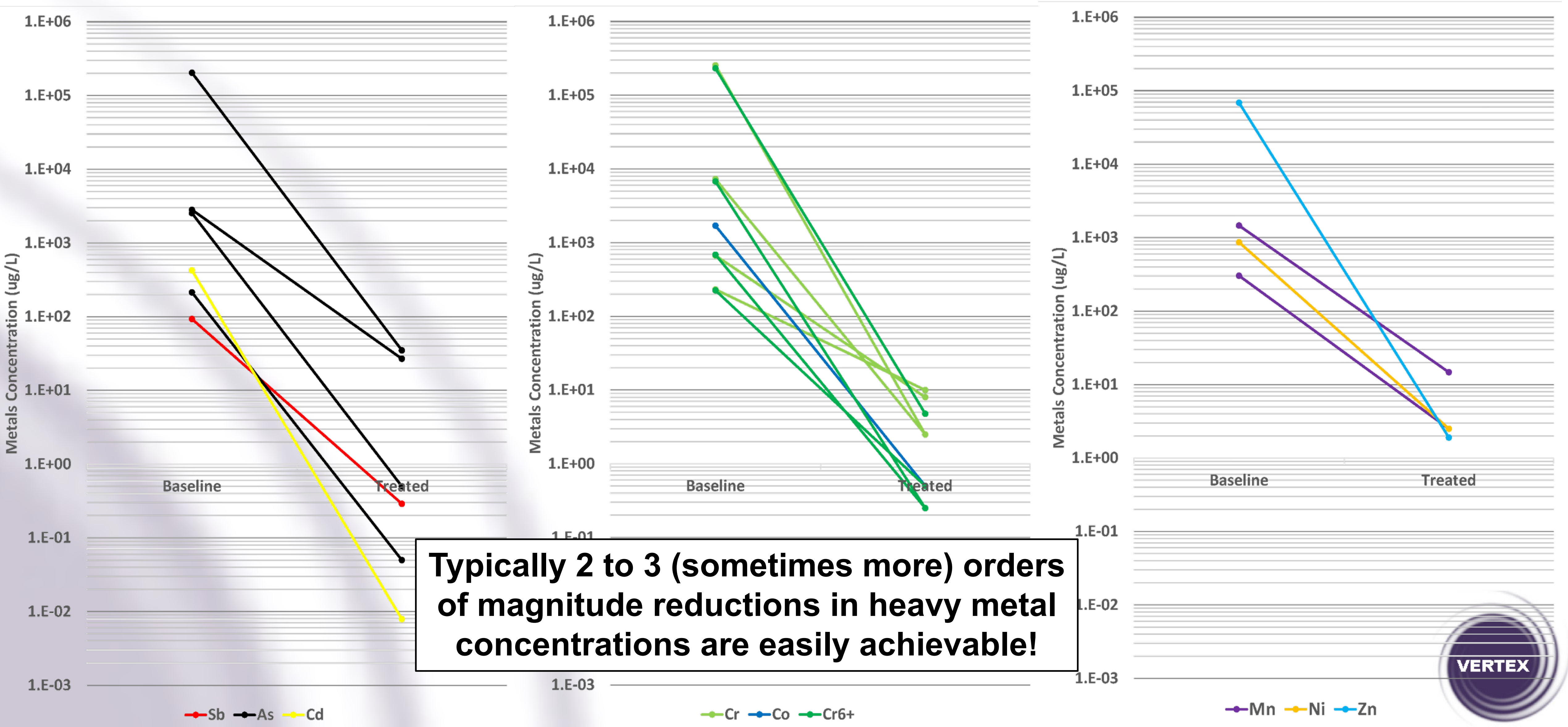
Case Study Part 1 – Bench-Scale Methodology

- Obtain samples of impacted groundwater from sites
- Set-up static batch reactors with different reactive media
- Assess performance
- Set-up multiple flow-through column reactors with preferred reactive media
- Record flow rates (contact times) and analyze effluent
- Interactively adjust reactive media composition to provide better performance and longevity

VERTEX

Case Study Part 1 – Bench-Scale Results

Examples of Heavy Metal Reductions in Groundwater Using ZVI (some pH buffered)



Typically 2 to 3 (sometimes more) orders of magnitude reductions in heavy metal concentrations are easily achievable!

Case Study Part 1 – Bench-Scale Results

Parameter	Percent Reductions Achieved
Antimony	>99%
Arsenic	>99% to >99.9%
Cadmium	>99.99%
Chromium	>95 to >99.999%
Cobalt	>99.9%
Hex. Chromium	>99% to >99.99%
Manganese	>99%
Nickel	>99%
Zinc	>99.99%

Bench-scale testing can be (and has been) used to demonstrate that heavy metal impacts from MN/ARD & other industrial sites can be passively treated over the long-term

VERTEX

Detailed Design & Sensitivity Analysis

Detailed Design & Sensitivity Analysis

Detailed Design:

- Profile PRB alignment – chemical & physical
- Contaminant mass flux across PRB
- Required contact time for percent reductions needed (e.g. half lives)
- Lifetime demand of remedial amendment(s)
- Minimum density required for contact
- Apply safety factors (typically 100%)

