Welcome to the CLU-IN Internet Seminar

Practical Models to Support Remediation Strategy Decision-Making – Part 2

Sponsored by: U.S. EPA Office of Superfund Remediation and Technology Innovation

Delivered: October 17, 2012, 1:00 PM - 3:00 PM, EDT (17:00-19:00 GMT)

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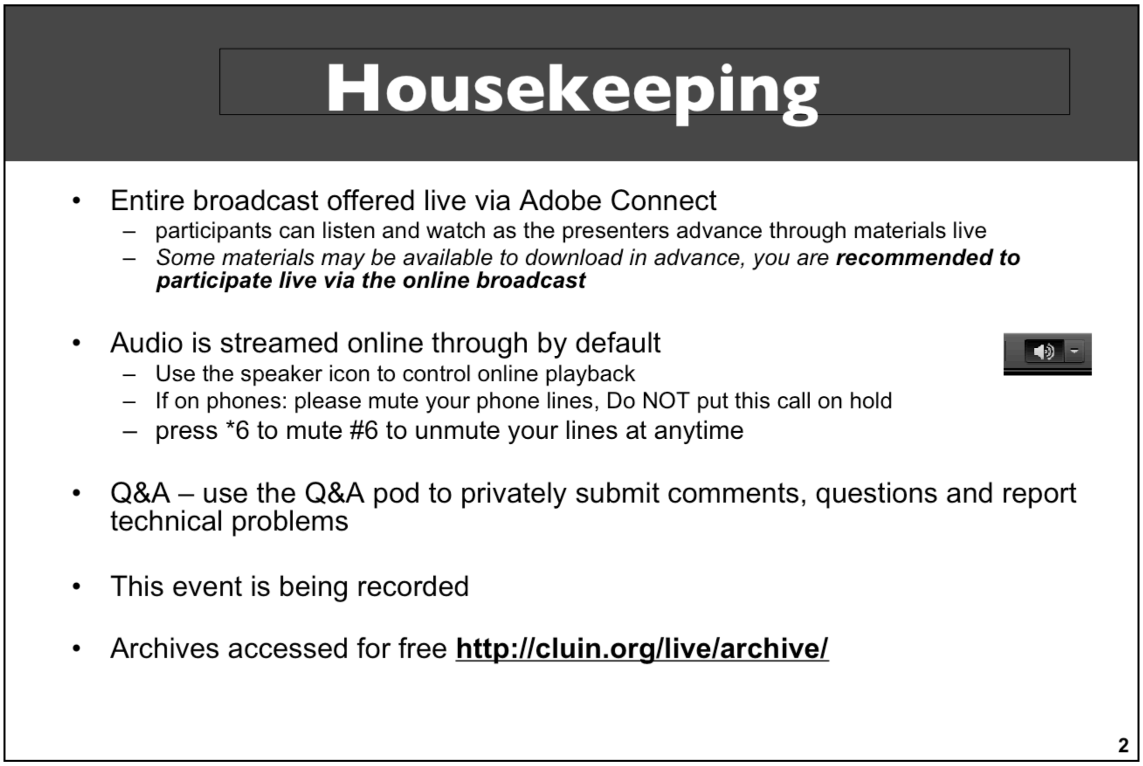

Although I'm sure that some of you have these rules memorized from previous CLU-IN events, let's run through them quickly for our new participants.

