DESIGN AND IMPLEMENTATION OF EISB SYSTEMS FOR CHLORINATED COMPOUND REMEDIATION

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LESSONS LEARNED

"We know a thing or two because we've seen a thing or two."

– Farmer's Insurance Company

PRESENTATION OUTLINE

When to Consider EISB

Bioremediation 101

Basic EISB Systems

The Design Process

Other Considerations

DNAPL Source Areas

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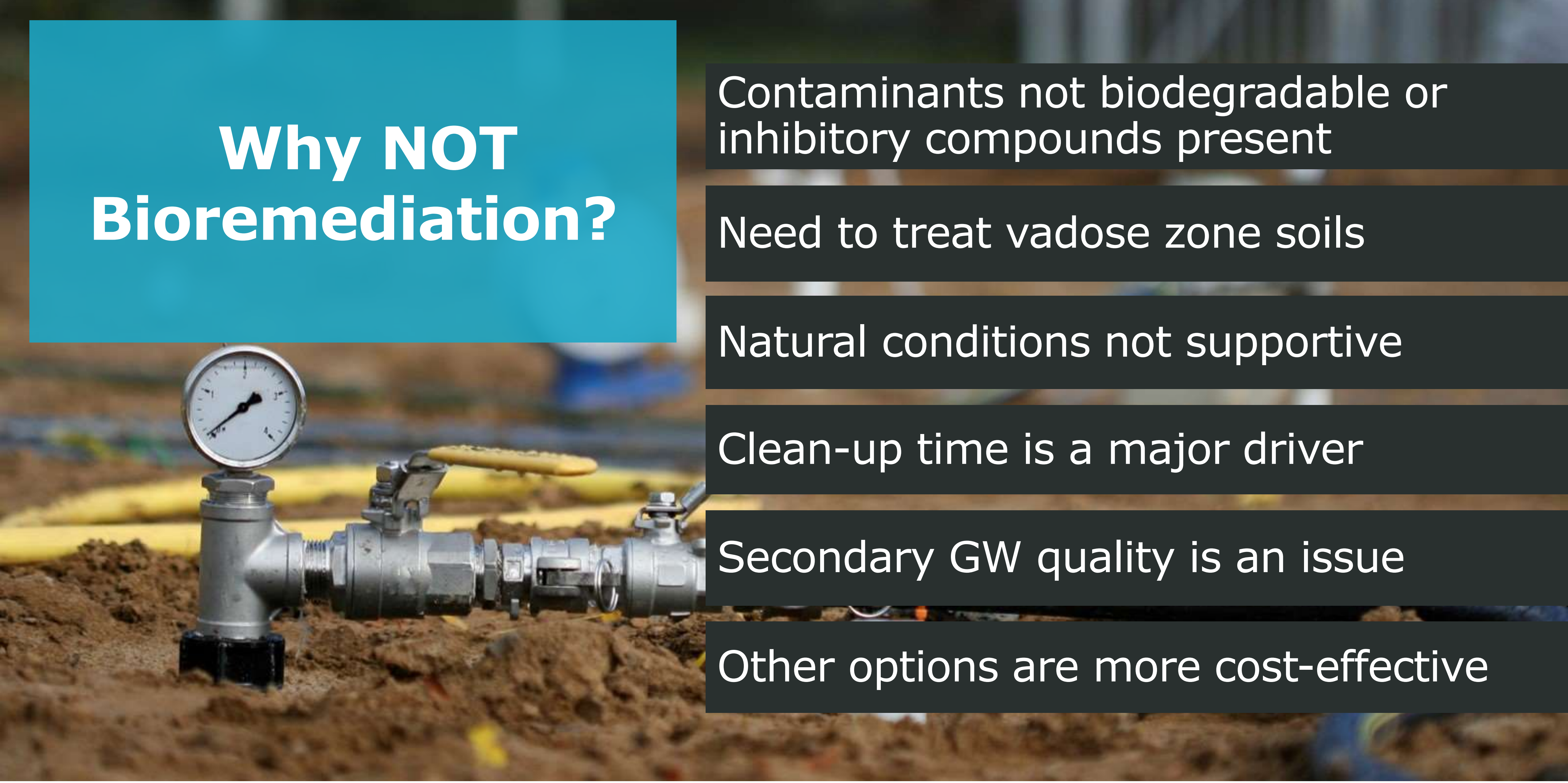
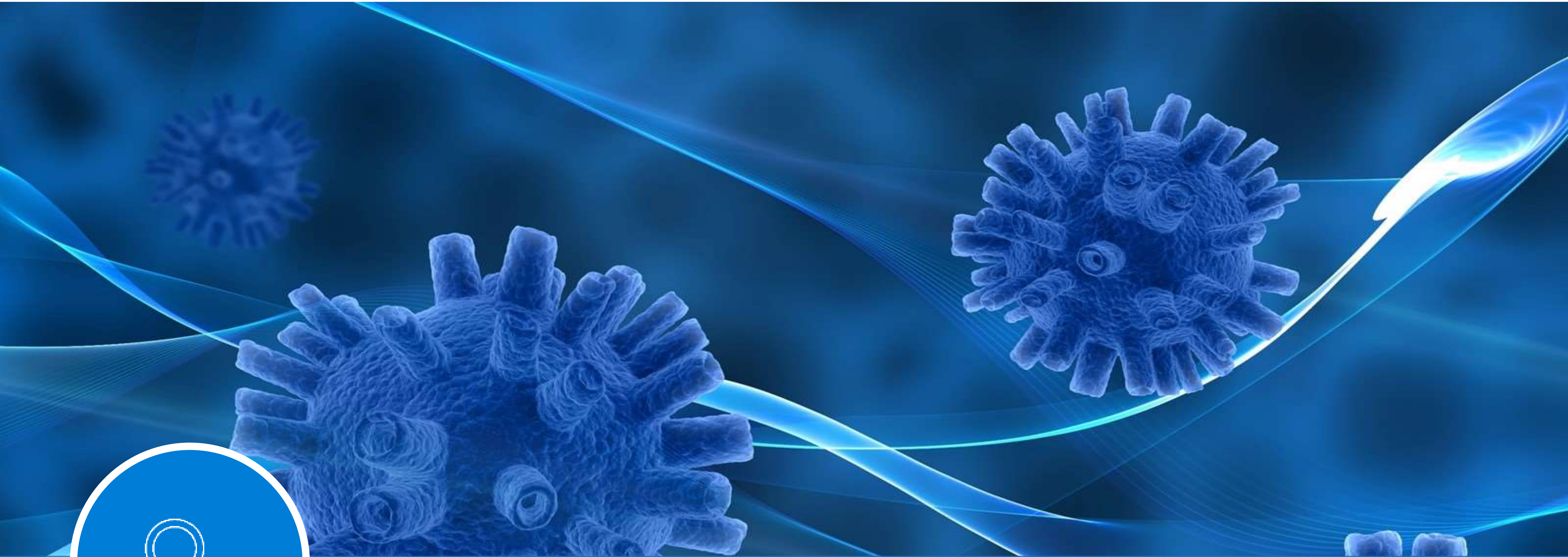
Why Bioremediation?

- Usually highly cost-effective
- Effective for most common GW contaminants
- Applicable to source areas and plumes
- Uses simple and safe substrates and nutrients
- Minimal above-ground profile
- Low O&M requirements and operational risk
- Flexible and sustainable (low carbon footprint)
- Compatible with natural attenuation



Why NOT Bioremediation?

- Contaminants not biodegradable or inhibitory compounds present
- Need to treat vadose zone soils
- Natural conditions not supportive
- Clean-up time is a major driver
- Secondary GW quality is an issue
- Other options are more cost-effective



MICROBIOLOGY 101

MICRO-BIOLOGY 101

Microorganisms (bacteria) are everywhere. There are 10^5 - 10^7 bacteria in every gram of soil.

Like all organisms, bacteria need to eat and breathe. They eat electron donors and breathe electron acceptors.

Bacteria need low levels of other nutrients like nitrogen, phosphate, and trace minerals.

Bacteria also need water and shelter (mineral surfaces). Given these, they can survive in extreme environments (from -25° to 120°C and from pH < 2 to pH > 12).

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MICROBIOLOGY 101

KEY DEFINITIONS

Aerobic

Environmental conditions where oxygen is present

Anaerobic

Environmental conditions where oxygen is absent

Biotic

Process mediated by bacteria

Abiotic

A purely physical or chemical process

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MICROBIOLOGY 101

ELECTRON DONORS

Electron Donor: A compound that loses electrons during biodegradation (source of energy for bacteria)

- Hydrogen is the main electron donor in most anaerobic biodegradation processes.
- Hydrogen is produced by the fermentation of complex organic compounds.
- Examples include natural organic matter, small organic acids, fermentable substrates, waste solvents (i.e. methanol, acetone), landfill leachate, BTEX compounds

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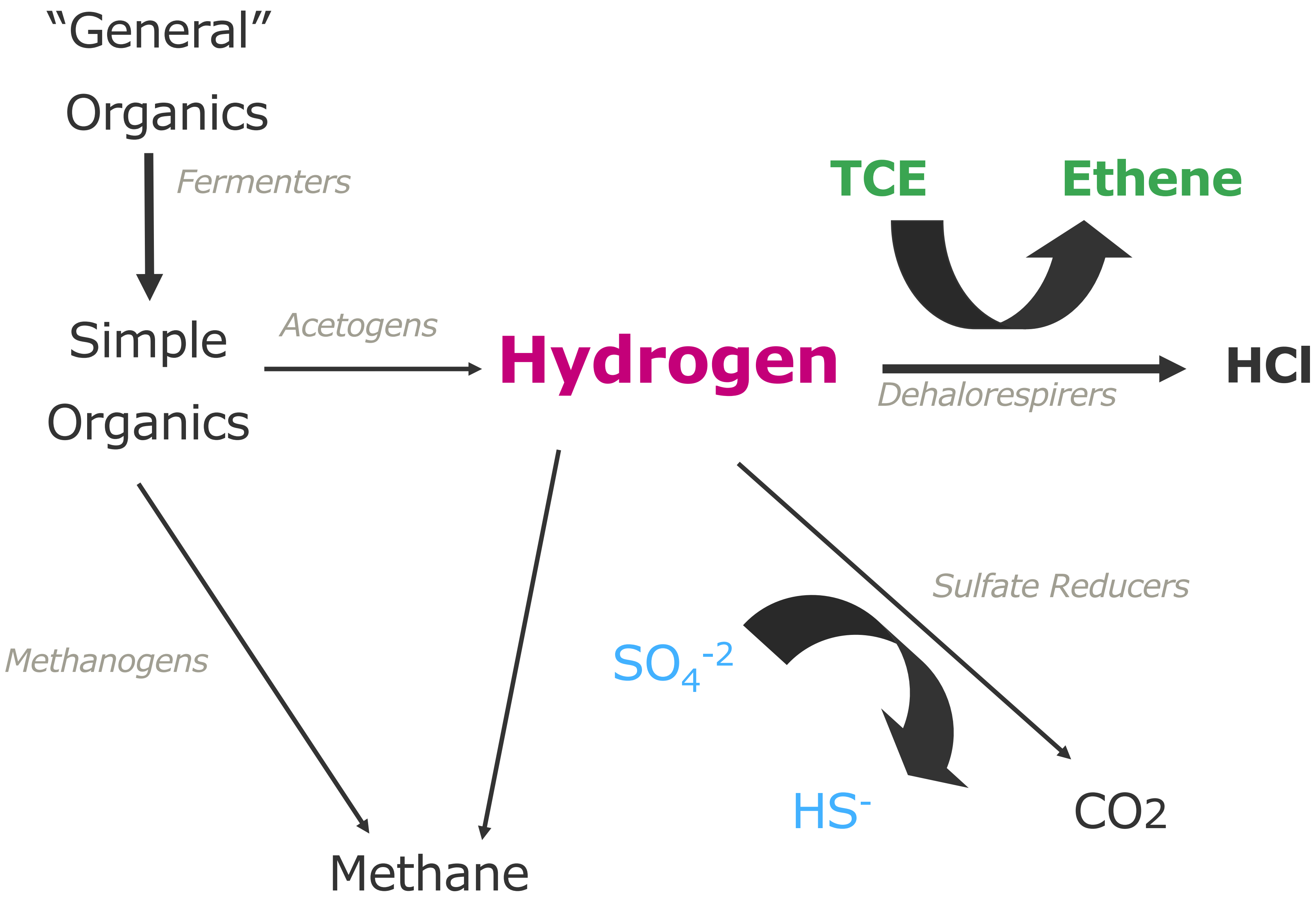
MICROBIAL COMMUNITIES INVOLVED IN ANAEROBIC REDUCTIVE DECHLORI-NATION



MICRO-BIOLOGY 101

CHLORINATED COMPOUNDS AS ELECTRON ACCEPTORS

Respiration	Redox Range	Bacteria
O_2 => CO_2/H_2O	+0.8 to +0.2	Aerobic
NO_3 => N_2	+0.5 to +0.2	Nitrate reducing
Fe^{+3} => Fe^{+2}	+0.3 to 0	Iron reducing
SO_4 => H_2S	-0.1 to -0.3	Sulfate reducing
CO_2 => CH_4	-0.2 to -0.4	Methanogenic
CO_2 => CH_3COOH	-0.2 to -0.4	Acetogenic