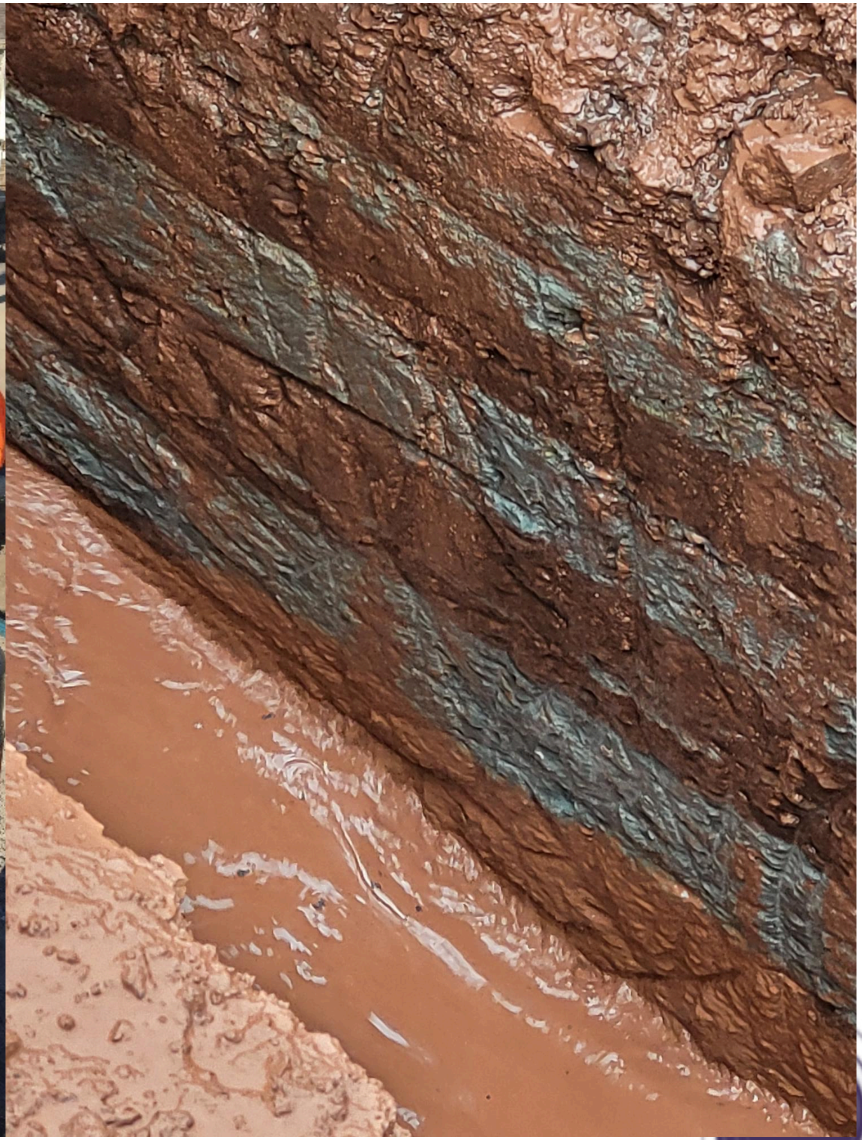
Sensitivity Analysis:

- Effect of variability / uncertainties (in order of importance):
  - Contaminant concentrations in soil and groundwater
  - Hydraulic conductivity
  - Hydraulic gradient
  - Formation porosity

VERTEX

Installation Techniques

Installation Techniques – Excavation



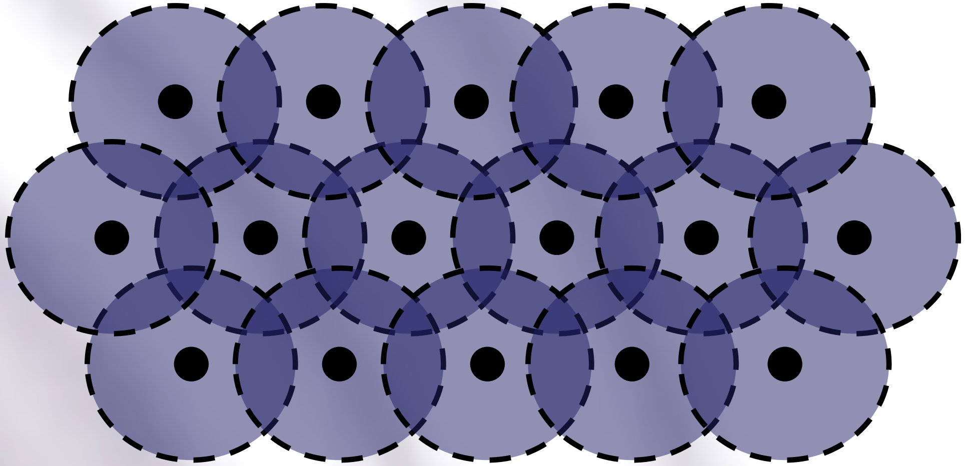
Installation Techniques – Overburden Injection

VERTEX

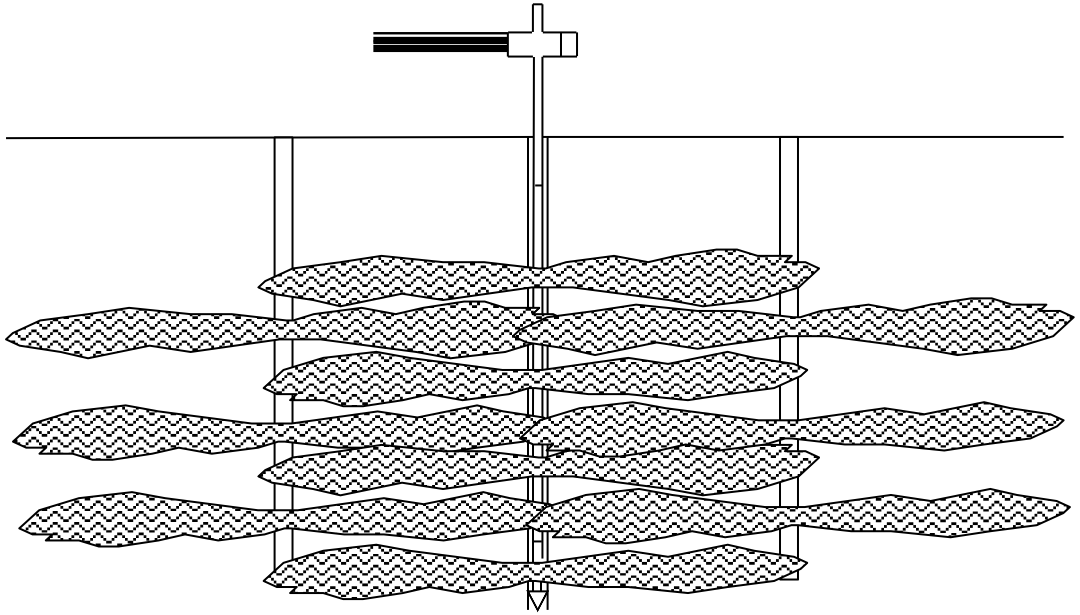
Installation Techniques – Overburden Injection