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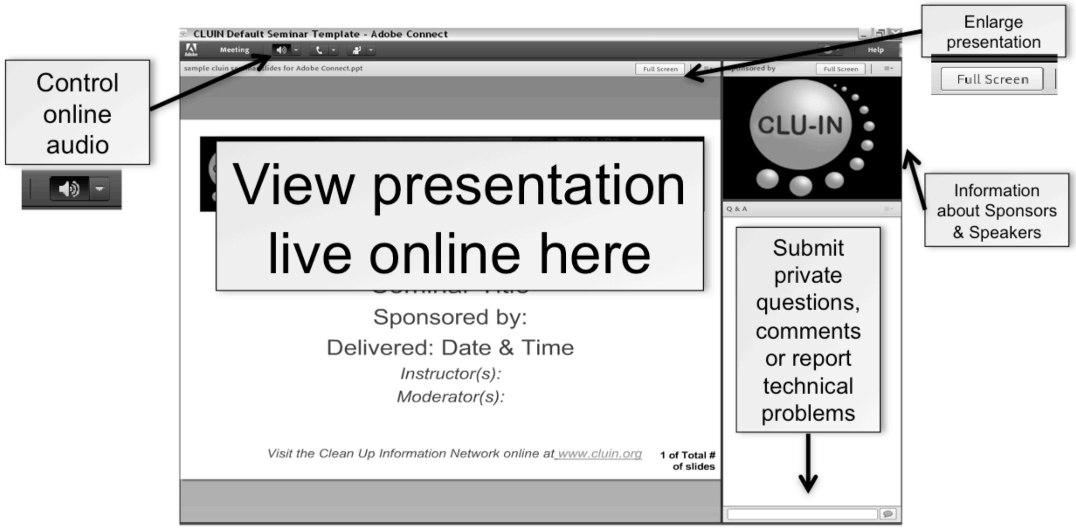
You should note that throughout the seminar, we will ask for your feedback. You do not need to wait for Q&A breaks to ask questions or provide comments. To submit comments/questions and report technical problems, please use the ? Icon at the top of your screen. You can move forward/backward in the slides by using the single arrow buttons (left moves back 1 slide, right moves advances 1 slide). The double arrowed buttons will take you to 1st and last slides respectively. You may also advance to any slide using the numbered links that appear on the left side of your screen. The button with a house icon will take you back to main seminar page which displays our agenda, speaker information, links to the slides and additional resources. Lastly, the button with a computer disc can be used to download and save today's presentation materials.

With that, please move to slide 3.

New online broadcast screenshot



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Practical Models to Support Remediation Strategy Decision-Making

Ronald W. Falta, Ph.D
Brian Looney, Ph.D
Charles J. Newell, Ph.D, P.E.
Karen Vangelas
Shahla K. Farhat, Ph.D

Module 2 - October 2012

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Seminar Disclaimer

- **The purpose of this presentation is to stimulate thought and discussion.**
- **Nothing in this presentation is intended to supersede or contravene the National Contingency Plan**

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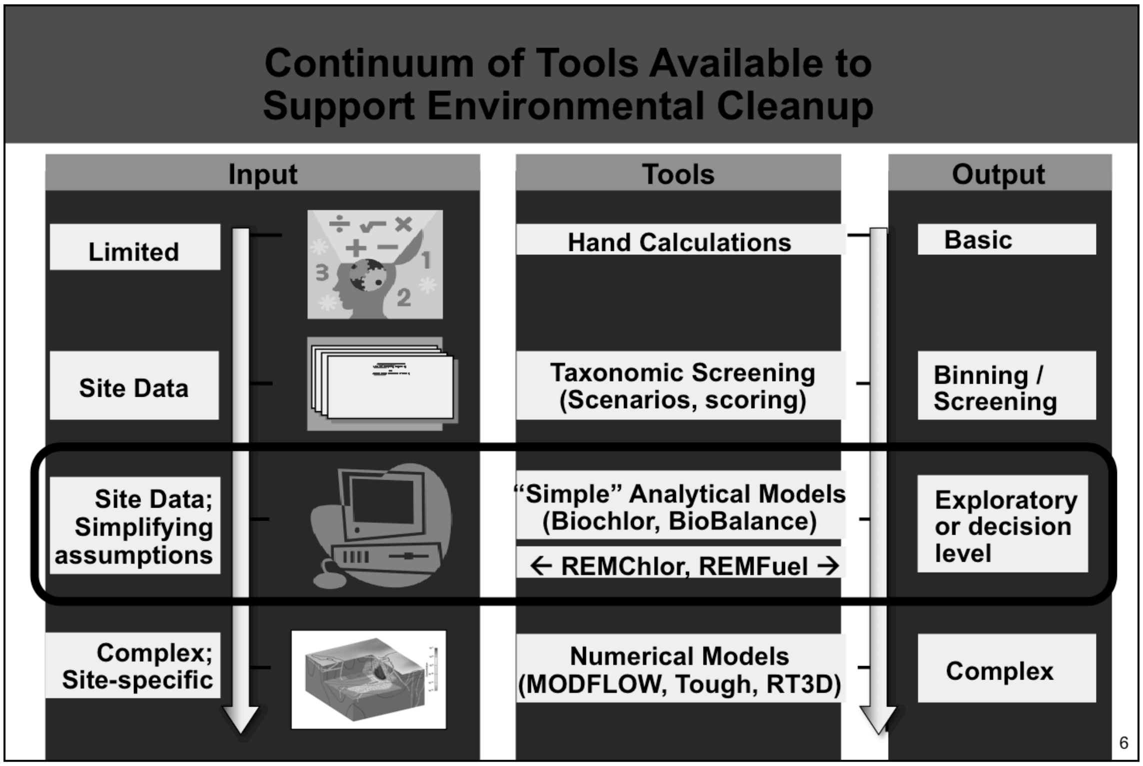

