CDM

# Conceptual System Design

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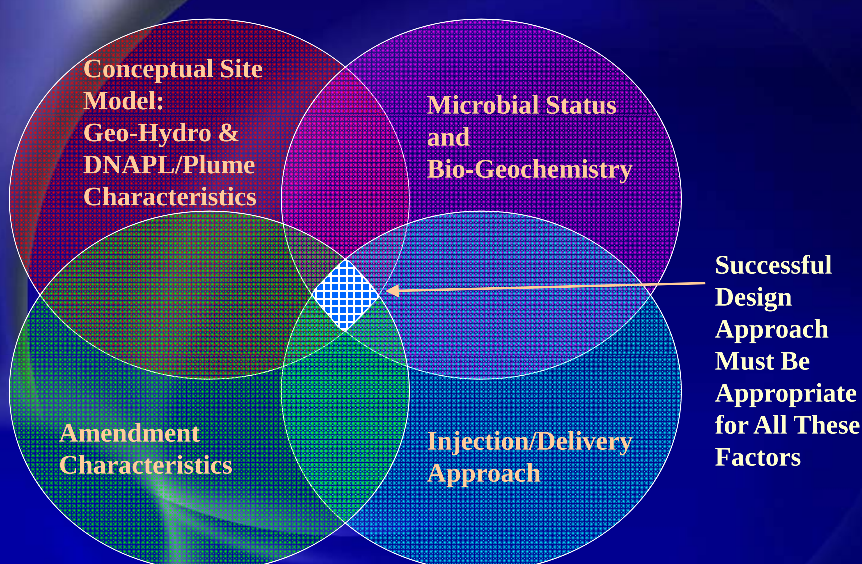
## Presentation Outline

- Introduction – focus on chlorinated ethenes
- Data needs
  - Site characterization
  - Bench scale testing
  - Environmental molecular diagnostics
  - Pilot testing
- Amendment injection design
  - Amendment selection
  - Injection methods and layout
- Monitoring needs

## Conceptual Design for Bioremediation

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## Data Needs - Site Characterization

- Contaminants
  - Parent chlorinated aliphatic hydrocarbons (CAH) compounds and their dechlorination products
  - PCE, TCE, cis-DCE, VC, ethene, and ethane
- Co-contaminants that may impact bioremediation rate and extent
  - BTEX compounds can stimulate reductive dechlorination
  - Other solvents can inhibit reductive dechlorination (e.g. TCA, CT, CF)

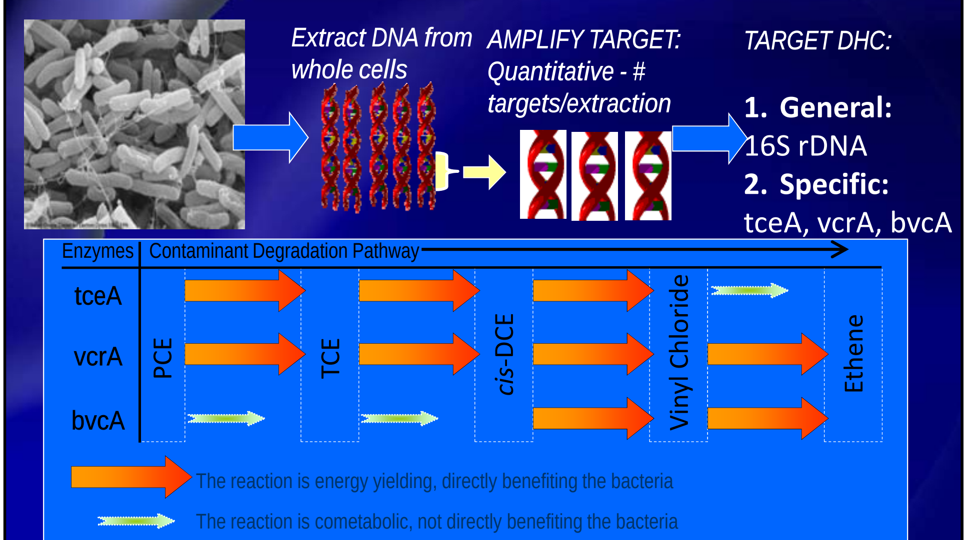
## Data Needs - Site Characterization (cont.)