The Goal:

- Uniform Distribution
- Contact between remedial amendment and contaminants



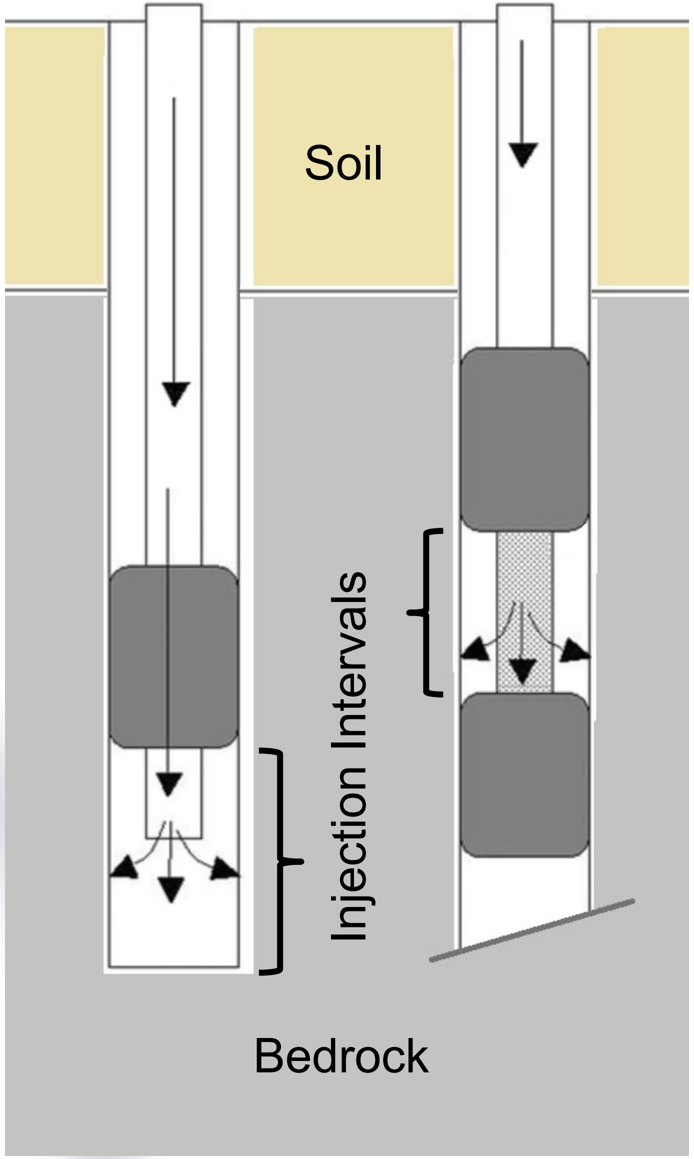
Plan View



Profile View

VERTEX

Installation Techniques – Bedrock Injection



Case Study
Part 2 – Full-Scale Installation

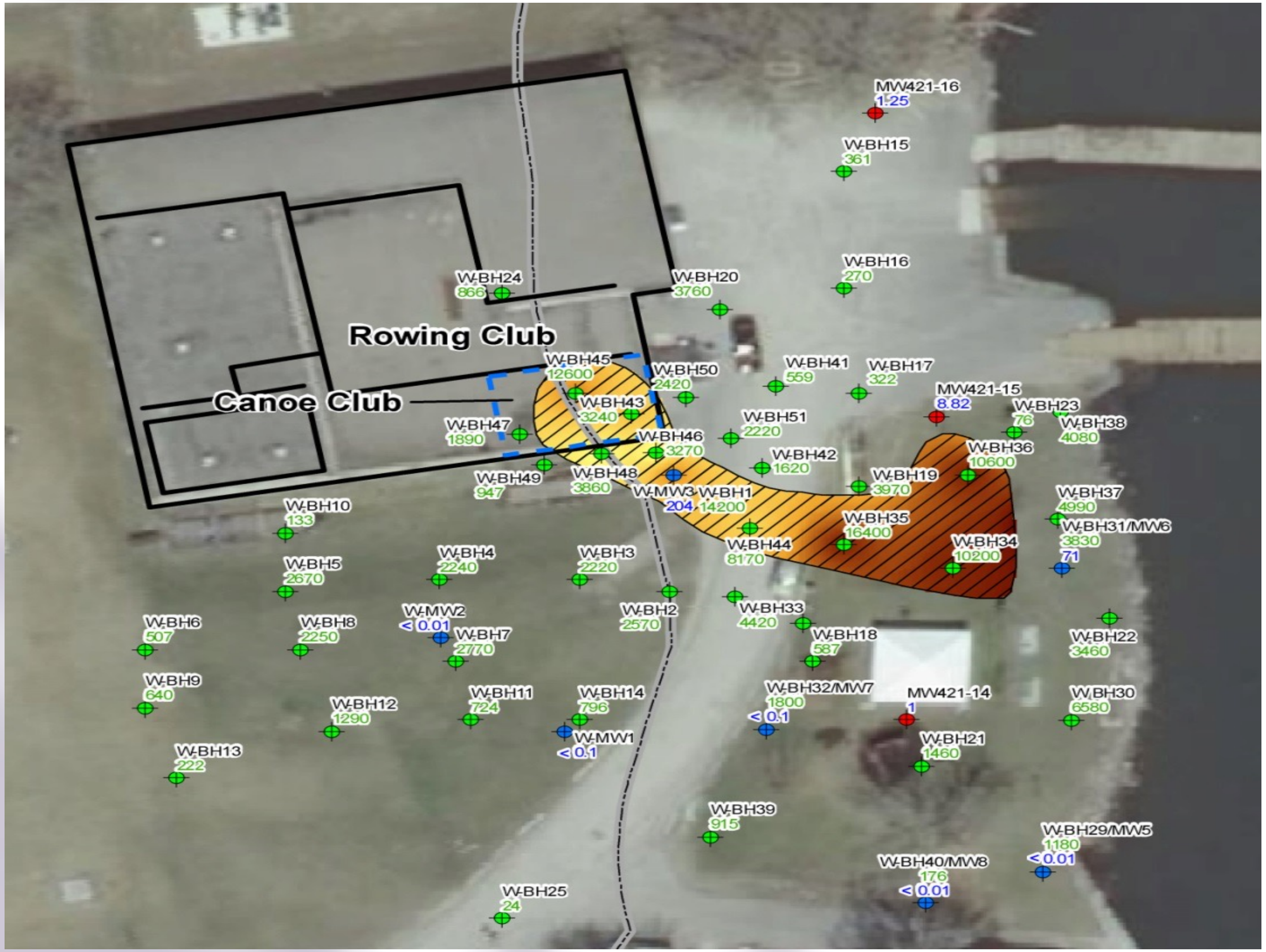
Approach: Injected and
Funnel & Gate Trenched PRBs