Continuum of Tools Available to Support Environmental Cleanup
Input
Tools
Output
Limited
Hand Calculations
Basic
Site Data
Taxonomic Screening (Scenarios, scoring)
Binning / Screening
Site Data; Simplifying assumptions
"Simple" Analytical Models (Biochlor, BioBalance)
← REMChlor, REMFuel →
Exploratory or decision level
Complex; Site-specific
Numerical Models (MODFLOW, Tough, RT3D)
Complex
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[redacted] *Ron Falta, Ph.D.*

- **Professor, Dept. of Environmental Engineering & Earth Sciences, Clemson University**
  - Ph.D. Material Science & Mineral Engineering, U. of California, Berkley
  - M.S., B.S. Civil Engineering Auburn University
- **Instructor for subsurface remediation, groundwater modeling, and hydrogeology classes**
- **Developer of REMChlor and REMFuel Models**
- **Author of Numerous technical articles**
- **Key expertise:** Hydrogeology, contaminant transport/ remediation, and multiphase flow in porous media

[redacted] *Charles J Newell,* Ph.D., P.E.

- **Vice President, GSI Environmental Inc.**
  - Diplomate in American Academy of Environmental Engineers
  - NGWA Certified Ground Water Professional
  - Adjunct Professor, Rice University
- **Ph.D. Environmental Engineering, Rice Univ.**
- **Co-Author 2 environmental engineering books; 5 environmental decision support software systems; numerous technical articles**
- **Expertise:** Site characterization, groundwater modeling, non-aqueous phase liquids, risk assessment, natural attenuation, bioremediation, software development, long term monitoring, non-point source studies

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[redacted] *Vangelas, Looney, Farhat*

- **Karen Vangelas, Savannah River National Lab**
  - M.S. Environmental Engineering, Penn State
  - Groundwater, remediation
- **Brian Looney, Savannah River National Lab**
  - Ph.D. Environmental Engineering, U. of Minnesota
  - Vadose zone, remediation, groundwater modeling
- **Shahla Farhat, GSI Environmental**
  - Ph.D. Environmental Engineering, U. of North Carolina
  - Decision support tools, remediation, modeling

BREAK FOR DISCUSSION OF HOMEWORK EXERCISE 1 AND RESPONSES TO MODULE 1 QUESTIONS FROM PARTICIPANTS

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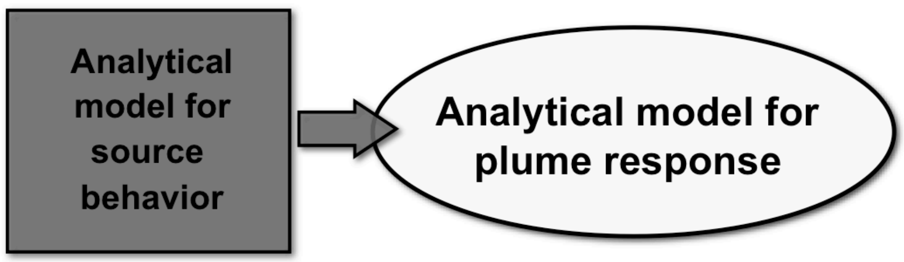
Explanation of How the *Plume* Works in REMChlor



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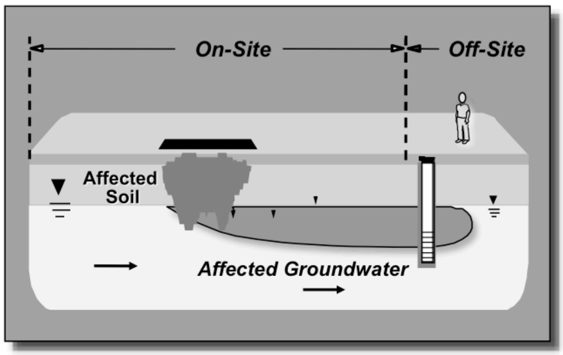
Key Concept 2: Plumes



Key Driver

- **Discharge from source**

Key Processes

- **Advection**
- **Dispersion**
- **Adsorption**
- **Degradation**

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Key Material Balance Equations - Plume

Plume equation solved for each species. Equations are linked through the chemical reaction terms.