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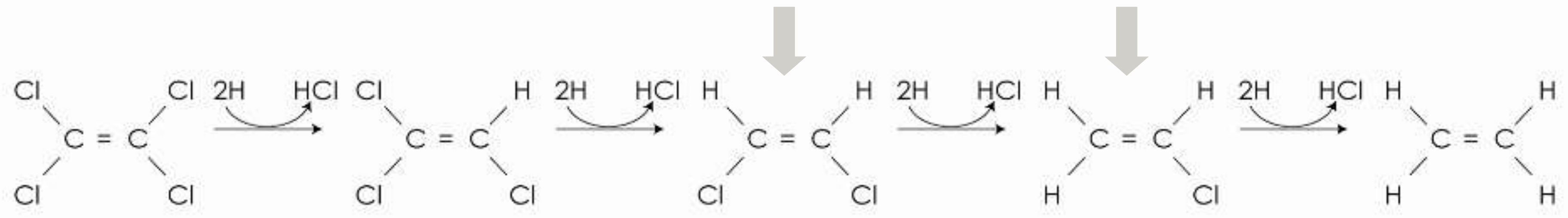
MICROBIOLOGY 101

REDUCTIVE DECHLORINATION PATHWAY

Can accumulate if requisite bacteria are absent



PCE TCE cis-1,2-DCE VC Ethene

Dehalobacter
Dehalospirillum
Desulfitobacterium
Desulfuromonas

Dehalococcoides

Geobacter

Multiple strains within a single group *(Dehalococcoides)*

ESIB SYSTEMS

WHEN WE TRY TO FIGHT MOTHER NATURE, WE USUALLY LOSE…

Match the remedy to the natural environment
Anaerobic aquifers → EISB or ISCR (not ISCO)
Aerobic aquifers → more options (but avoid EISB in high-flow situations)
Low permeability soils → modify injection method and use solid amendments

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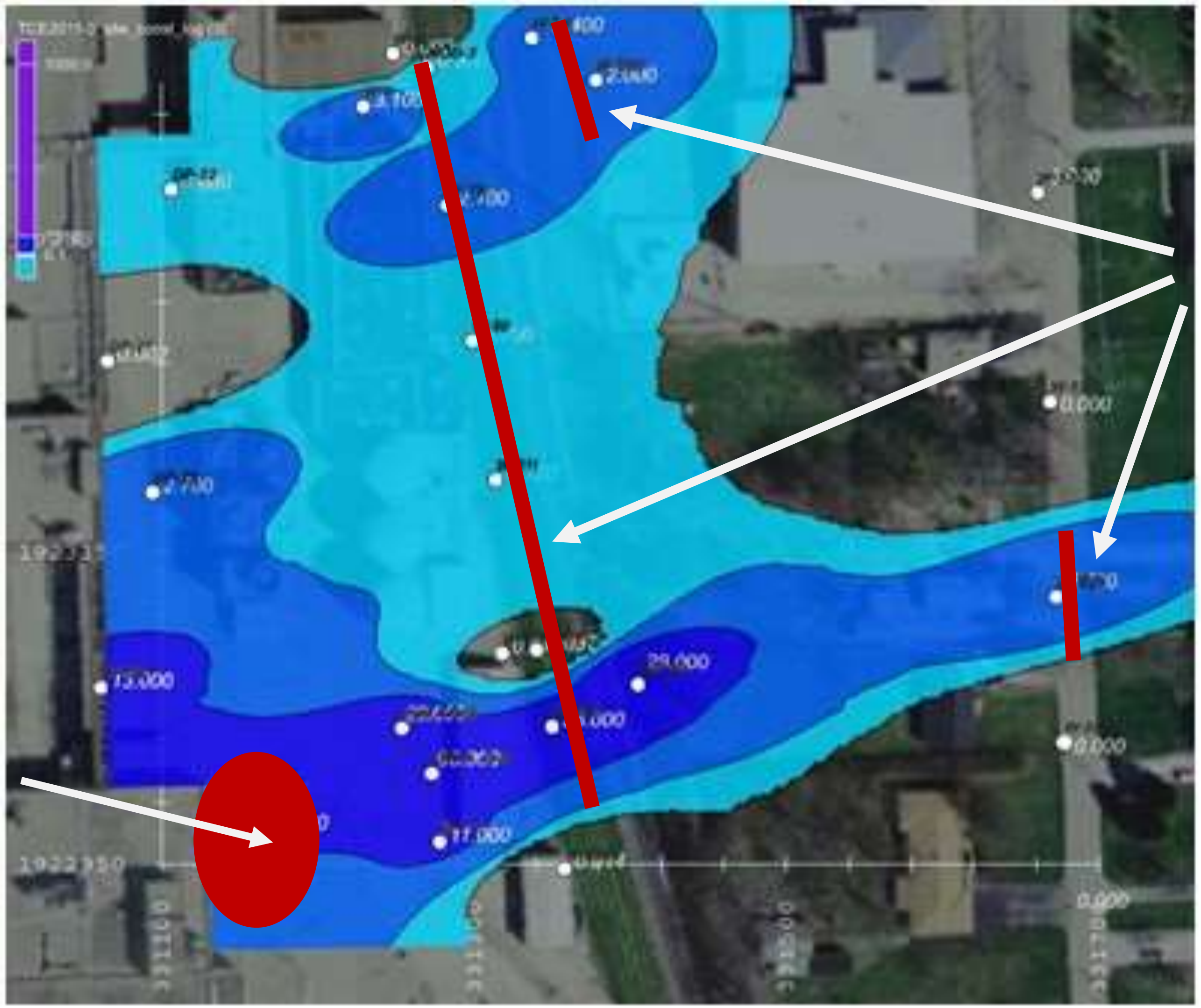
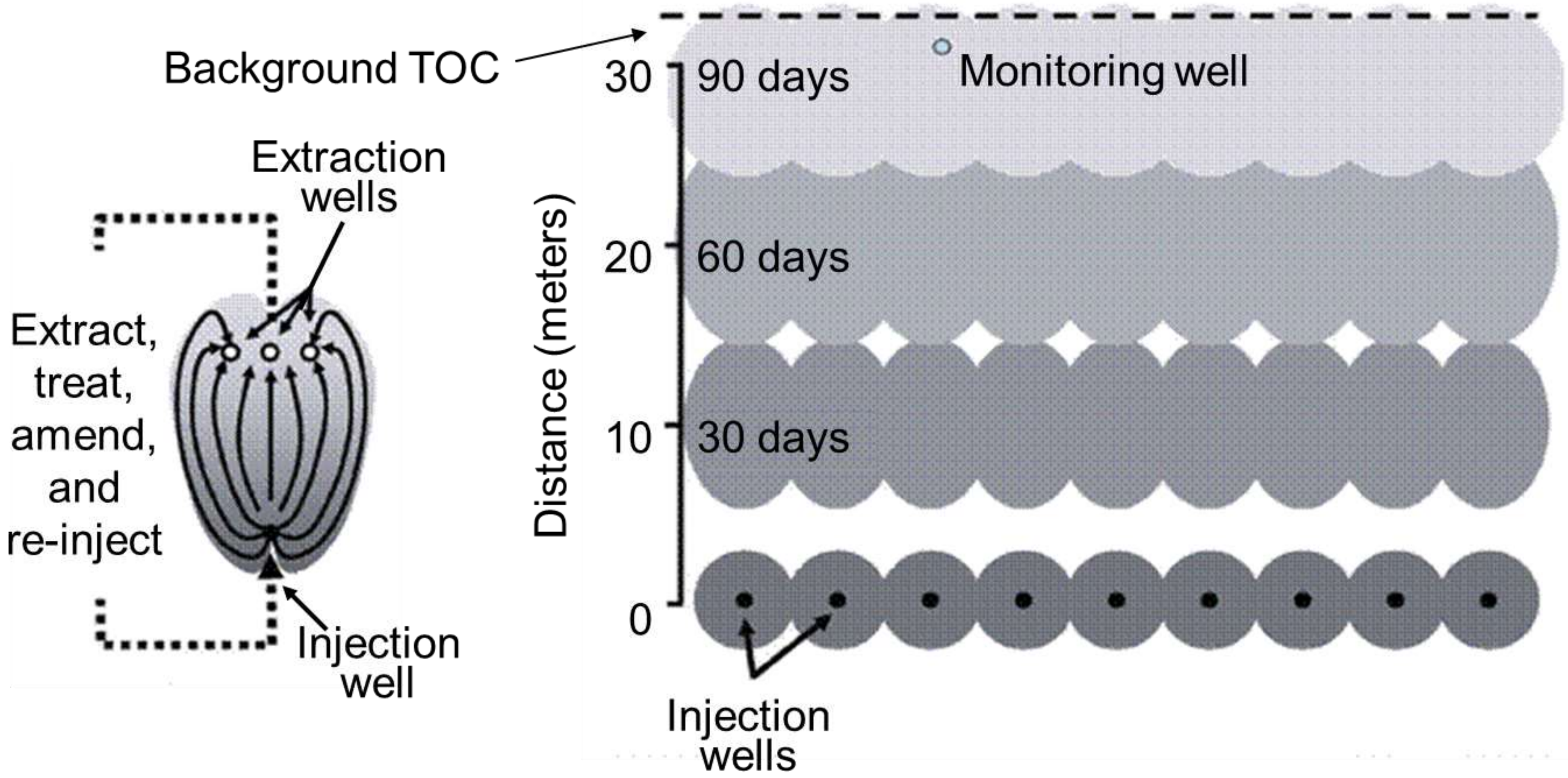
TREATMENT OPTIONS



Biobarriers

Source treatment

TYPES OF EISB SYSTEMS



groundwater velocity = 0.3 m/day

Active or Semi-Passive

Passive

ITRC Technology Overview: In Situ Bioremediation of Chlorinated Ethene DNAPL Source Zones (BIODNAPL-1, 2005)

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COMMON DELIVERY METHODS

Operation	Delivery Method	Donors	Amendment Frequency
Passive	▪ Discrete Injection Points (injection points, temporary or permanent injection wells) ▪ Good for reactive barriers	Solid or slow-release (e.g., EVO)	Annually to multi-year
Semi-Passive	Batch addition with intermittent recirculation	▪ Soluble ▪ Slow-release	Monthly to annually
Active	▪ Continuous recirculation ▪ Capture and recharge	Soluble	Daily to weekly

COMMON DELIVERY METHODS

	Passive	Semi-Passive	Active
# Well Required (Cap $)	High	Med	Low
Infrastructure (Cap $)	Low	Med	High
Operation (O&M $)	Low	Med	High
Fouling of Wells (O&M $)	Low	Med	High
Distribution in GW	Least	Better	Best
Control of Dose	Least	Better	Best
Maintains Water Quality	Least	Better	Best

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ELECTRON DONOR CHOICES

Soluble

- Lactate/other organic acids
- Methanol/ethanol
- Molasses/other carbohydrates
- Dairy whey

Slow Release

- Edible oils and oil mixtures
- Lactate polymers
- Chitin (glucosamine polymer)
- Plant matter products

Delivery methods change as a function of amendment type

Key Point: Amendment choice and injection design are closely linked.

INJECTION MATRIX

Low pressure fluid injection is not appropriate for low permeability soils

Table 4-4. Site-Specific Impacts on Reagent Distribution Technique

Parameter	Vertical Injection Wells	Vertical Recirculation Wells	Horizontal Wells	Direct-push Technology Injection	Hydraulic Fracture	Pneumatic Fracture
Amenability to Media Type						
Unconsolidated media	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
Consolidated media	Excellent	Good	Excellent	Not recommended	Excellent	Excellent
Fracture Continuity						
Good fracture continuity	Good	Good	Fair	Not recommended	Good	Good
Poor fracture continuity	Fair	Poor	Poor	Not recommended	Good	Good
Hydraulic Conductivity						
$>10^{-3}$ cm/sec	Excellent	Excellent	Excellent	Excellent	Poor	Poor
$<10^{-3}$ but $>10^{-4}$ cm/sec	Good	Fair	Fair	Excellent	Fair	Fair
$<10^{-4}$ but $>10^{-5}$ cm/sec	Fair	Poor	Poor	Good	Good	Good
$<10^{-5}$ but $>10^{-6}$ cm/sec	Poor	Not recommended	Not recommended	Fair	Excellent	Excellent
$<10^{-6}$ cm/sec	Not recommended	Not recommended	Not recommended	Not recommended	Excellent	Excellent
Lithology						
Homogeneous (Kmax/Kmin <1,000)	Excellent	Excellent	Excellent	Excellent	Excellent	Fair
Heterogeneous (Kmax/Kmin >1,000)	Fair	Fair	poor	Good	Fair	Fair

Source: Best Practices for Injection and Distribution of Amendments, Technical Report TR-NAVFAC-EXWC-EX-1303, March 2013

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Donor Emplacement by Direct Injection

ESIB DESIGN PROCESS

What is a treatability test?