Objective: Remediate a plume of high
concentration arsenic in groundwater
from migrating to an adjacent water body

Case Study Part 2 – Full-Scale PRB Installation

- Former site of lead smelting and leather tanning operations
- Significant soil and groundwater impacts from arsenic
- Concern over discharge of impacted groundwater to adjacent river

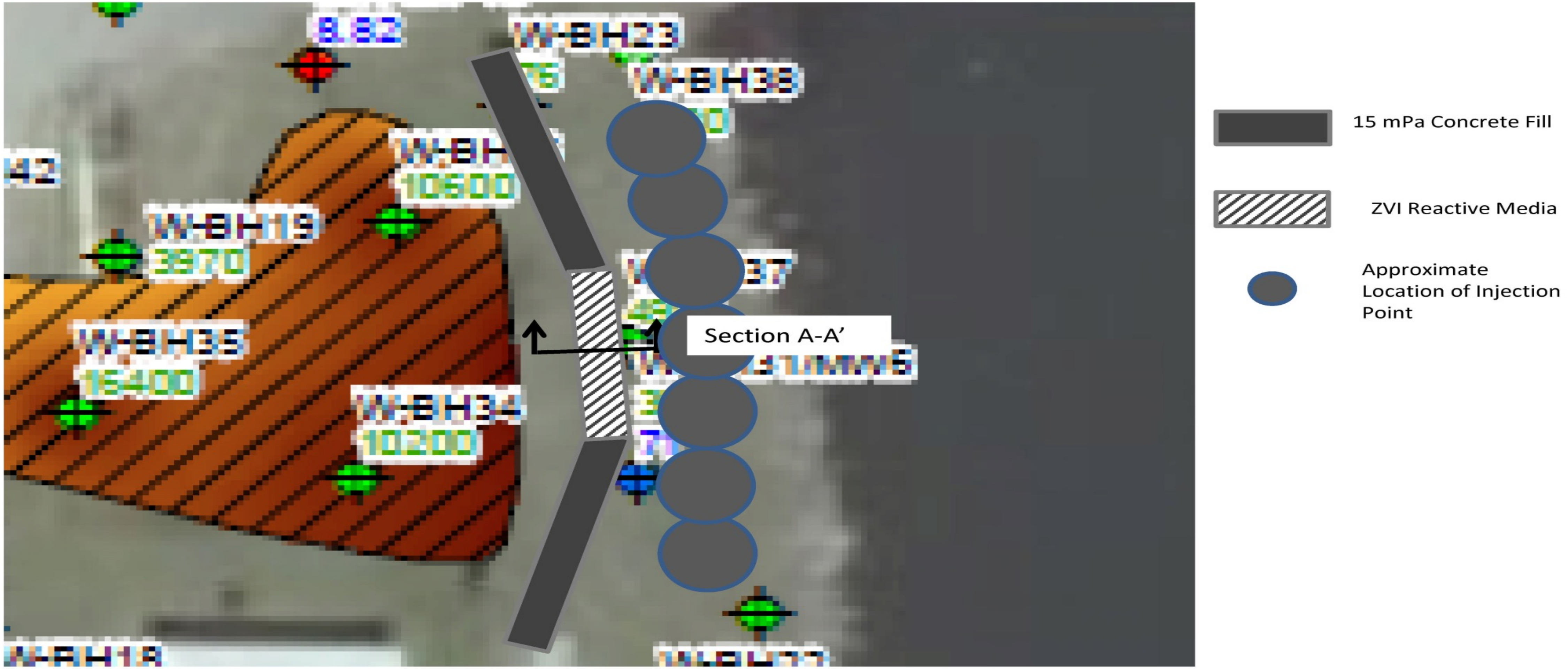
Case Study Part 2 – Site Background



- Arsenic in soil >16,000 ppm
- Soils were leachate toxic (hazardous) waste
- Arsenic in groundwater >200,000 ppb in source area
- Original RFP was for a pump & treat (i.e., active) system

VERTEX

Case Study Part 2 – PRB Conceptual Design



Alternate proposal for a "funnel & gate" cut and fill ZVI PRB with injected ZVI PRB as a back-up

Case Study Part 2 – Full-Scale Installation – Injection

- Injected PRB first installed near shoreline (too close to excavate)
- Injected micro-scale ZVI in a slurry using Geoprobe
- Then trenched and emplaced macro-scale ZVI mixed with concrete sand into main “funnel & gate” PRB