First-Order Decay reactions

$$R\frac{\partial C_i}{\partial t} = -v\frac{\partial C_i}{\partial x} + \alpha_x v\frac{\partial^2 C_i}{\partial x^2} + \alpha_y v\frac{\partial^2 C_i}{\partial y^2} + \alpha_z v\frac{\partial^2 C_i}{\partial z^2} + rxn_i$$

Retardation Coefficient

Longitudinal Dispersivity

Transverse Dispersivity

Vertical Dispersivity

Groundwater Seepage Velocity

Hydraulic Conductivity

Hydraulic Gradient

Effective Soil Porosity

$$V = \frac{K\,i}{n_e}$$

Groundwater Transport Processes - Biodegradation

- Indigenous micro-organisms are capable of degrading many contaminants.
- Need electron donor and electron acceptor.
- [redacted] like benzene serve as **electron donor.** Oxygen, nitrate, sulfate, iron are **electron acceptor.**
- [redacted] act as **electron acceptor.** Hydrogen/acetate serve as **electron donor.**

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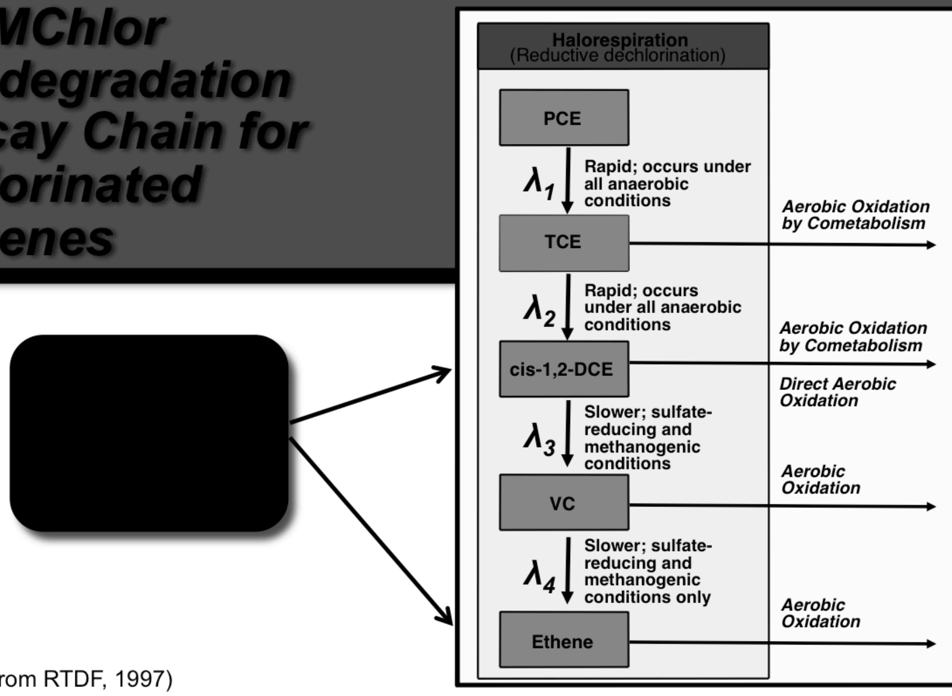
REMChlor Biodegradation Decay Chain for Chlorinated Ethenes



(Adapted from RTDF, 1997)

All these reactions are First Order Decay.

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Example REMChlor Sequential Reactions

$$PCE \xrightarrow{\lambda_1} TCE \xrightarrow{\lambda_2} DCE \xrightarrow{\lambda_3} VC \xrightarrow{\lambda_4} ETH$$