- Laboratory based “bench-scale” testing
- Uses site soil, sediment or rock and groundwater, typically in batch bottles
- Used to assess biodegradation potential under site-specific conditions
- Usually 4-12 months long
- Column studies can also be performed, but are much less common

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Why do Treatability Studies?

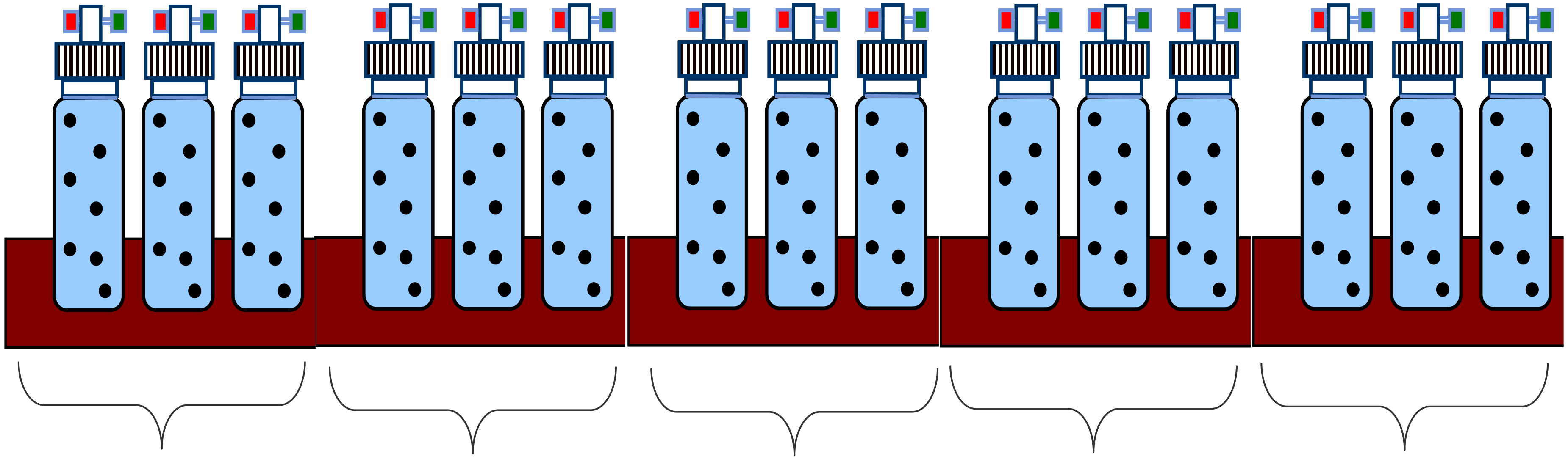
- Relatively low cost
- Test multiple variables at the same time – narrows potential options prior to going to the field
- Identify potential complications and address them before they cause problems in the field
- Obtain regulator or client buy-in prior to investing in field-scale tests

<u>Typical Cost</u>

Lab treatability study - $20-30 K

Field pilot test - $100-300 K

BIOTREAT-ABILITY STUDY DESIGN



Sterile Control

autoclaved and poisoned

Active Control

unamended

Biostimulation

addition of electron donors

Bioaugmentation

addition of known degrading DHC populations

Nutrients

addition of YE, DAP

Importance of Sample Collection

- The sample is "alive"
- Collect using core tube
- Minimize field disturbance
- Cap and seal ends, store on ice
- Ship to lab quickly
- Lab should transfer soil to glass container and store under anaerobic conditions
- Set up study quickly
- Understand that soil has a "shelf life"

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PILOT TESTING

Why Perform a Pilot Test?

- Reduce scale up uncertainty and better estimate full-scale project cost
- **Verify amendment distribution**
  - Injection well/injection point spacing
  - Fluid injection rates
  - Amendment transport
  - Potential for surfacing
- Identify implementation problems (biofouling, aquifer plugging)
- Obtain regulator and/or client buy-in

Important to measure what we put into the ground

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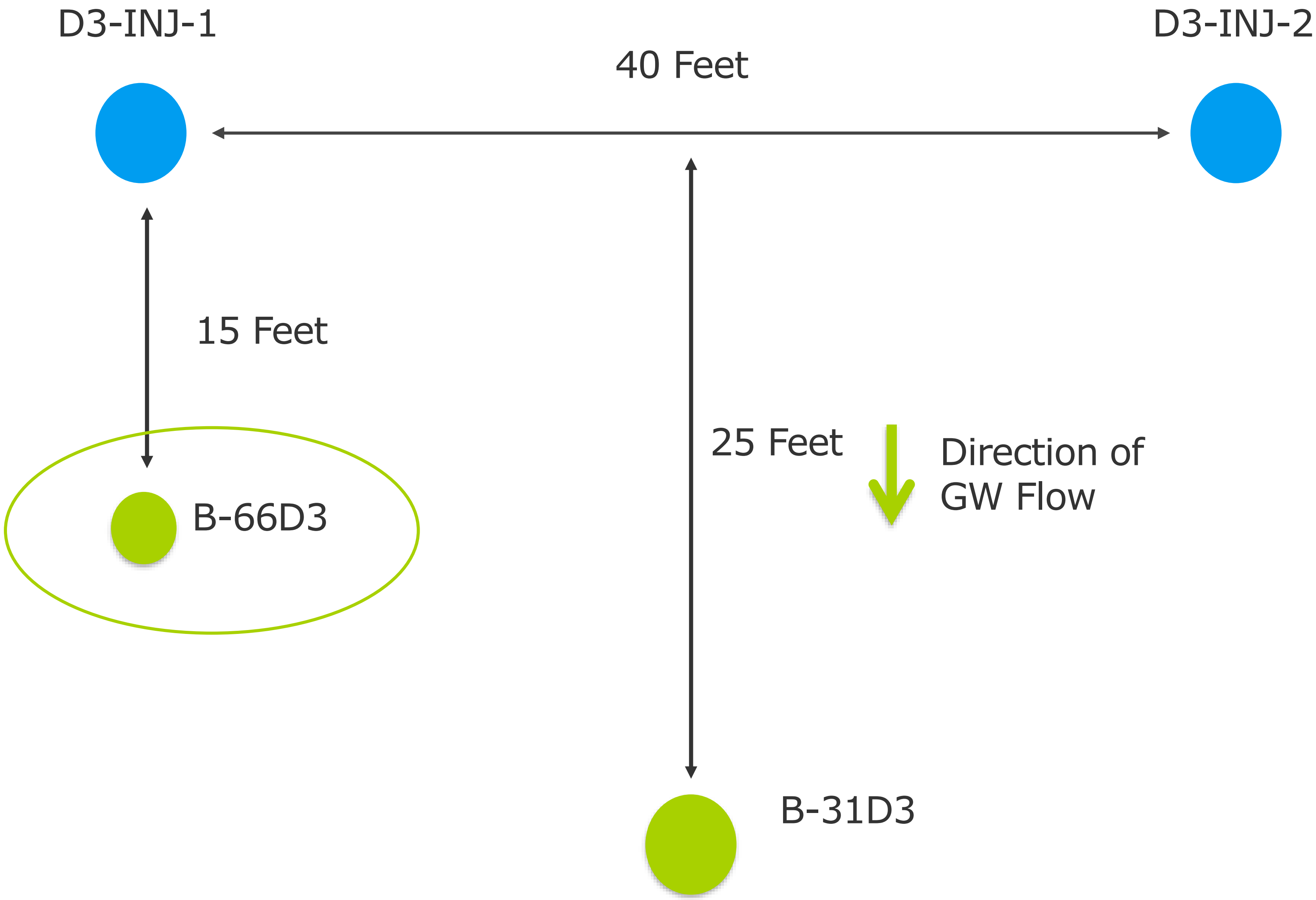
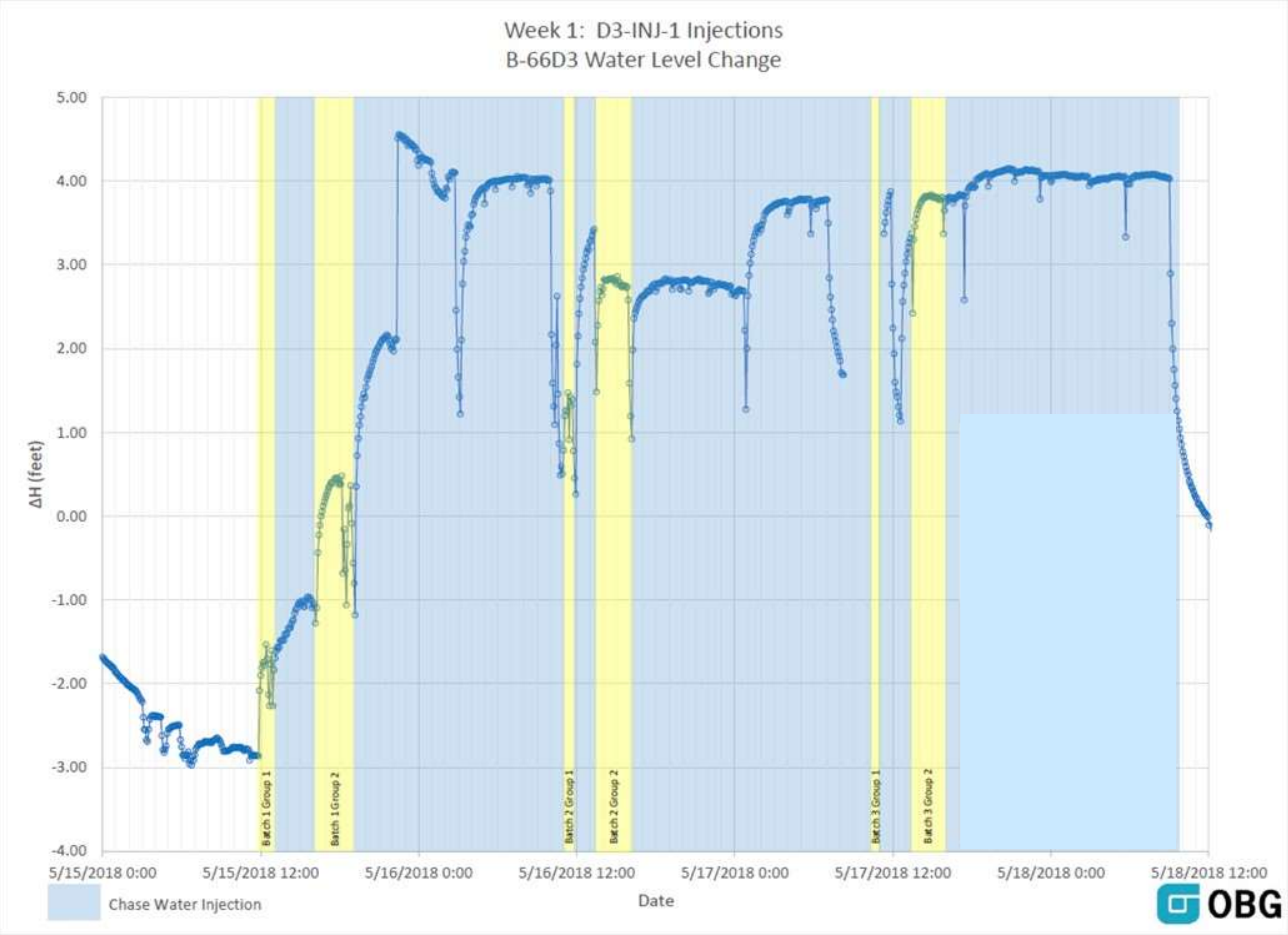
D3 PILOT TEST – PHASE 1 LAYOUT