VERTEX

Case Study Part 2 – Full-Scale Installation – Trenching

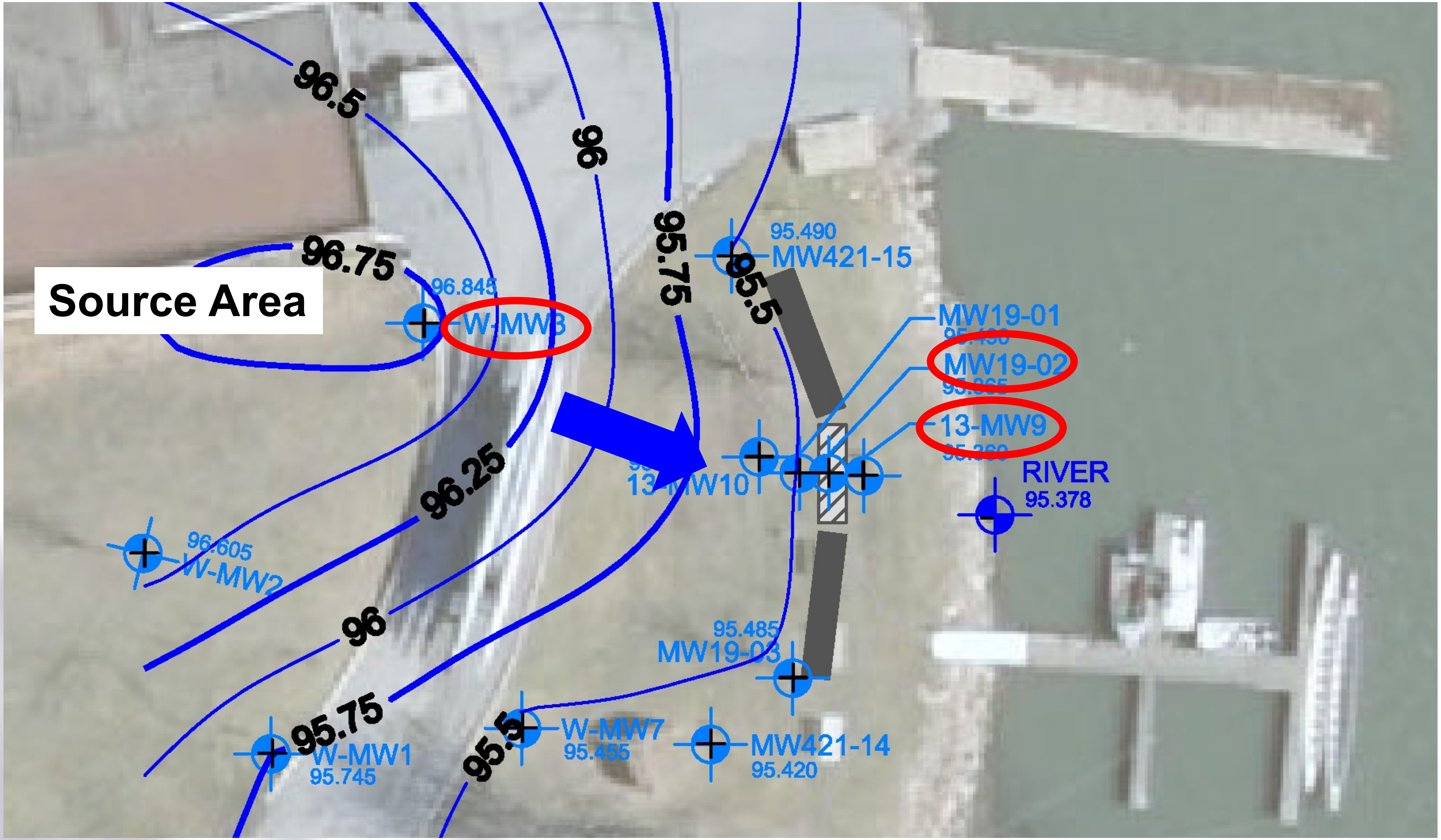
Line of temporary points for injected PRB

Excavation for “cut & fill” PRB

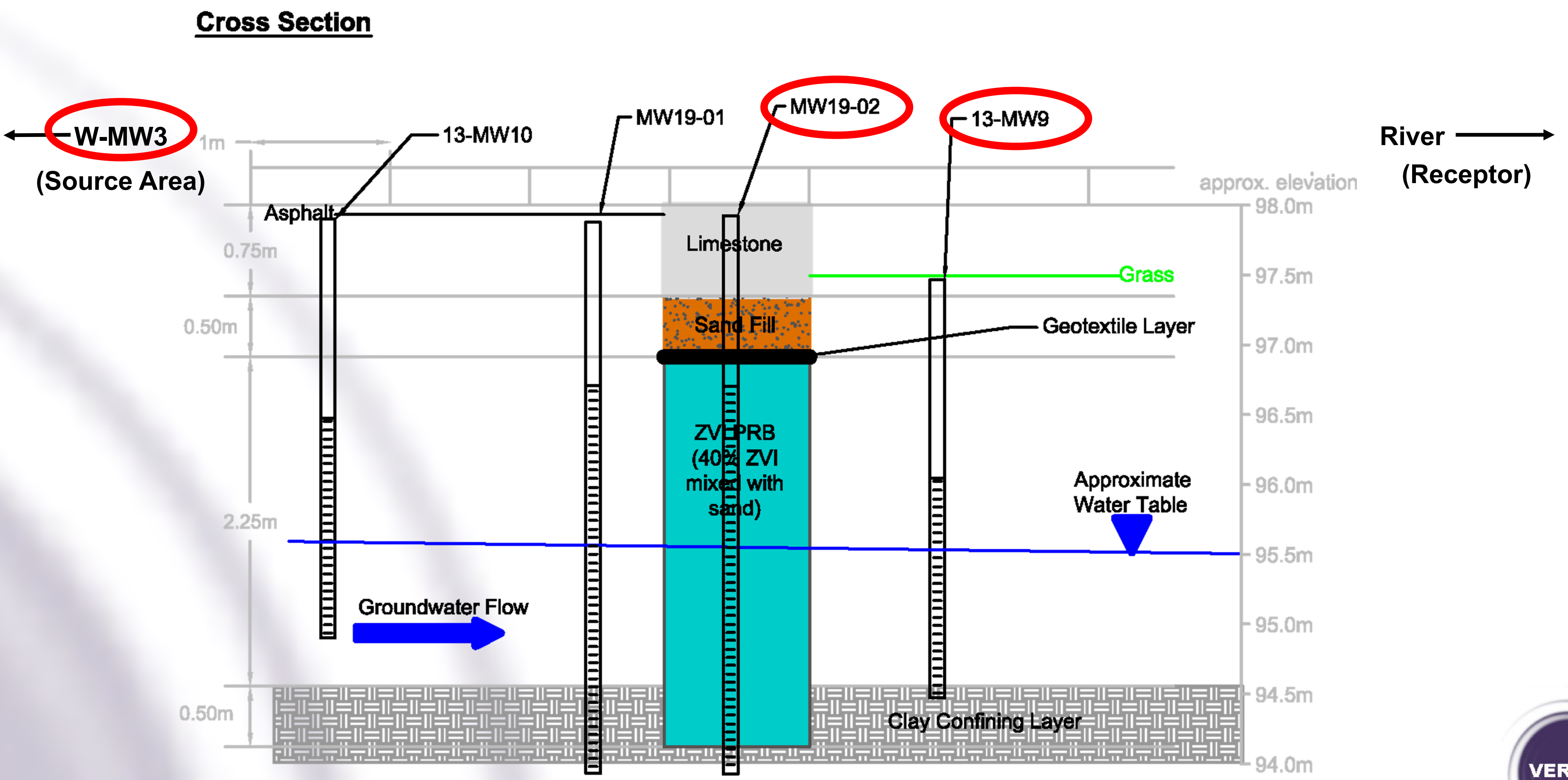
Main “funnel & gate” direct place ZVI PRB installation