$$Rate_{PCE} = -\lambda_1 C_{PCE}$$

$$Rate_{TCE} = \lambda_1 y_1 C_{PCE} - \lambda_2 C_{TCE}$$

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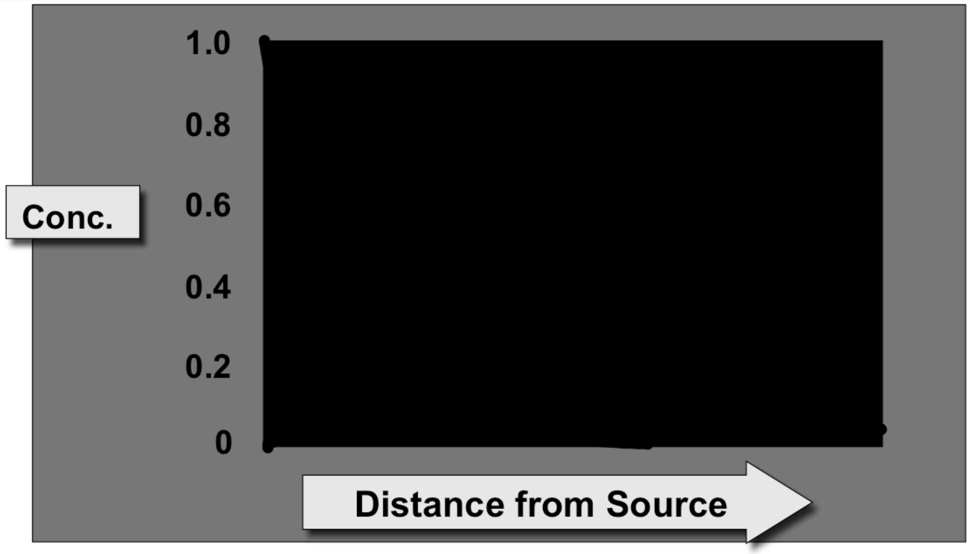
Example Results of Sequential Reactions



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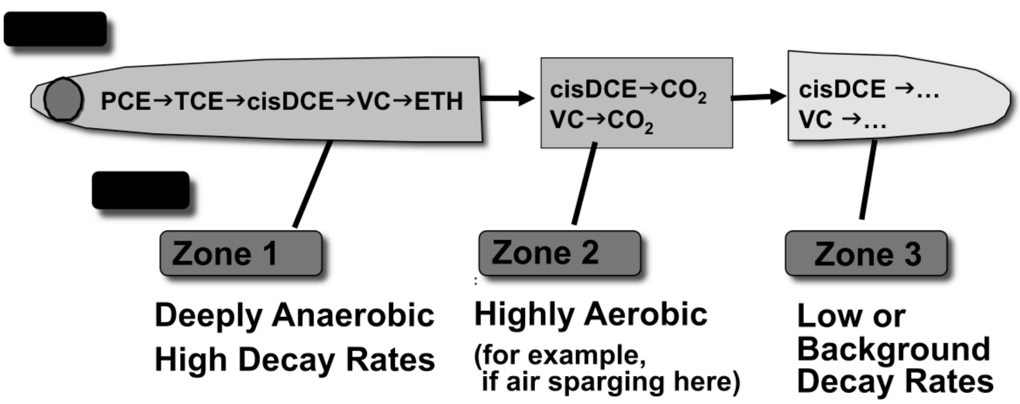
REMChlor Model: Other Features

[redacted]



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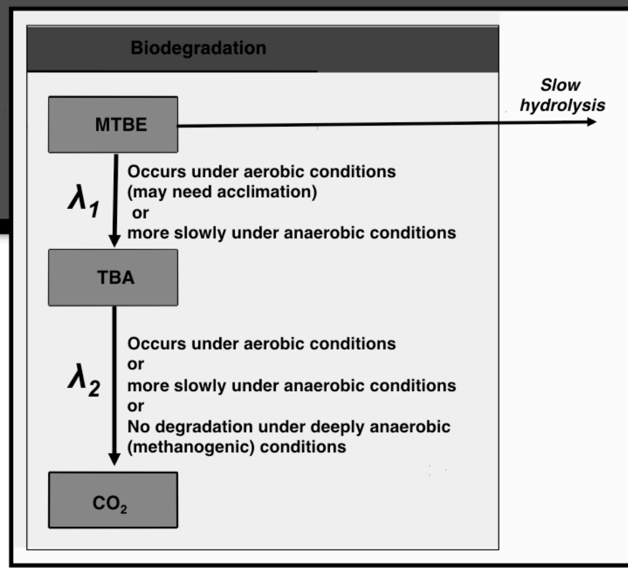
REMFuel Simplified Biodegradation Decay Chain for MTBE



All these reactions are First Order Decay.