PRESSURE TRANSDUCER DATA

Phase 1 Pilot - Week 1



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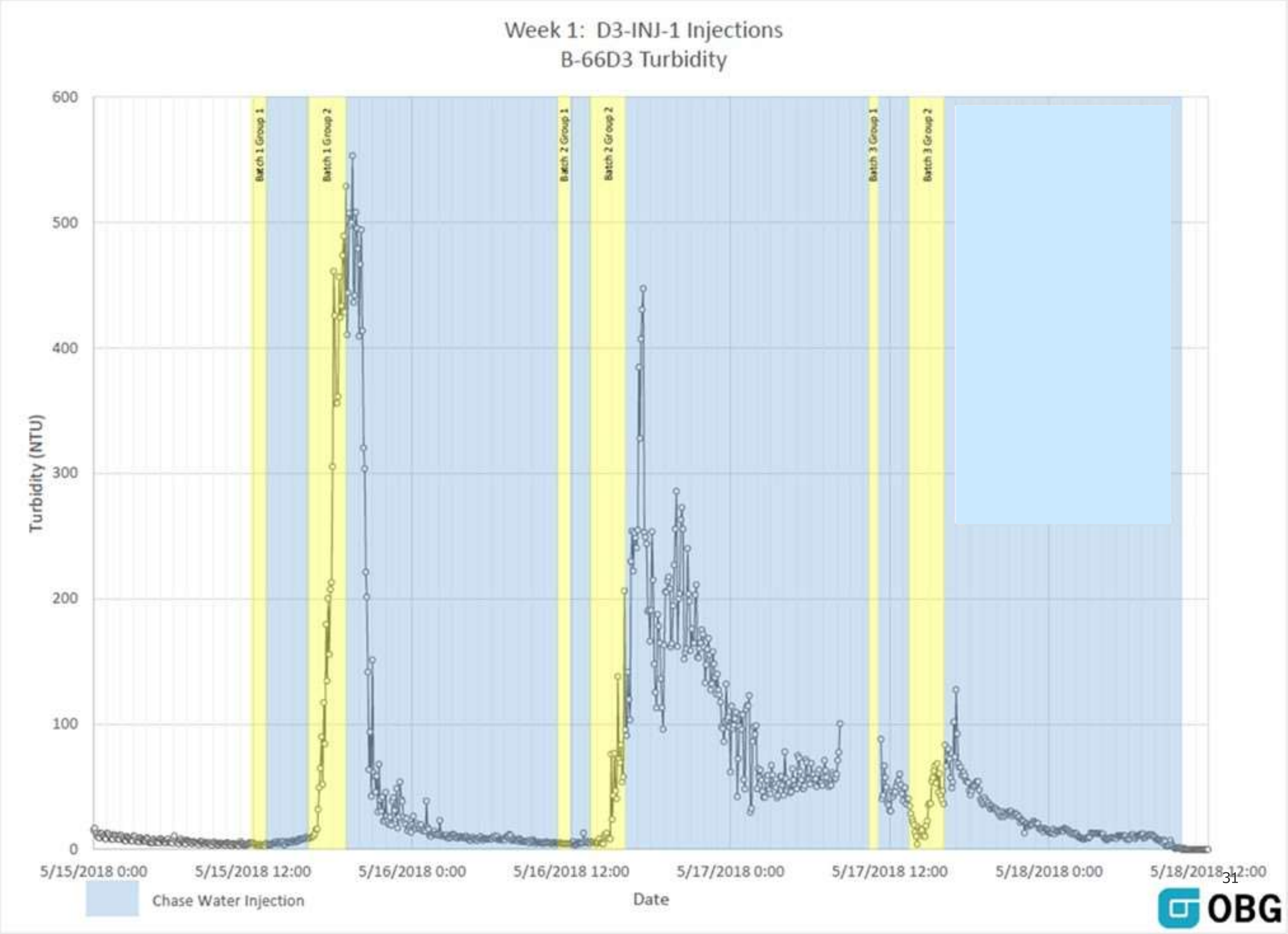
PROBE TURBIDITY DATA

Phase 1 Pilot - Week 1



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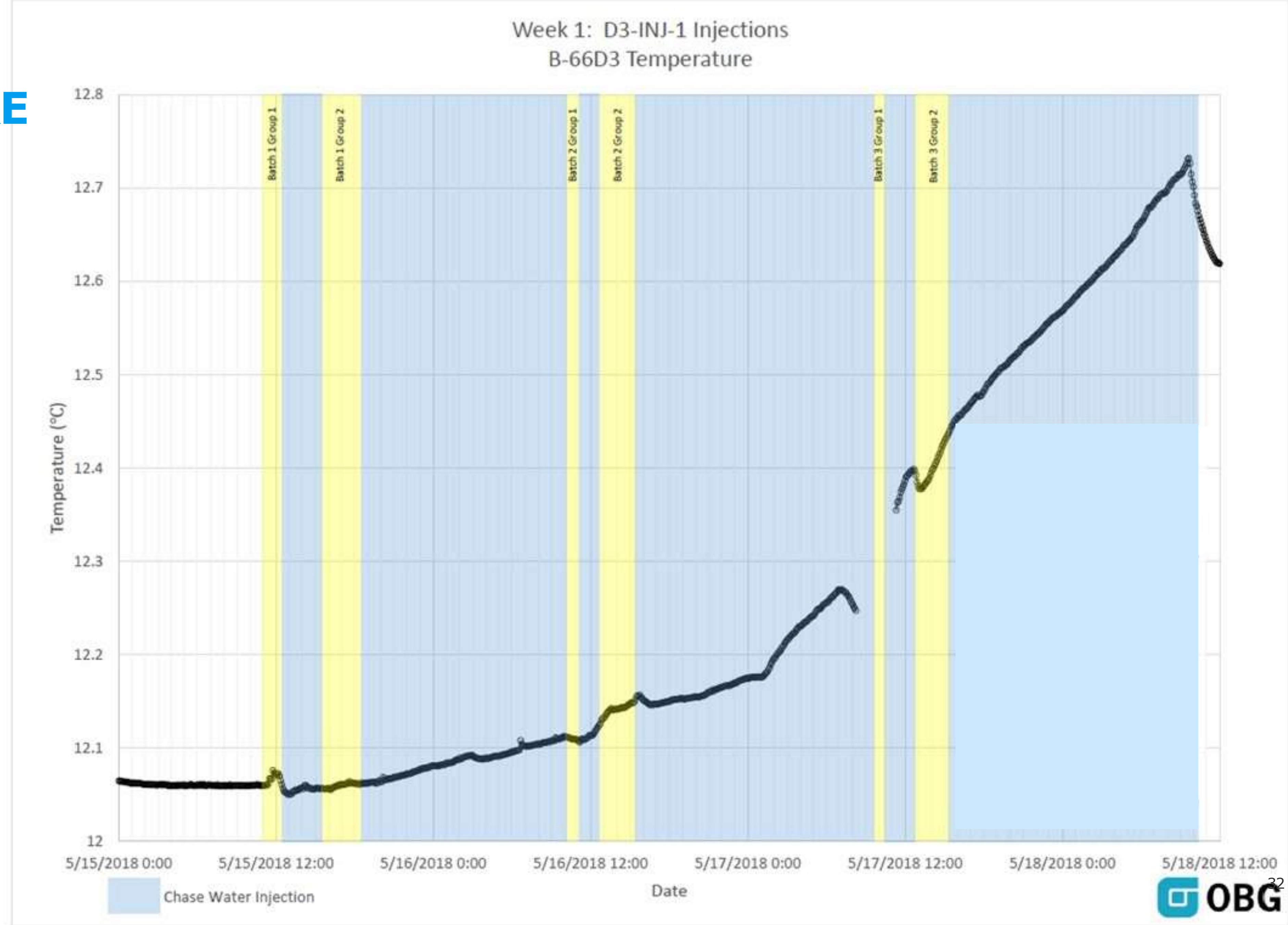
PROBE TEMPERATURE DATA

Phase 1 Pilot - Week 1



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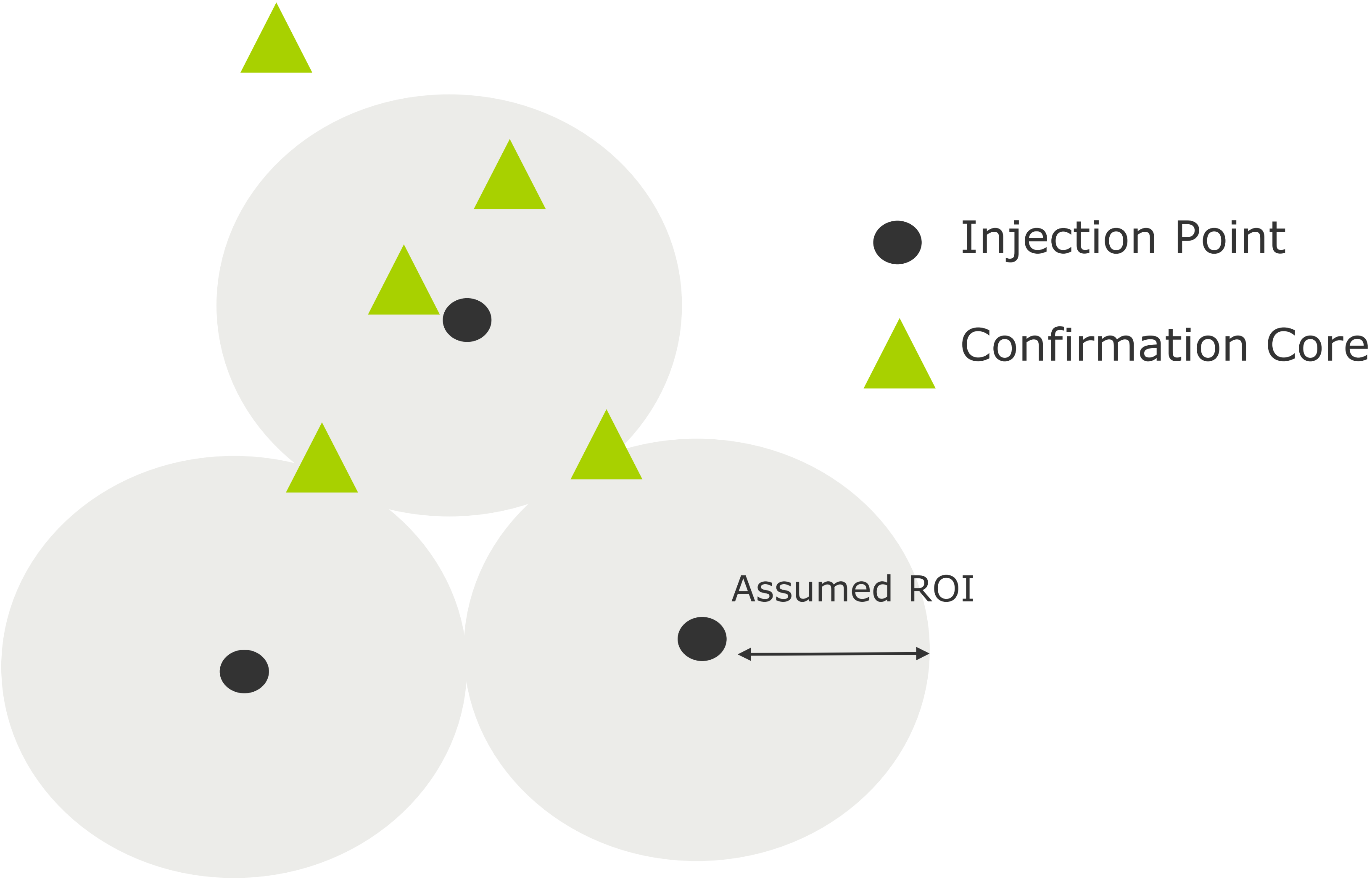
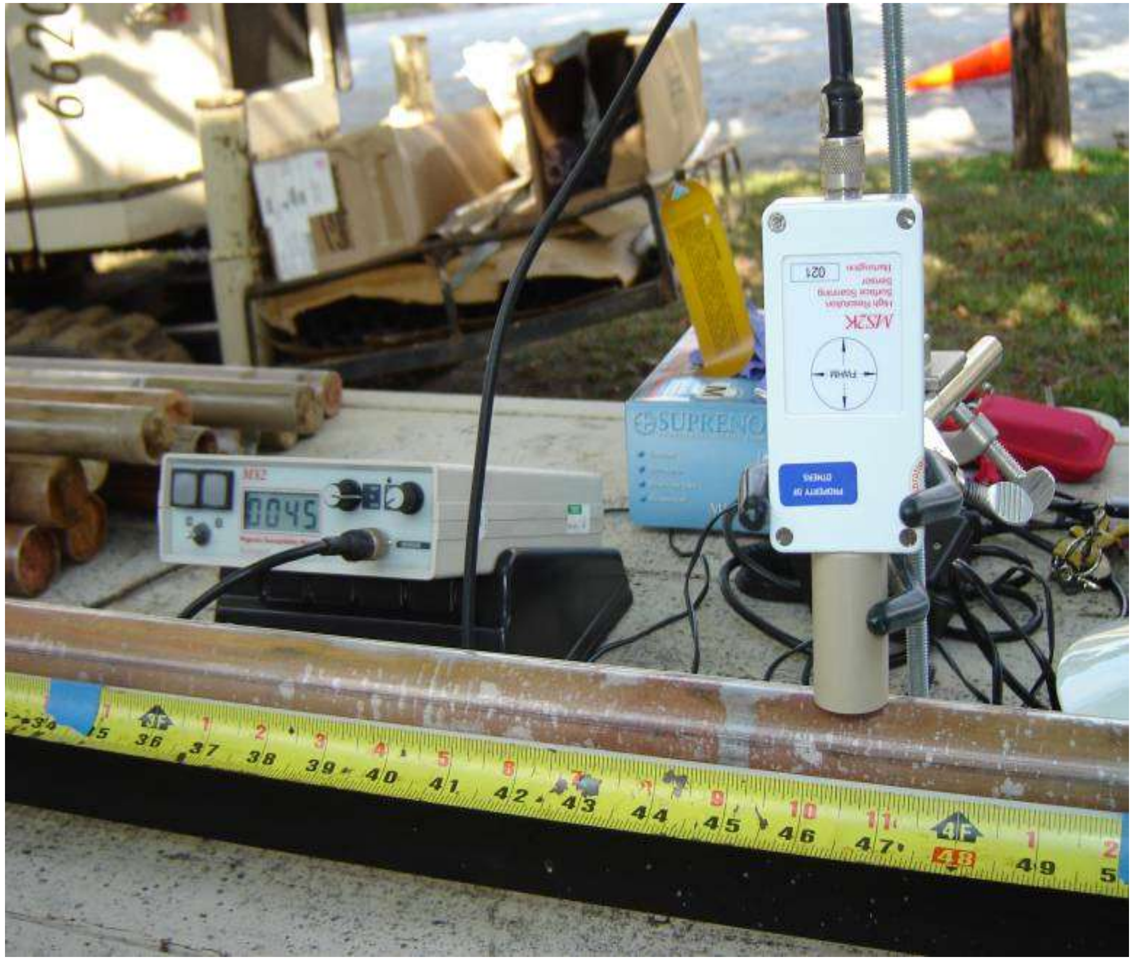
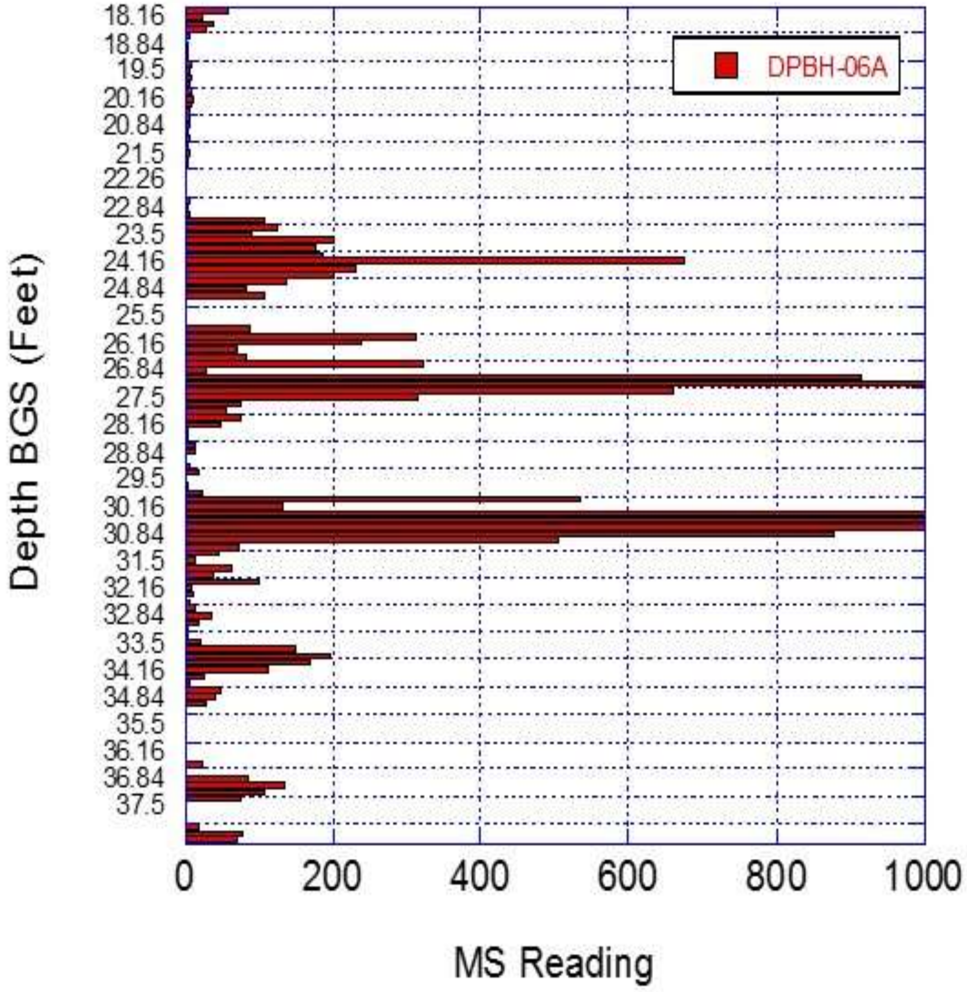
OBG