- Electron donor parameters
  - Indicators of bioavailable carbon
  - Chemical oxygen demand (COD), total organic carbon (TOC), or specific volatile fatty acids (VFA's)
- Indicators of prevailing redox conditions
  - Oxidation-reduction potential (ORP), dissolved oxygen (DO), ferrous iron, sulfate, and methane
- Biological activity indicators and water quality parameters
  - pH, temperature, specific conductance, alkalinity
  - metals

## Data Needs – Environmental Molecular Diagnostics

- Advanced diagnostics can be useful during site characterization
  - Quantitative polymerase chain reaction (qPCR) for *Dehalococcoides spp.* (DHC) and for functional genes (vcrA, bvcA, and tceA)
    - Useful to assess whether bioaugmentation may be needed
    - Absence of bacteria during pre-bioremediation characterization doesn't always mean bioaugmentation will be needed

## Monitoring for DHC using qPCR



## Data Needs – Environmental Molecular Diagnostics (cont.)

- Other tools can be useful but are not required to design a bioremediation system
  - Phospholipid Fatty Acid (PLFA)
    - Provides information on entire bacterial community through analysis of microbial membranes
  - Denaturing gradient gel electrophoresis (DGGE)
    - DNA-based technique which generates a genetic profile of the microbial community
  - Compound specific isotope analysis (CSIA)
    - Generates isotopic characterization of individual compounds which can be used to quantitatively assess degradation processes.

## Data Needs – Bench scale testing

- Bench scale testing purposes
  - Assess whether bioremediation will work
  - Determine design parameters
- Bench scale testing to assess whether bioremediation can be stimulated is not required at most sites
  - Many limiting conditions can be overcome through design (i.e. low pH, high sulfate, etc.)
  - Site characterization should identify any site conditions that would preclude bioremediation
- Exception – presence of co-contaminants that are known to inhibit reductive dechlorination.

## Data Needs – Bench scale testing (cont.)

- Bench scale testing can provide some useful design information
  - Relative comparison of electron donors in terms of concentration, longevity, dechlorination rate, etc.
  - Relative comparison of bioaugmentation cultures
- Use caution when applying degradation/growth rates from lab studies to the field
- In situ microcosms can overcome these limitations

Dehalococcoides

## Data Needs – Pilot Testing

- The most useful and accurate design information is derived from pilot studies
- Small-to-moderate scale electron donor injection(s) and periodic monitoring
- Provides site-specific information:
  - Electron donor distribution
  - Time to onset of degradation
  - Time to complete dechlorination
  - Need for bioaugmentation

## Fundamental Bioremediation Design Goals

- Inject and distribute electron donor into the target treatment area in order to:
  - Manipulate the aquifer’s redox status
  - Expand populations of fermenting bacteria
  - Enhance early-stage dechlorination metabolism
  - Initiate (if necessary) and expand late-stage dechlorination
  - Dissolve and desorb DNAPL mass (for source area applications)

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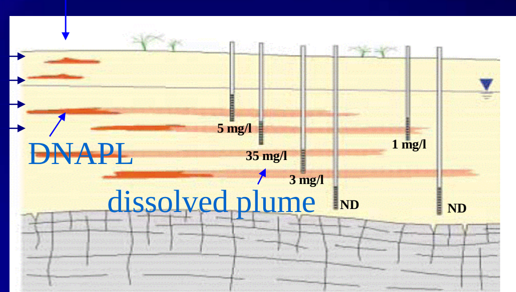
## Considerations for Source Zones

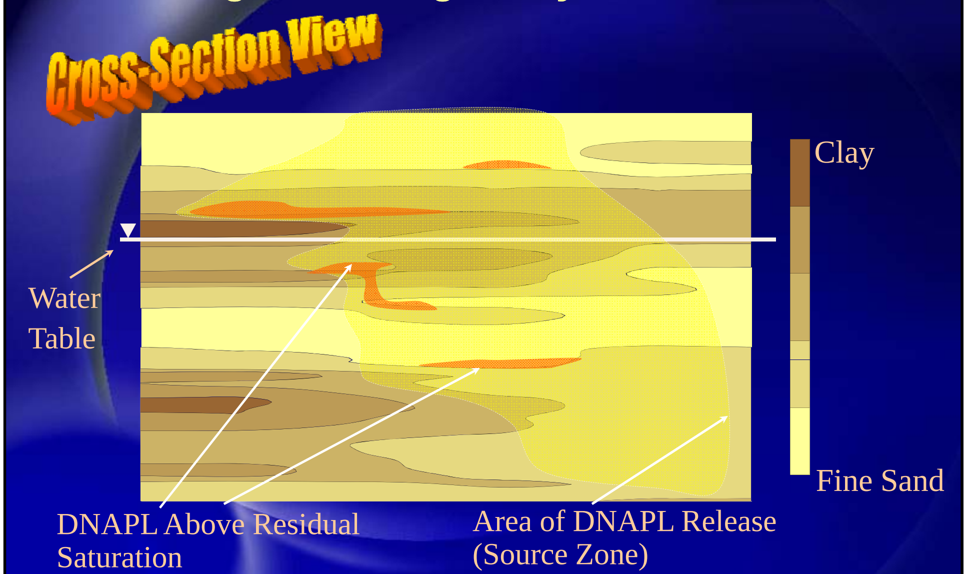
- Bioremediation can be successfully implemented in chlorinated solvent source zones (ITRC, 2008)
- Design must account for:
  - Delineation of source mass
  - Source area hydrogeology
  - Context of monitoring data