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REMFuel Sequential Reactions

$$MTBE \xrightarrow{\lambda_1} TBA \xrightarrow{\lambda_2} CO_2$$

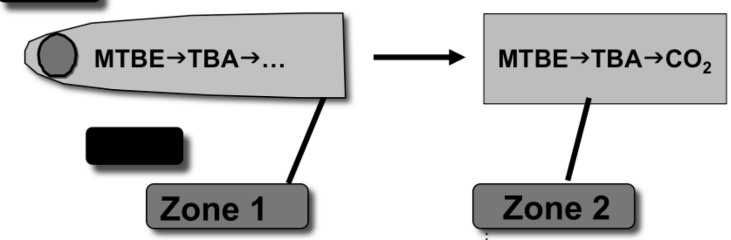
$$Rate_{MTBE} = -\lambda_1 C_{MTBE}$$

$$Rate_{TBA} = \lambda_1 y_1 C_{MTBE} - \lambda_2 C_{TBA}$$

REMFuel Model: Other Features

[redacted]

[redacted]



[redacted]

Zone 1

Deeply Anaerobic (Methanogenic)

MTBE degrades but no TBA degradation

Zone 2

Aerobic

Both MTBE and TBA degrade

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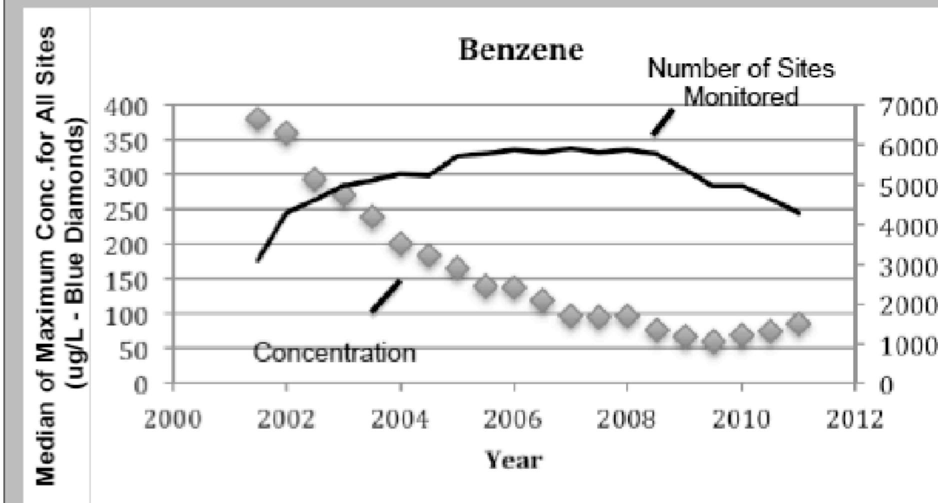
Maximum Site Concentrations Over Time California Geotracker Database (most with some type of remediation)



McHugh et al., 2012

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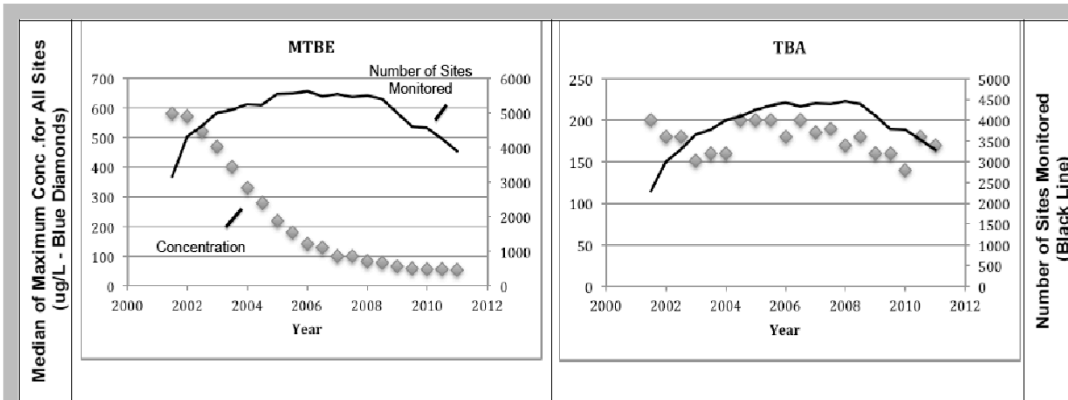
Maximum Site Concentrations Over Time
California Geotracker Database
(most with some type of remediation)