ROI DETERMINATION FOR DONOR INJECTION PROGRAMS



MAGNETIC SUSCEPTIBILITY MEASUREMENT





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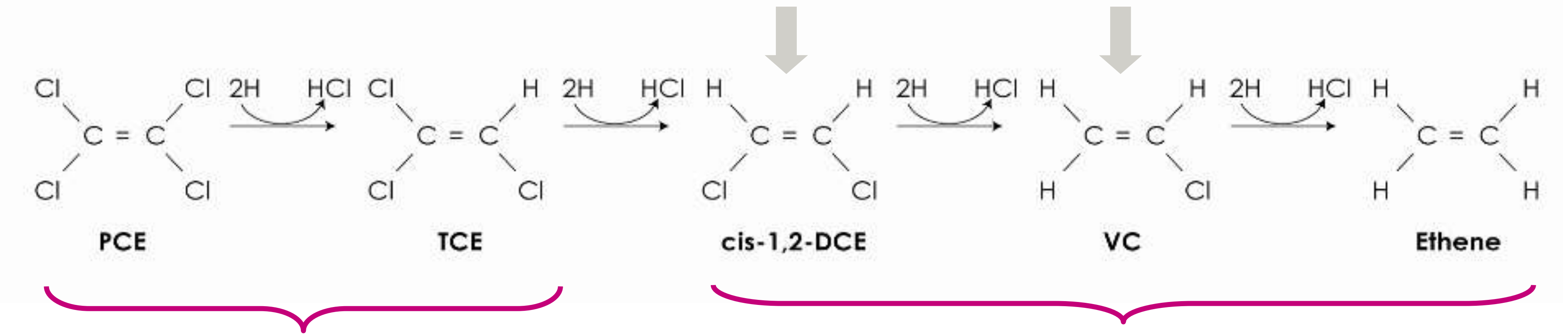
Arnason, J.G., Harkness, M., Butler-Veytia, B., Evaluating the Subsurface Distribution of Zero-Valent Iron Using Magnetic Susceptibility, Groundwater Monitoring & Remediation 34, no. 2/ Spring 2014/pages 96–106.

OTHER COMMON OPTIONS

REDUCTIVE DECHLORINATION PATHWAY

Can accumulate if requisite bacteria are absent



Dehalobacter
Dehalospirillum
Desulfitobacterium
Desulfuromonas

Dehalococcoides

Geobacter

Multiple strains within a single group *(Dehalococcoides)*

Bioaugmentation Culture Application

Dhc requires anaerobic conditions and neutral pH

Bioaugmentation culture should be added after the amendment and when ORP measurements indicate the subsurface is anaerobic

Some advocate short-cutting the process by injecting bioaugmentation culture with the amendments *(not recommended)*

Chase water should be used to “push” bacteria out into the formation

Chase water should be anaerobic and neutral pH

Both biological and chemical amendments are available to create anaerobic chase water

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PH EFFECTS IN EISB

- EISB processes produce acid as the result of donor fermentation and reductive dichlorination.

Fermentation of EVO

- $C_{18}H_{32}O_2 + 16H_2O => 9C_2H_3O_2^- +$ **$9H^+$** $+ 14H_2$

Dechlorination of TCE to Ethene

- $C_2HCl_3 + 3H_2 => C_2H_4 +$ **$3H^+$** $+ 3Cl-$

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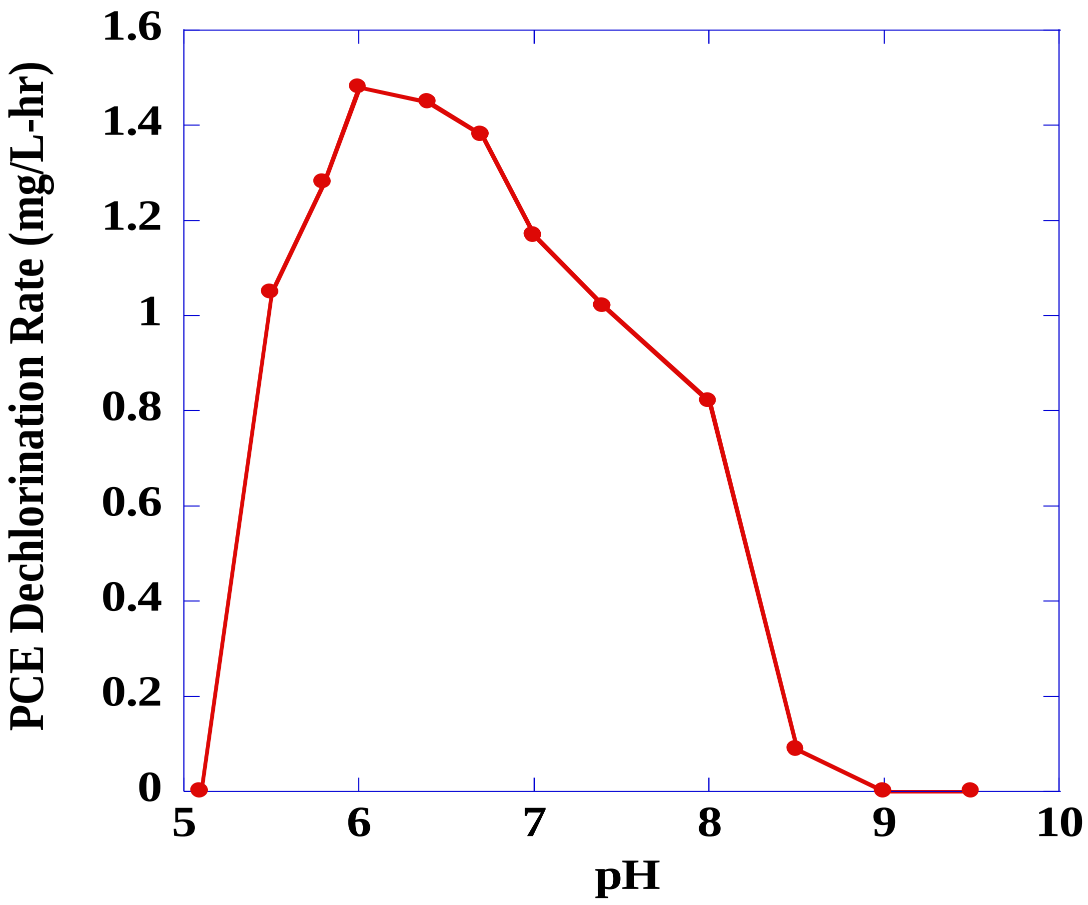
IMPACT OF PH ON DECHLORINATION BY DHC



(Shaw Environmental)

Dhc have an optimum pH range of 6 - 8. Groundwater pH outside of this range will slow or inhibit reductive dechlorination activity.

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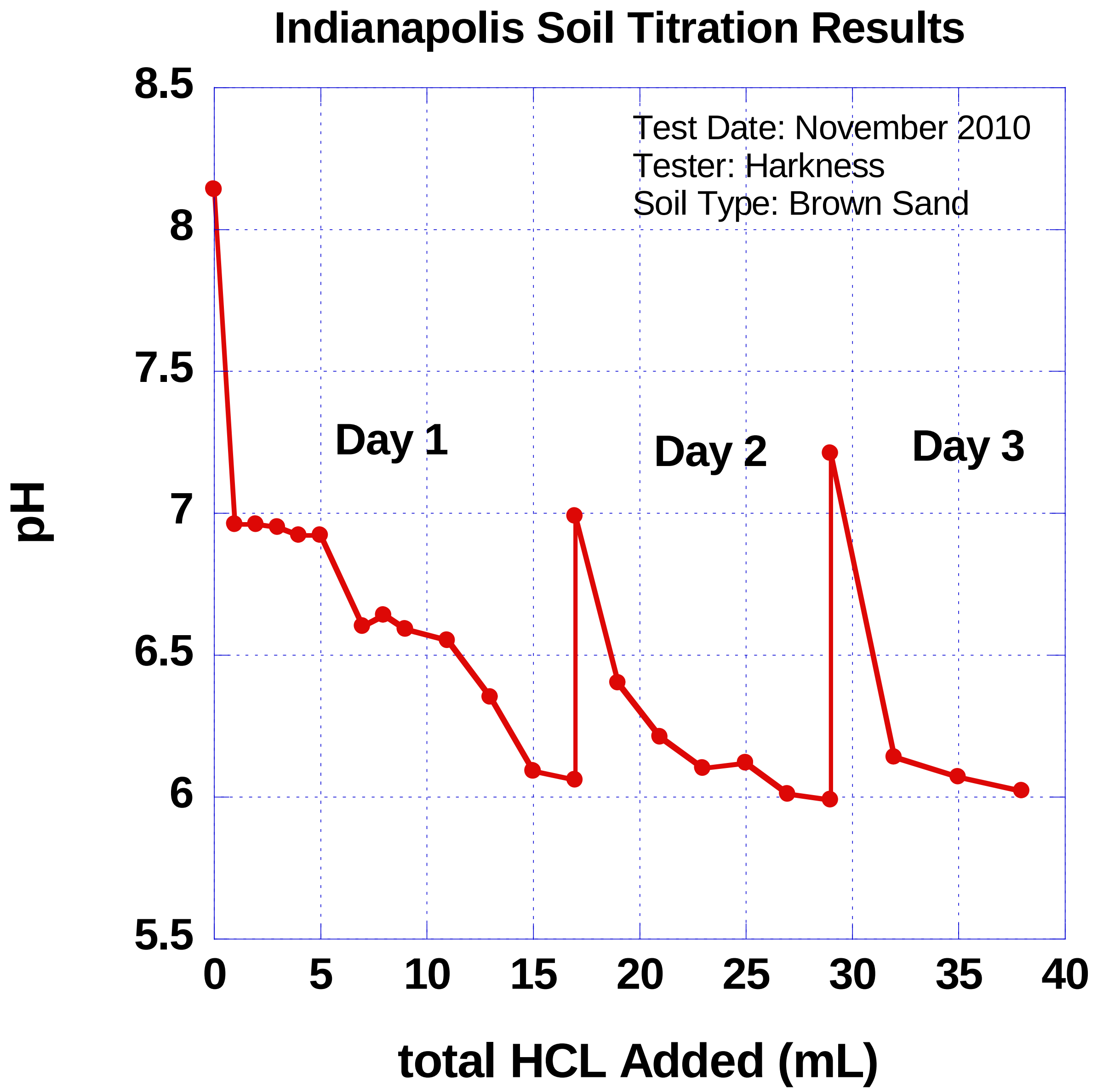
TITRATION TEST RESULTS