VERTEX

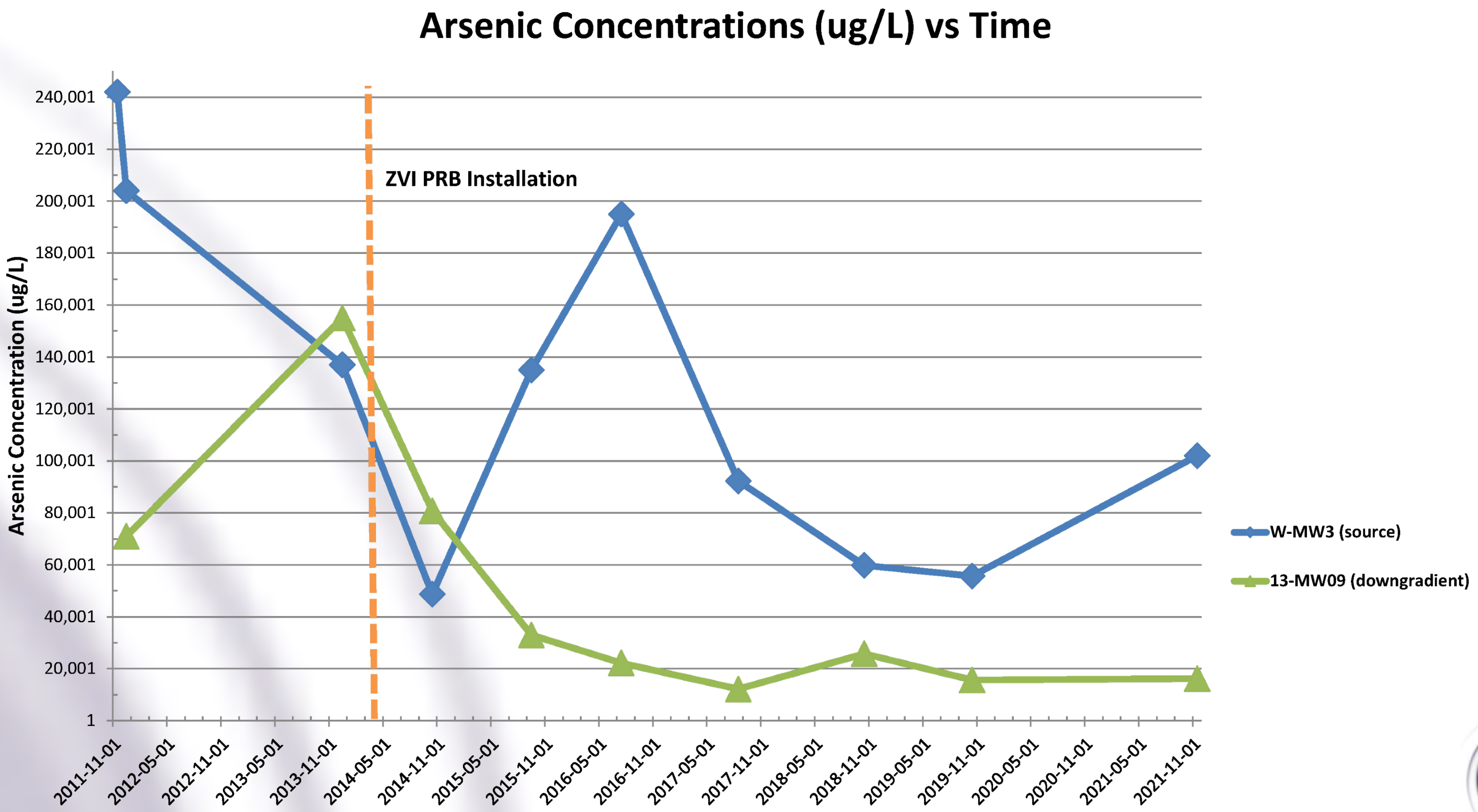
Case Study Part 2 – Groundwater Flow Pattern