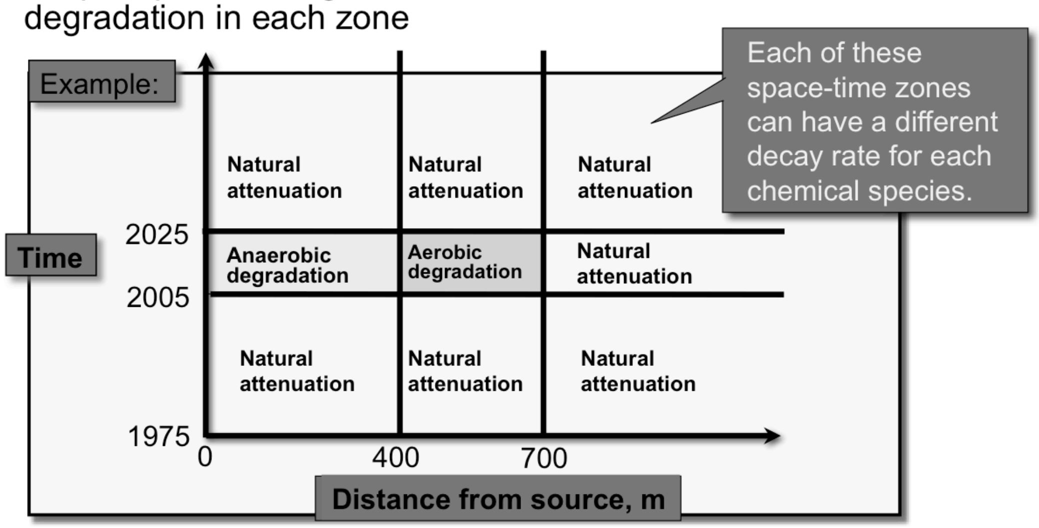


Note: Charts show median of maximum concentration for all sites vs. time for UST sites in California with any monitoring data available between 2001 and 2011.

McHugh et al., 2012

REM's Plume Remediation Model

Divide space and time into "reaction zones", solve the coupled parent-daughter reactions for chlorinated solvent degradation in each zone



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Wrap-Up: *Describing Your Plume's "Space-Time Story" With REMC and F*

1. **Both models allows plume to develop for any number of years before remediation (Neat!) (Very Important).**
2. **You can simulate three natural reaction zones.**
3. **You can remediate all or part of the plume by increasing degradation rates for three specific time periods (1 year? 5 years? You pick).**
4. **The plume will respond to all of these factors:**

natural attenuation processes
+ plume remediation
+ source decay
+ source remediation (eventually!)

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Agenda

- **Class Objectives**
- **What Tools are Out There?**
- [redacted]
  - *Will Source Remediation Meet Site Goals?*
  - *What Will Happen if No Action is Taken?*
  - *Should I Combine Source and Plume Remediation?*
  - *What is the Remediation Time-Frame?*
  - *What is a Reasonable Remediation Objective?*

Note: Many of these questions are interrelated!

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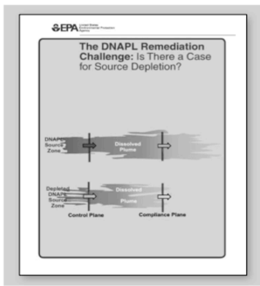
Will Source Remediation Meet Site Goals?
What are the Goals?   Two Examples

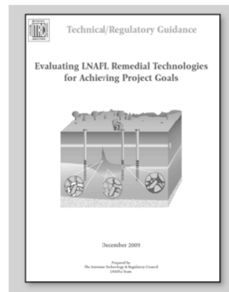
U.S. EPA DNAPL Challenge (2003)

- Reduce potential for DNAPL migration
- Reduce long-term management requirements
- Enhance natural attenuation
- Reduce loading to receptor
- Attain MCLs
- “Stewardship”



ITRC LNAPL Guidance (2009)

- Reduce LNAPL to residual saturation range
- Terminate/reduce potential LNAPL body migration
- Abate/reduce unacceptable soil vapor and/or dissolved phase concentrations from LNAPL
- Aesthetic LNAPL concern Abated (saturation or (composition)



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Will Source Remediation Meet Site Goals?