DNAPL release




Kueper, BH et al., 2003 – An illustrated handbook of DNAPL transport and fate in the subsurface

# Effect of Source Zone Geologic Heterogeneity

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# Subsurface Conditions Affecting Injection Designs

- Heterogeneity and/or low permeability strata
- DNAPL distribution
  - Area
  - Volume
  - Depths below grade
  - Depths below water table
- Target treatment zone
  - Location
  - Extent
- Depth to groundwater
  - And other factors influencing injection well costs
- Groundwater flow rates
- Geochemical conditions affecting
  - Bioremediation
  - Groundwater quality

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## Elements of Bioremediation Injection Design

- Electron donor selection
- Delivery method
- Injection volume and concentration
- Injection frequency
- Need for bioaugmentation

## Electron Donor Amendment Characteristics

- Carbon donors vary in several properties
  - Manner of hydrogen production
  - Chemical composition
  - Electron equivalents released per unit mass of amendment
  - Microbiological responses
  - Geochemical impact
  - Chemical / physical properties
  - Transport characteristics
  - Longevity

**Edible Oil Emulsions**

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## Electron Donor Amendments

- Soluble (i.e. Fast-release)
  - Lactate / other organic acids
  - Methanol / ethanol
  - Molasses / other carbohydrates
  - Dairy whey
- Slow-release
  - Edible oils and oil mixtures
  - Chitin (glucosamine polymer)
  - Lactate polymers
  - Mixtures of lactate and long-chain fatty acids
  - Solids (mulch)
- Key point: amendment choice and injection design are closely linked

**Increasing Product Development Creating a Continuum**

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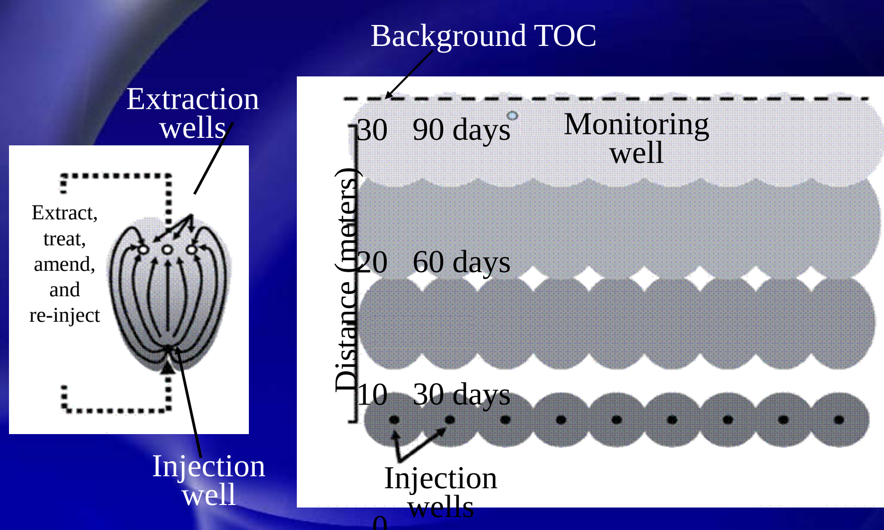
## Transport Considerations for Highly Soluble Amendments

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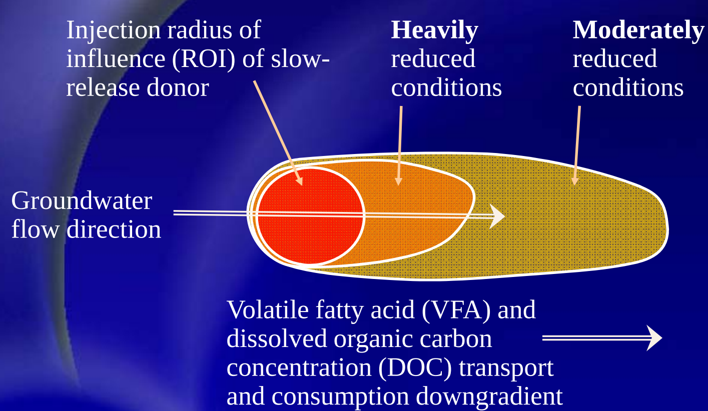
## Transport Considerations for Slow Release Amendments