Response of well buffered soil to 0.725 N HCl addition

Note – periodic rebound reflects rate limited dissolution of calcite from soil

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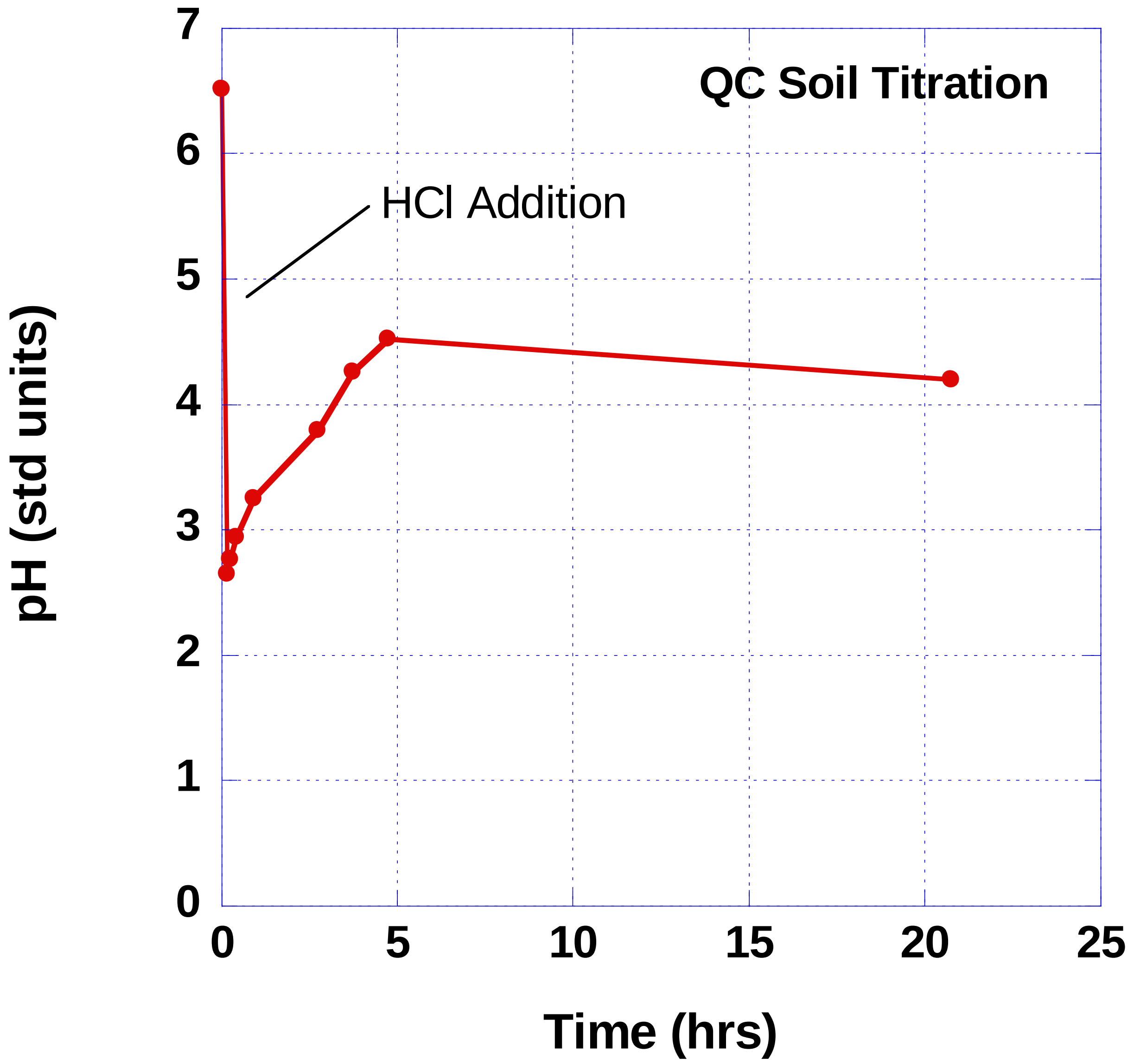
TITRATION TEST RESULTS



Response of poorly buffered soil to addition of 1 mL of 0.725 N HCl

BUFFERING OPTIONS IN EISB SYSTEMS

Need to add base to counteract the impact of acid generation due to donor fermentation and reductive dichlorination.

Addition of strong bases like sodium hydroxide can raise the pH of the system too much (e.g., produce a pH of 10 or higher), which can kill the bacteria.

Addition of weak bases are preferred since the pH rise is limited to 8.5.

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BUFFERING OPTIONS IN EISB SYSTEMS

Sodium or potassium bicarbonate are effective buffers. These are soluble compounds that may require periodic addition.

CAUTION: Extensive use of bicarbonate buffers will alter groundwater geo-chemistry and may result in precipitation of insoluble residuals (e.g., calcium sulfate), with potential for aquifer plugging.

Commercial forms of slower release buffers are also available (e.g., calcium carbonate, magnesium hydroxide). These are typically combined with dispersants to allow them to travel in the aquifer.

APPLICATION OF EISB TO SOURCE AREAS

APPLICATION OF EISB TO SOURCE AREAS

EISB initially was applied to almost exclusively to plumes due to concern over microbial inhibition at high source area contaminant concentrations.

We now know that dechlorinating bacteria are active at near saturation concentrations for PCE and TCE.

In fact, there are several benefits to treating source areas using EISB

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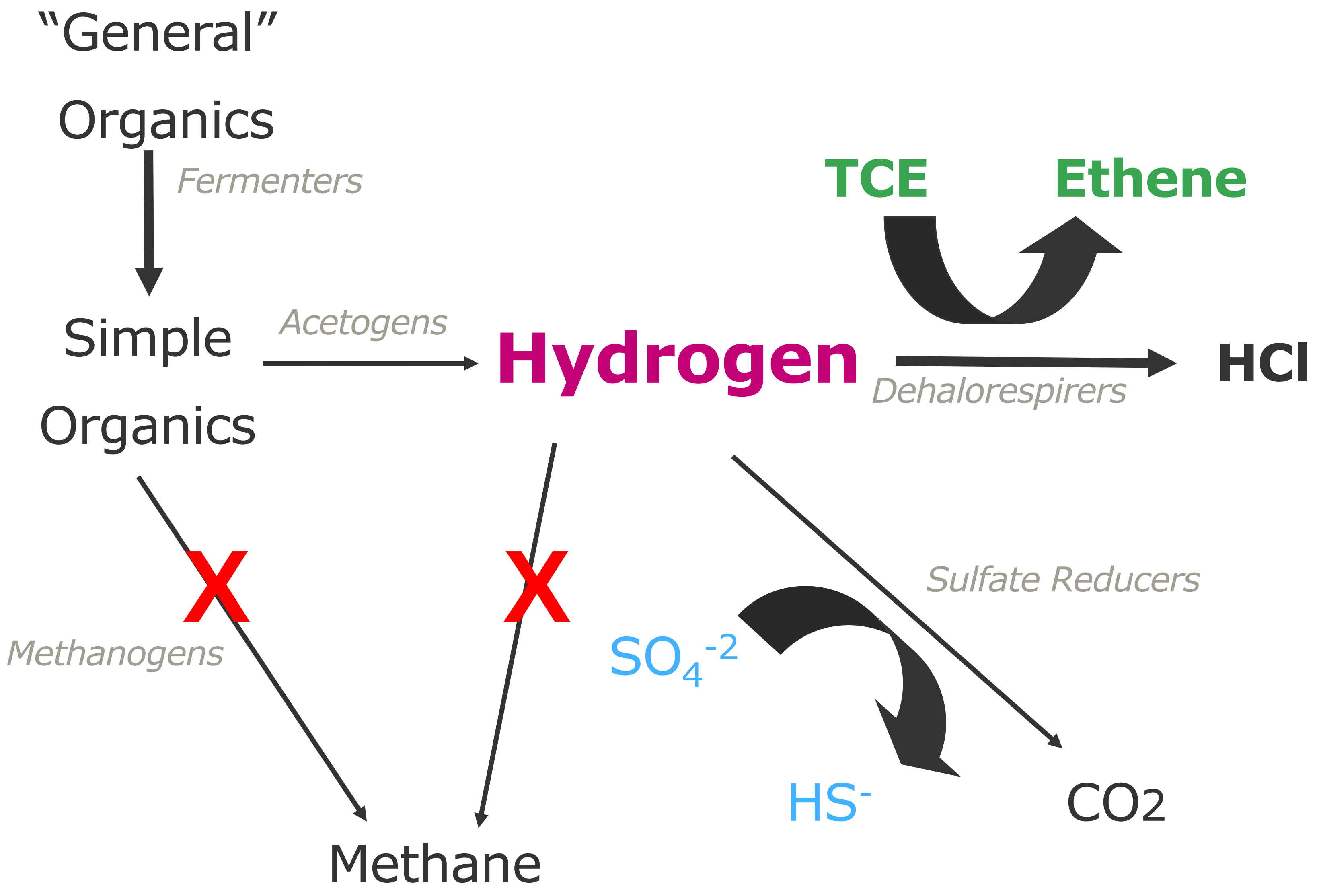
BENEFITS OF SOURCE AREA BIOLOGICAL TREATMENT: METHANOGEN INHIBITION



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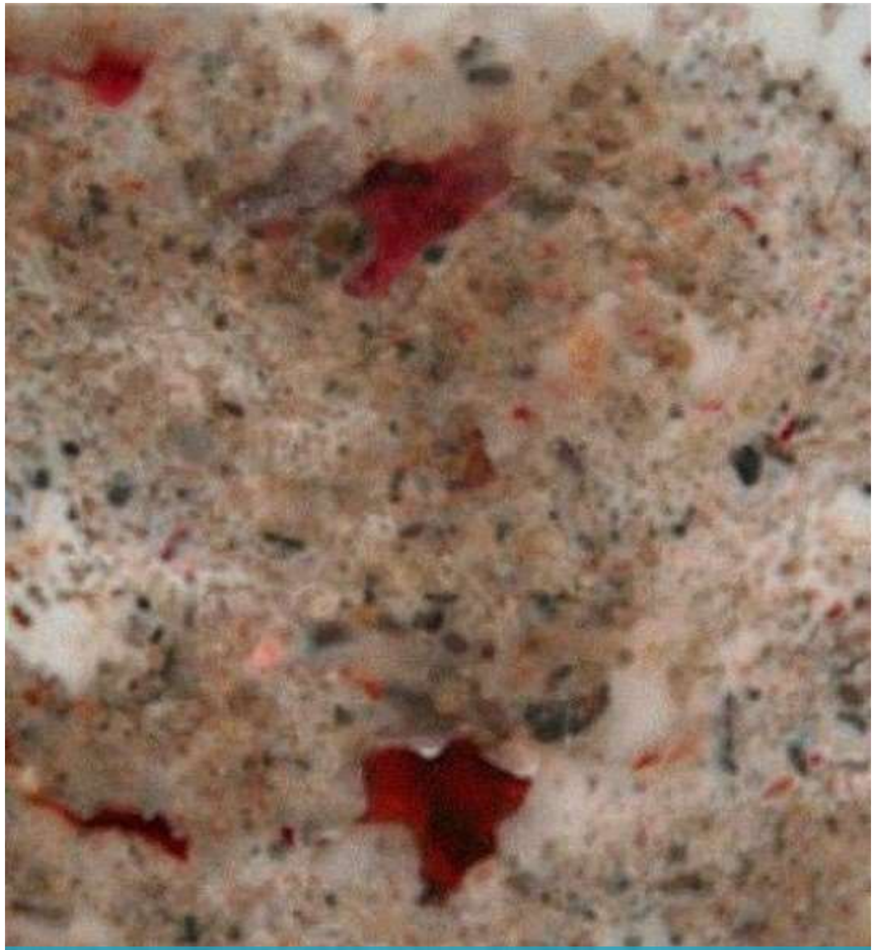
BENEFITS OF SOURCE AREA BIOLOGICAL TREATMENT: PARTITIONING DONOR BEHAVIOR (EVO)