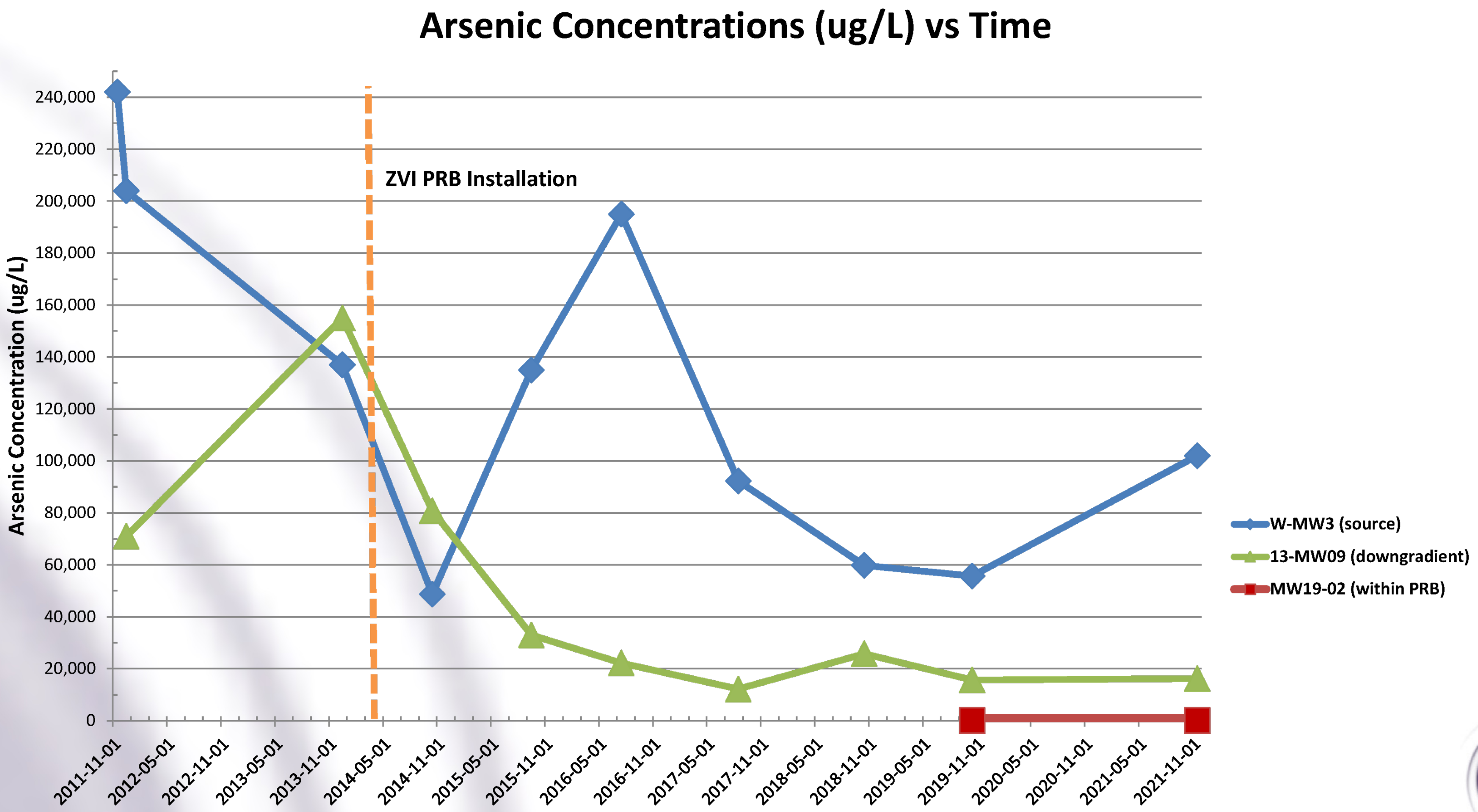
Case Study Part 2 – Performance Monitoring – Locations



Case Study Part 2 – Performance Monitoring – Observations



Case Study Part 2 – Performance Monitoring – Observations



VERTEX

Case Study Part 2 – Full-Scale Results

- Passive PRB and source area capping proposed as an alternate, more cost-effective and sustainable solution to requested pump & treat system
- Two-stage PRB installed:
  - Injected ZVI PRB close to the shoreline as a back-up
  - Main funnel and gate trenched PRB installed further inland
- Full-scale implementation completed in 2014 with seven years of post-installation performance monitoring data available:
  - As concentrations in source area remain high (>100,000 ug/L)
  - Downgradient well has sustained As concentrations much lower (~20,000 ug/L) but suggests residual impacts likely downgradient of first PRB
  - Additional treatment of groundwater will occur from second PRB before discharge to river
  - ~99.98% reduction of As in groundwater within PRB

QA/QC Testing

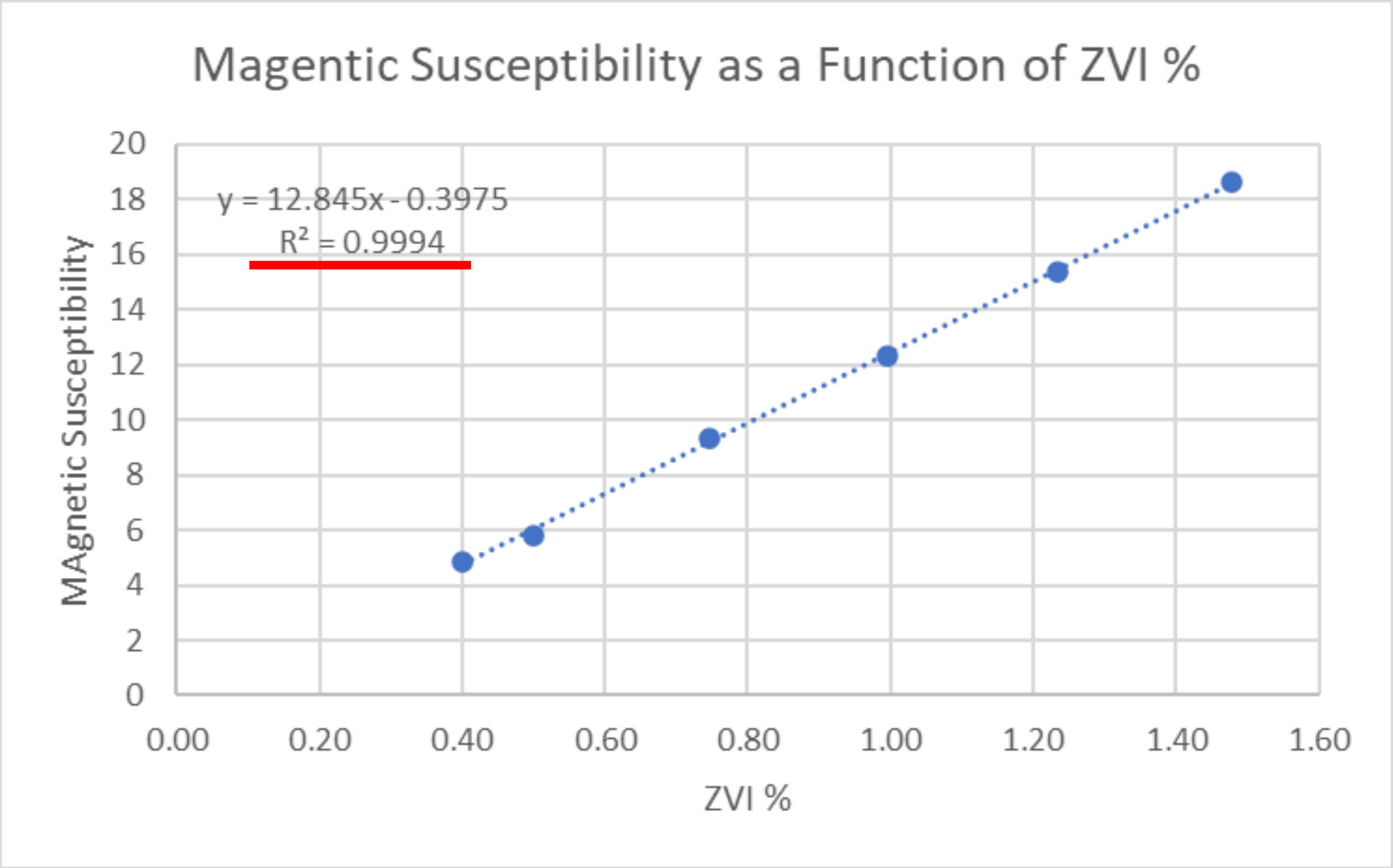
Quality Assurance / Quality Control – Old School