Scale of process is highly dependent on site conditions

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## Secondary Amendments

- pH buffers
  - Carbonate/bicarbonate
  - Offset the production of hydrogen ion (H+) and volatile fatty acids (VFAs)
- Nutrients
  - Nitrogen (N), phosphorus (P) and potassium (K); also vitamin B12
  - Generally not needed for anaerobic bioremediation
  - Can compete as electron donors
- Bioaugmentation
  - May be needed if process is stalled at cis-DCE or VC
  - Not needed if appropriate microbial consortium is present
  - May accelerate process at some sites
- Chemical reagents
  - e.g., zero valent iron (ZVI), other reductants

## Overview of Delivery Techniques – Trenching

Trenching

- Generally used to emplace solid phase amendments (i.e. bark or mulch)
- Usually configured as one or a series of permeable reactive barrier oriented perpendicular to groundwater flow
- Installed using conventional excavation or biopolymer slurry.

## Overview of Delivery Techniques – Trenching (cont.)

Advantages:

- Can mitigate uncertainty caused by subsurface heterogeneity because it allows distribution across an entire cross-section of the plume
- Can be most cost effective means to emplace large mass of amendments

Disadvantages

- Can only be performed at shallow sites
- Not effective for delivering liquid amendments

## Overview of Delivery Techniques - Fracturing

### Fracturing

- This delivery technique applies high pressure to the subsurface to create cracks (fractures) in the soil
  - Hydraulic fracturing delivers a "proppant" into the fractures (such as sand) to prop them open; amendment can be mixed with the proppant
  - Pneumatic fracturing uses air or nitrogen as a carrier to deliver amendments into the fracture
- Generally used to deliver solid phase amendments

## Overview of Delivery Techniques – Fracturing (cont.)

### Advantages:

- Can successfully deliver amendments at low permeability sites and at sites with deep contamination
- Can actually increase the hydraulic conductivity of a formation; flow preferentially flows through fractures
- Individual fractures can be mapped, providing an accurate depiction of amendment distribution.

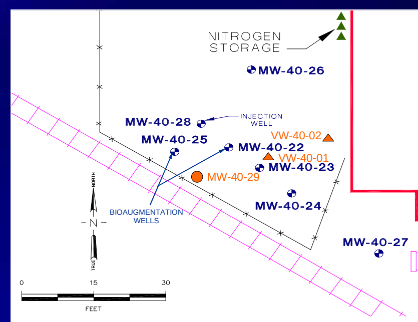
### Disadvantages

- Radius of influence decreases at shallower sites
- Not effective for delivering liquid amendments
- Requires specialized equipment and specialty vendors

## Overview of Delivery Techniques – Injection Wells

### Passive injection wells

- Standard wells installed at regular spacing used to inject amendments
- Well spacing and construction can be varied depending on goals
- Generally used to emplace aqueous amendments
- Amendments are injected and allowed to transport advectively




## Overview of Delivery Techniques – Injection Wells (cont.)

### Advantages:

- Can distribute large volumes of amendments over large areas with relatively few injection locations
- Standard technology readily available almost anywhere
- Can be used at sites with deep water table and at fractured rock sites, although costs may be high

### Disadvantages

- Radius of influence decreases at low permeability sites
- May not be effective at sites with low groundwater velocity
- Not effective for delivering solid amendments

## Overview of Delivery Techniques – Direct Push Technology

**Direct Push Technology**

- Injections are performed into temporary borings created using DPT
- DPT spacing can be varied depending on goals
- Generally used to emplace aqueous amendments
- Amendments are injected and allowed to transport advectively

## Overview of Delivery Techniques – Direct Push Technology (cont.)

**Advantages:**

- Many DPT points can be installed to inject over large areas
- Standard technology readily available almost anywhere
- Among the most cost effective techniques for delivering aqueous amendments

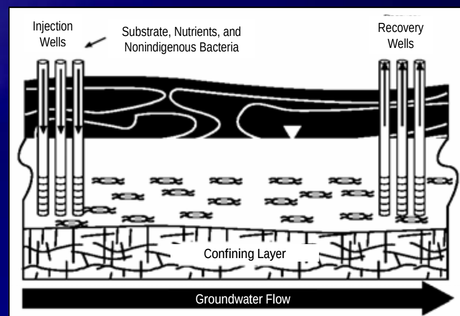
**Disadvantages**

- Radius of influence decreases at low permeability sites
- May not be effective at sites with low groundwater velocity
- Not effective for delivering solid phase amendments
- Infeasible for deep sites or fractured rock
- Generally not efficient at injecting large volumes