Three days


Six days

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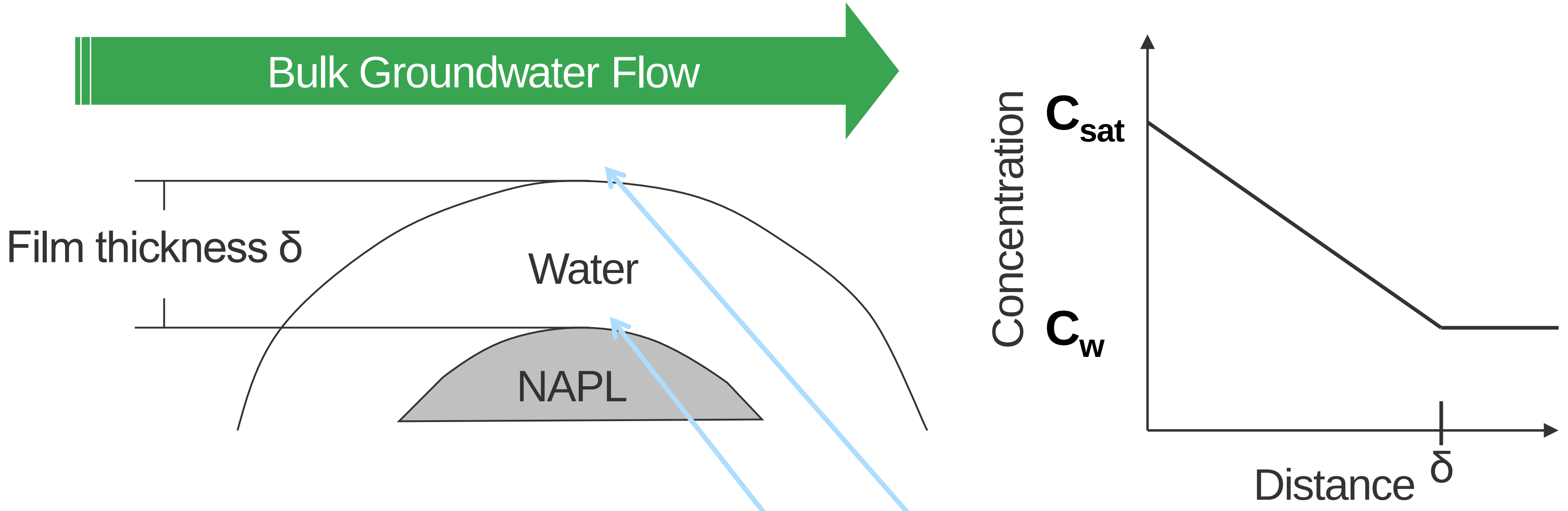
DNAPL DISSOLUTION AND MASS REMOVAL



$$J = \lambda\,(C_{sat} - C_w)$$

$$\lambda = f\,(\text{surface area, velocity})$$

J = flux

λ = mass transfer rate coefficient

C_{sat} = saturated concentration at the DNAPL/water Interface

C_w = bulk water concentration

(ITRC training)

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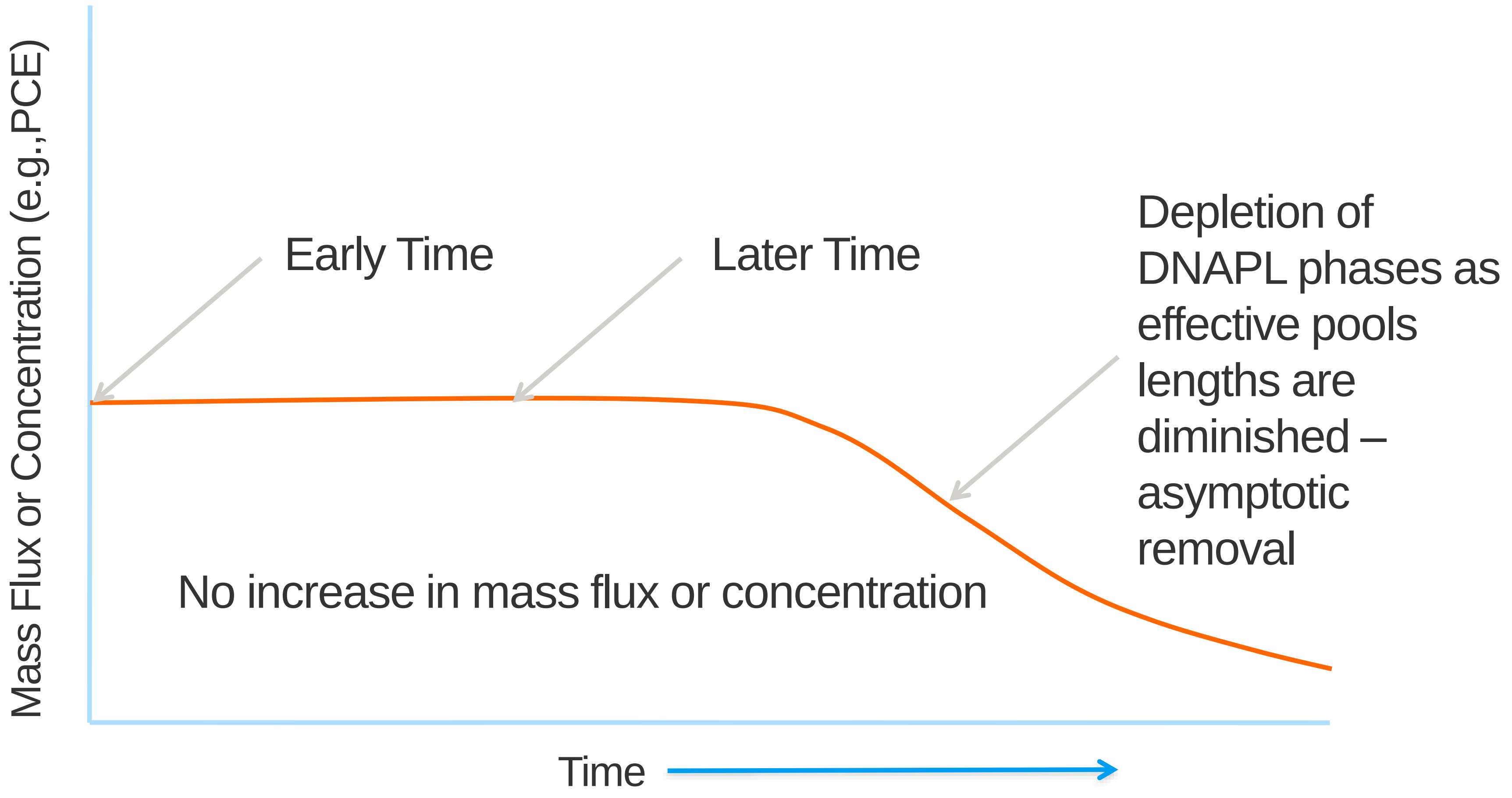
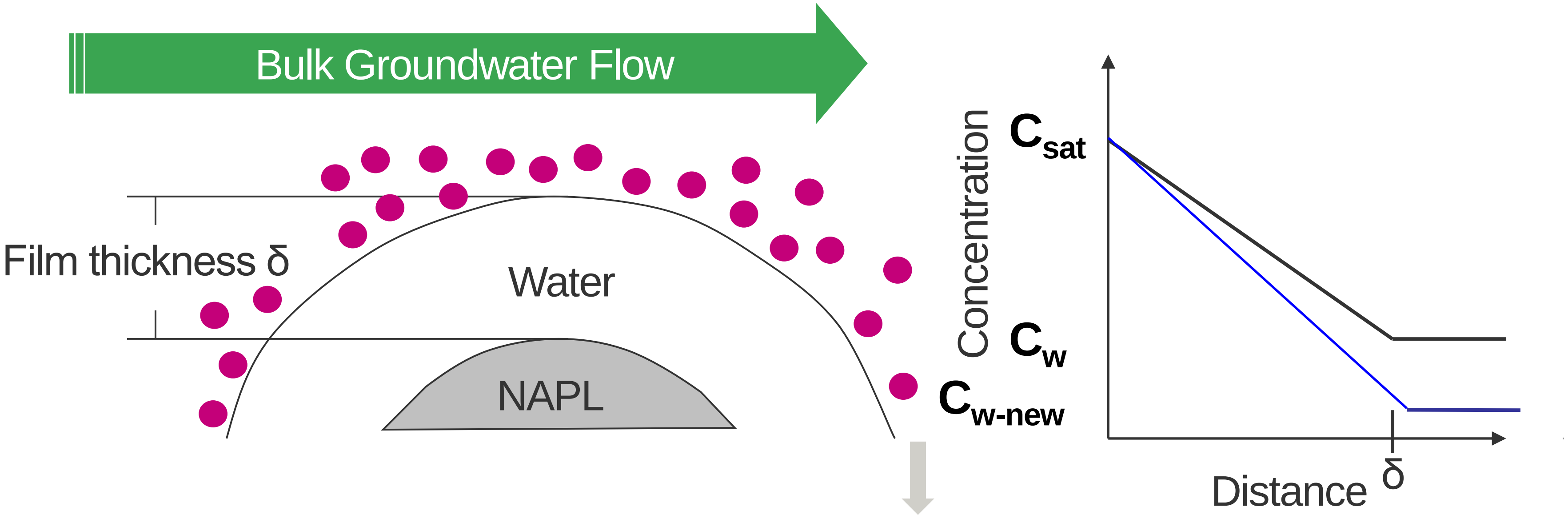
MASS REMOVAL OVER TIME WITHOUT EISB



(ITRC Modeling Study)