Date	Batch	ZVI (%)
26/04/2016	1	32.3%
26/04/2016	2	31.9%
26/04/2016	3	31.5%
28/04/2016	4	33.7%
28/04/2016	5	34.2%
Average		**32.7%**

- Samples of ZVI / sand mixture collected from each batch mixed for magnetic separation testing
- Post-installation boreholes drilled through reactive media portion of PRB for magnetic separation testing
- Results compared to target concentrations (e.g. 30% wt./wt.)
- Low accuracy; subject to human error

QA/QC Testing – New & Improved

Magnetic Susceptibility Testing for ZVI content



QA/QC Testing – Performance Monitoring

Ultimate PRB Validation:

- Sampling & laboratory analysis of upgradient vs downgradient heavy metal concentrations
- Monitoring expected changes in geochemistry (pH, ORP, etc.)
- Monitoring consistency in treatment over time

Closing Thoughts

Closing Thoughts – PRBs for ML/ARD

Applicability of PRBs to ML/ARD:

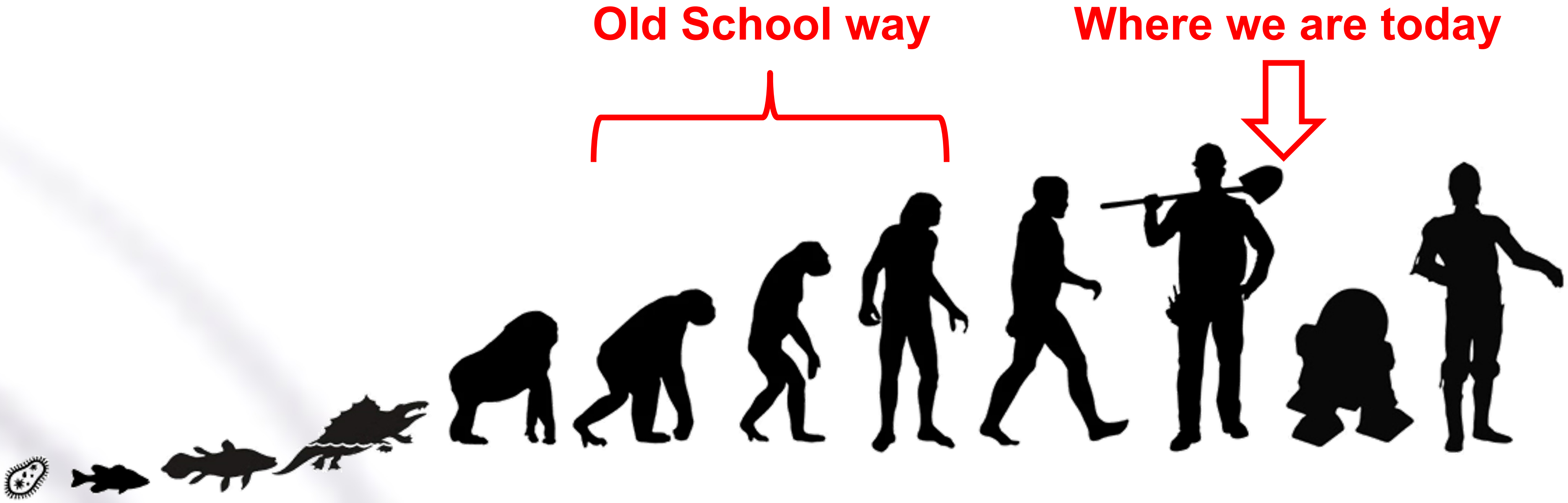
- Well-proven technology with a long track record of success
- Suitable for most heavy metals common in ML/ARD at mining & industrial sites
- Bench-scale testing for site-specific applicability & to optimize remedial amendments
- Flexible application / installation methods
- Excellent Risk Management option – plume containment & property boundary control
- Very long lasting (years to decades)
- Relatively inexpensive and sustainable (passive)

Closing Thoughts – PRB Design & Installation

Why the Design, Installation & Performance of PRBs is Better than Ever:

- Existing site characterization data (CSM) is reviewed & validated
- Desktop modeling & preliminary design is completed
- Significant data gaps / unacceptable uncertainties are identified
- Additional site data collected, if needed (HRSC, k testing) to resolve
- Potentially appropriate remedial amendment(s) selected
- Bench-scale testing completed to assess site-specific response
- Detailed design & sensitivity analysis completed; safety factors applied
- Robust QA/QC program to ensure field installation is as per design
- Results in a long-lasting, sustainable PRB that has been properly designed using defensible scientific and engineering principals & is tailored to the site

VERTEX



(The Evolution of PRB Design, Installation and Verification)

Questions?

Thank You for Your Time!

Kevin French, B.A.Sc., P.Eng.
Vertex Environmental Inc.
(519) 404-5442
kevinf@vertexenvironmental.ca
www.vertexenvironmental.ca