## Overview of Delivery Techniques – Active Recirculation

### Active Recirculation

- Injection and extraction wells used to recirculate groundwater across the treatment area
- Amendment "pulsed" into extracted water
- Amendments are injected and are transported under forced advection




From Major et. al, 2002

## Overview of Delivery Techniques – Active Recirculation (cont.)

### Advantages:

- Can distribute large volumes of amendments over large areas with relatively few injection locations
- Standard technology readily available almost anywhere
- Can be used at sites with deep water table and at fractured rock sites, although costs may be high
- Can distribute amendment at sites with low groundwater velocity

### Disadvantages

- Requires a significant amount of infrastructure
- O&M requirements high compared to inject and drift

## Application Suggestions

| | Aquifer permeability | Groundwater velocity | Aquifer matrix | Depth to contamination | Type of Substrate emplaced | Volume of Substrate emplaced |
|---|---|---|---|---|---|---|
| **Trenching** | Any | Any | Unconsolidated | Shallow (<40 ft) | Solid | High |
| **Fracing** | Low to moderate | Any | Unconsolidated; can work in some fracture media | Deeper than 25 ft | Solid | Low to moderate |
| **Passive injection** | Moderate to high | Moderate to high (>0.25 ft/day) | Any | Any | Aqueous | Low to high |
| **DPT** | Moderate to high | Moderate to high (>0.25 ft/day) | Unconsolidated | Shallow to moderate (up 50 ft) | Aqueous | Low to moderate |
| **Active Recirculation** | Moderate to high | Low to moderate | Any | Any | Aqueous | Low to high |

## Amendment Dosage

- The goal is to account for the demand imposed by all of the electron acceptors in the system
  - There is uncertainty in accurately determining or estimating the native electron donor demand
  - Typical safety factors of 5-10 or higher are commonly applied to the calculated dose to reflect the uncertainty
  - Significantly higher dosing may be used for source area applications
- Reasons for safety factors include
  - Unknown mass of electron acceptors (e.g., $Fe^{3+)}$ present within the treatment zone
  - Difficulty accurately predicting electron acceptor influx over time
  - “Wasteful” microbial activity (not linked to dechlorination)

## Amendment Injection Frequency

- Injection frequency depends on amendment that is being used and on type of application
  - Fast release donors may need to be injected every 4-12 weeks
  - Slow release donors may last up to two years or longer
  - Trenches/barrier application can be designed to be “recharged” with amendments
- Source area applications may require more frequent injections in order to maintain biologically active zone

## Bioaugmentation

- Bioaugmentation can be used to overcome microbiological limitations at sites
- Several cultures are commercially available for chlorinated solvents
- Several options for bioaugmentation exist
  - Add electron donor and only bioaugment when a microbiological limitation is evident
  - Bioaugment at the outset in order to reduce lag times and ensure that complete degradation will occur
  - Add electron donor for a short period of time to “pre-condition” the aquifer

## Monitoring during Operations

- Monitoring needs generally reduce as bioremediation projects progress from pilot studies to long-term operations
  - Pilot studies and initial operations will show which parameters are key at a given site
  - A "core list" of parameters still will be needed during operations, but frequency may decrease
- Some parameters may be important based on site-specific needs (e.g. metals, co-contaminants)

## Monitoring during Operations (cont.)

- Contaminants and degradation products
- Electron donor
  - COD or TOC
- Redox sensitive parameters
  - Ferrous iron
  - Sulfate
  - Methane
- Biological activity indicators and water quality parameters
  - pH
  - Alkalinity
  - Metals (site-specific basis)

## Monitoring during Operations (cont.)

- EMD’s can be useful during operations
- qPCR for DHC
  - commercially available and should be used during initial phases of operations
  - Location/frequency may be decreased over time
- CSIA
  - Can be useful at sites to demonstrate complete degradation is occurring
  - Probably more common during pilot studies/technology demonstration
- Others
  - Less common during operations

## Summary

- Standard groundwater chemistry parameters are needed to design a bioremediation system
- EMD’s are advanced diagnostic tools that can provide valuable information
- Bench scale studies can be useful but generally are not required
- Pilot studies are very useful at most sites
- Continuum of bioremediation amendments is available, with selection dependent on site conditions and remedial goals
- Amendment selection and delivery techniques are linked
- Monitoring needs generally decrease during bioremediation operations

## Questions and Answers

Q&A

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