DNAPL DISSOLUTION AND MASS REMOVAL



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WATER SOLUBILITY

Compound	mg/L	mM
PCE	150	0.9
TCE	1,100	8.4
cDCE	3,500	36
VC	2,700	43

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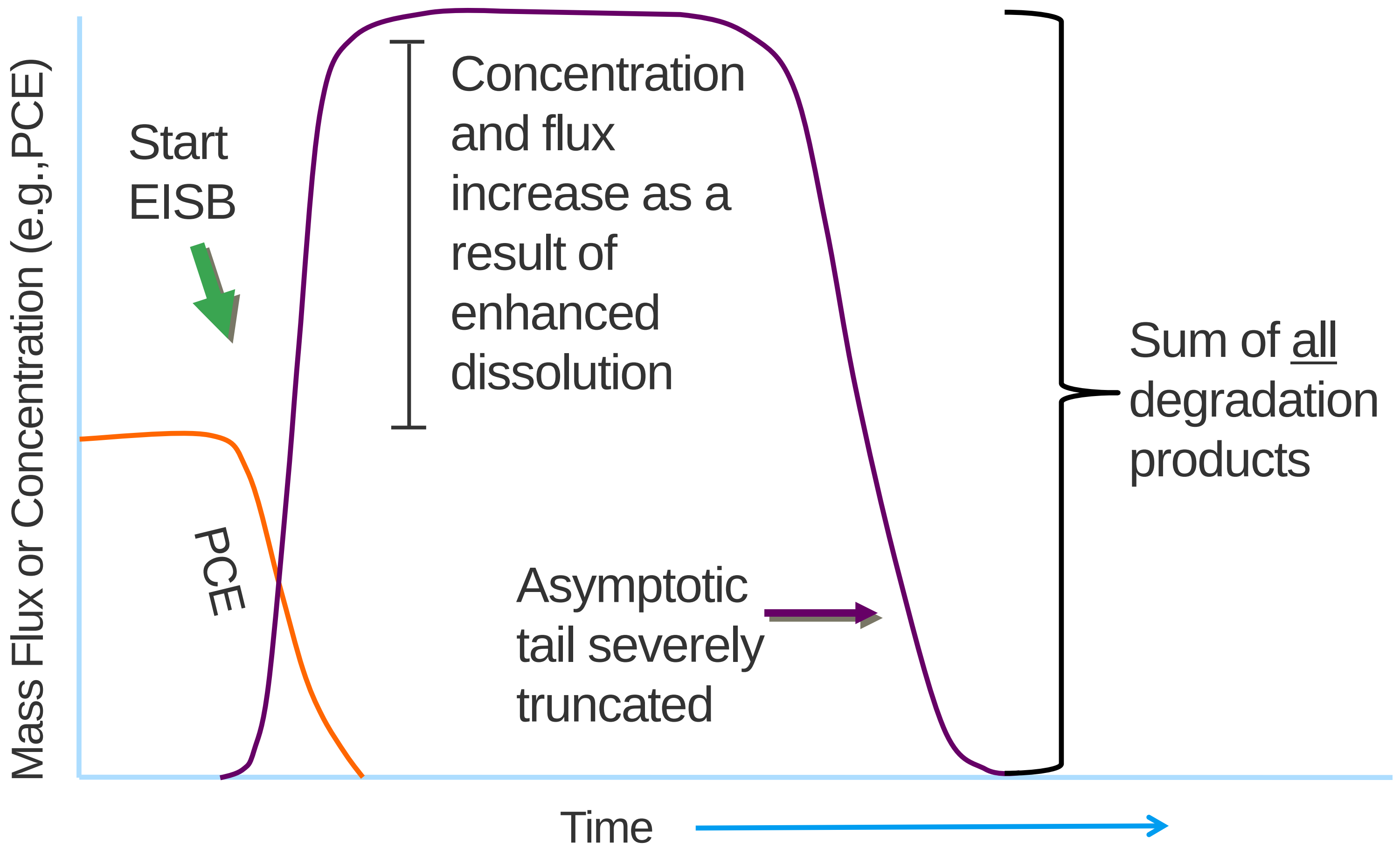
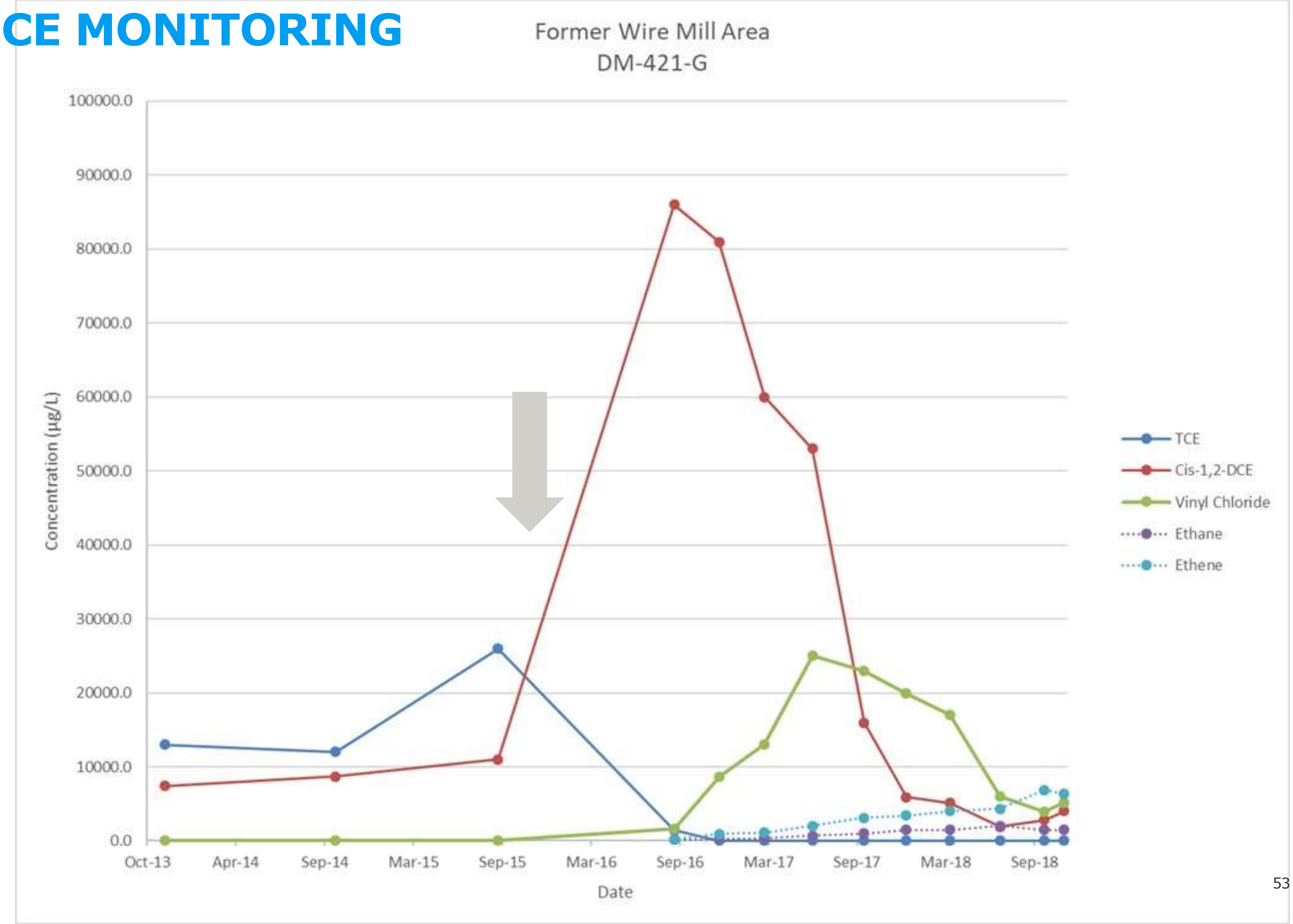
MASS REMOVAL OVER TIME WITH EISB



(ITRC Modeling Study)

PERFORMANCE MONITORING



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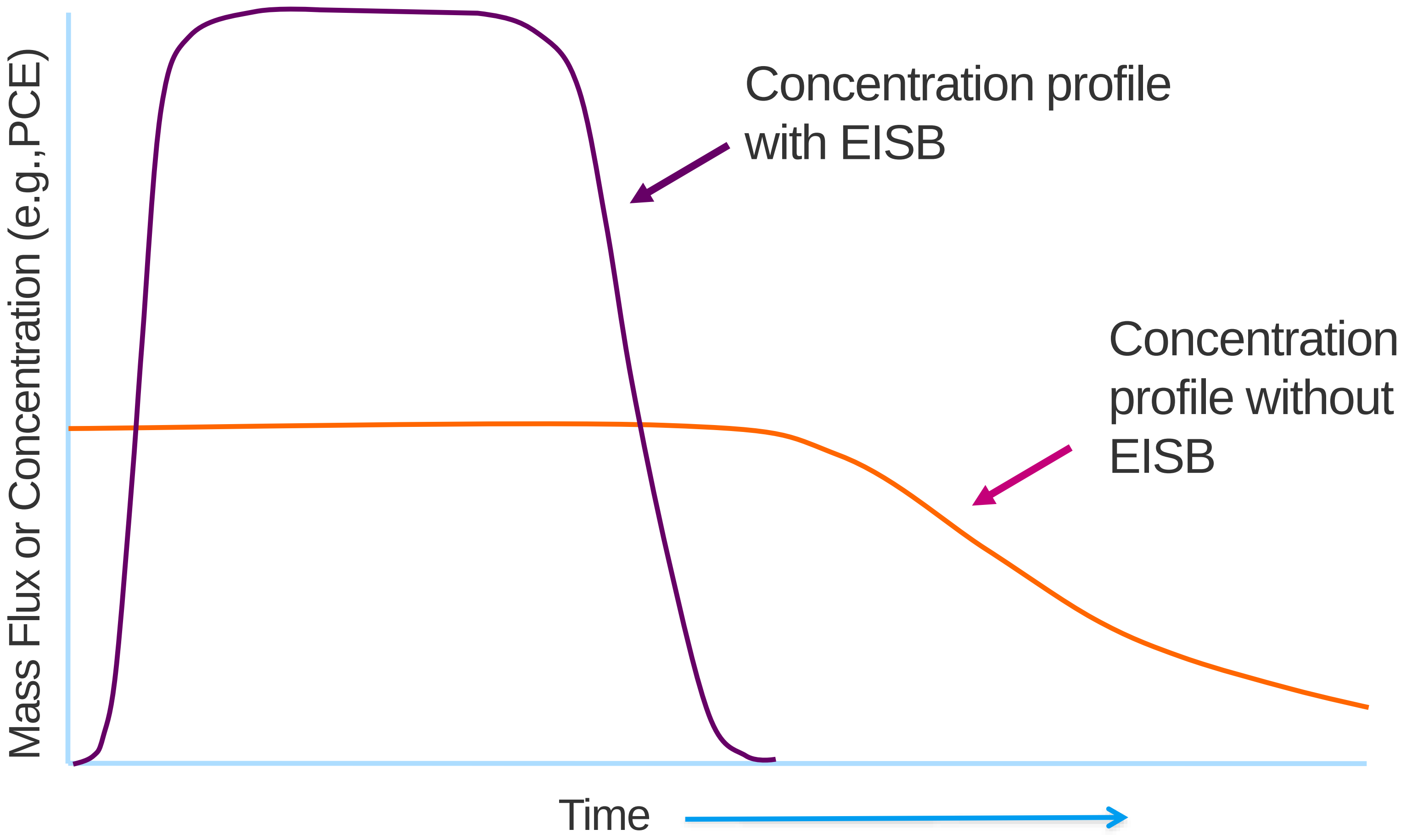
COMPARISON OF MASS REMOVAL OVER TIME



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DISSOLUTION ENHANCEMENT

How much should we expect?

	Compound	
	PCE	TCE
Solubility (mg/L)	150	1,100
Enhancement in Lab	5-15	~2
Enhancement in Field	3-5	~1.5

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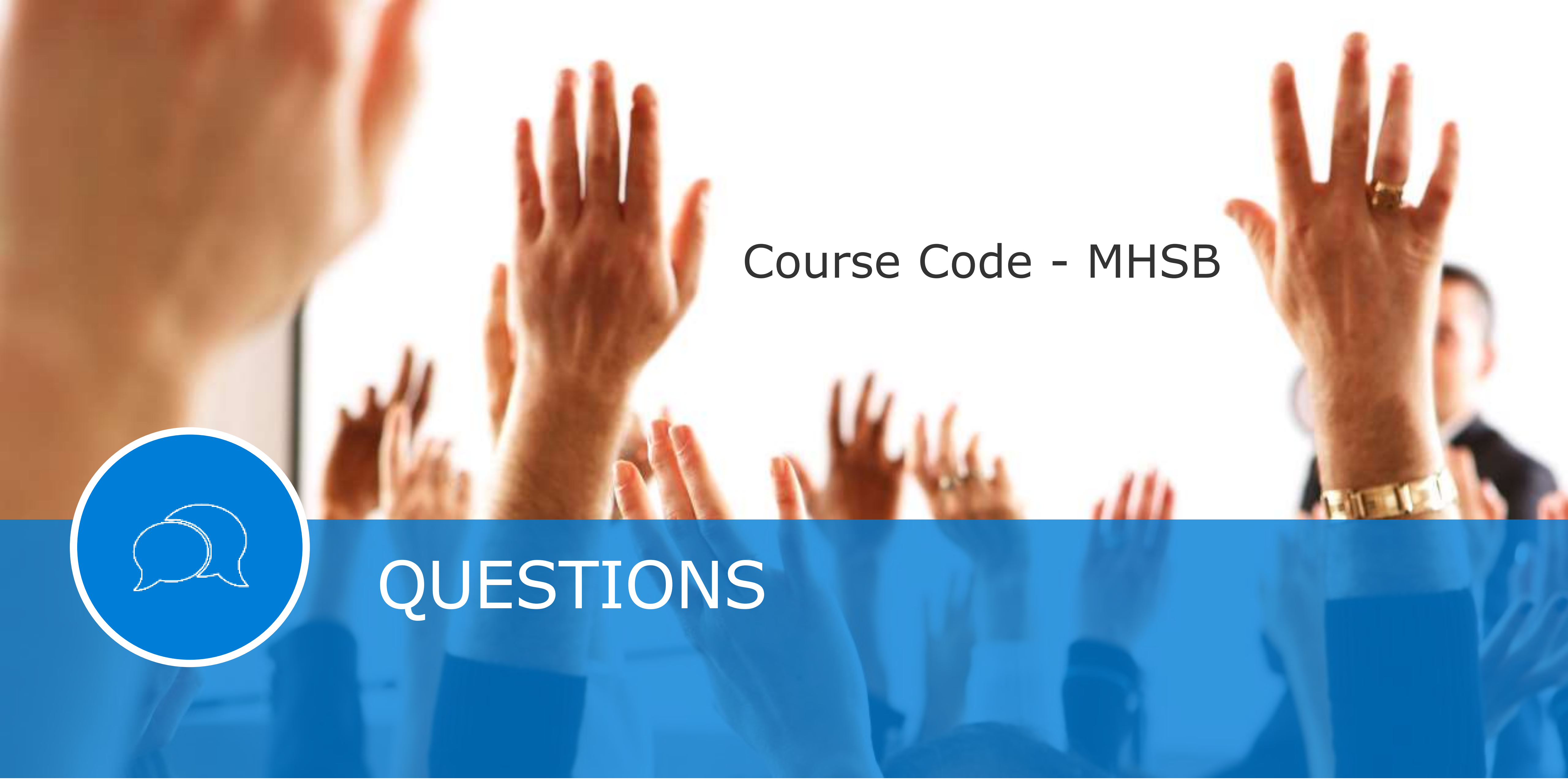

Course Code - MHSB

QUESTIONS

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