General Characteristics of Sites

Where is the bulk of the contaminant mass?	What is the nature of the plume over time? (assume that plume is relatively large)	How much concentration reduction is needed (maximum /desired)
SOURCE-DOMINATED Mostly in the NAPL source zone	Growing	Factor of ten
MIXED SOURCE/PLUME Partly in the source zone and partly in the dissolved plume	Stable	Factor of five hundred
PLUME-DOMINATED Mostly in the dissolved plume	Shrinking	Factor of ten thousand

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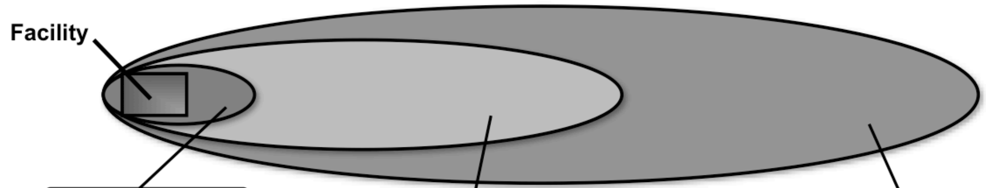
Applied Environmental Science Philosophy:
Anatomy of an Impacted Site



Disturbed zone

Characteristics:
Perturbed conditions (chemistry, Source NAPL, etc.)

Need:
Eliminate or mitigate disturbance by active engineered solution or improved design

Impact zone

Characteristics:
Area with observable and easily detectable impacts

Need:
Characterization data to quantify impacts and mitigation activities, as needed, to provide environmental protection

Transition / Baseline zone

Characteristics:
Area where impacts are minimal and conditions are similar to unimpacted settings

Need:
Careful characterization to provide a baseline for understanding impacts, development. Application of sensitive methods and early warning tools. Fundamental science!

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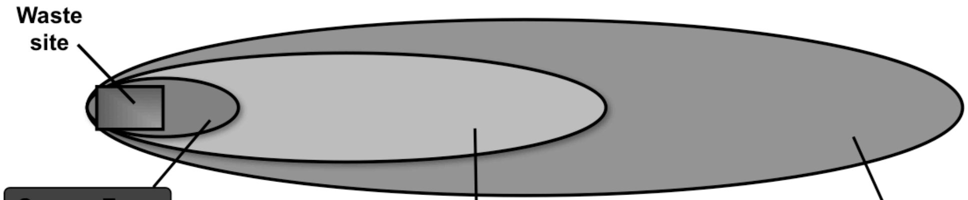
Diagnosing and Treating a Site



Source Zone

Costs:

$/lb contaminant or $/cu yd. Removal examples:
< $50-$100/cu yd or
< $100/lb for chlorinated solvents

hot spot characterization reduces cleanup volume

Primary Groundwater / Vadose Zone Plume

Costs:

$/treatment volume (gallon/cu ft) example:
<$0.5-$10 / 1000 gallons

zone of capture characterization needed, optimize extraction to reduce treatment volume

Dilute Plume/Fringe

Costs:

Operation and maintenance costs $/time

mass transfer and flux characterization needed

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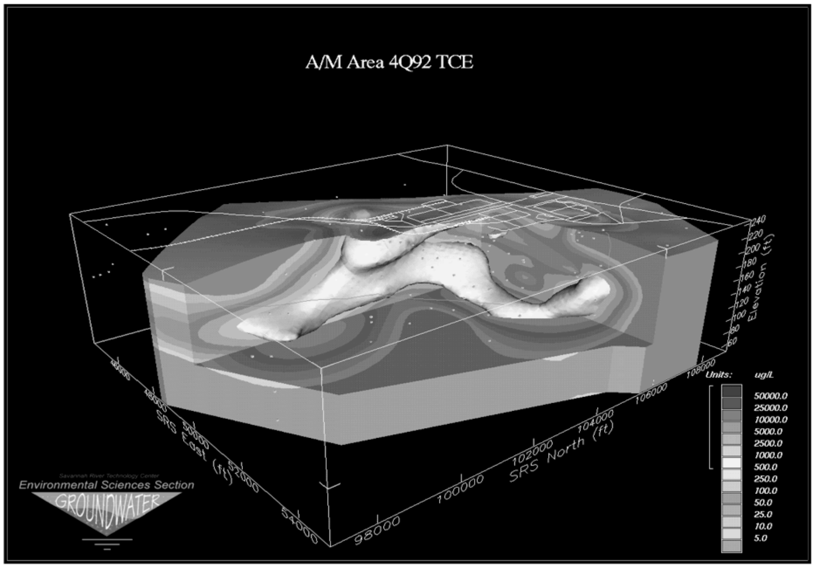
Real World Plume



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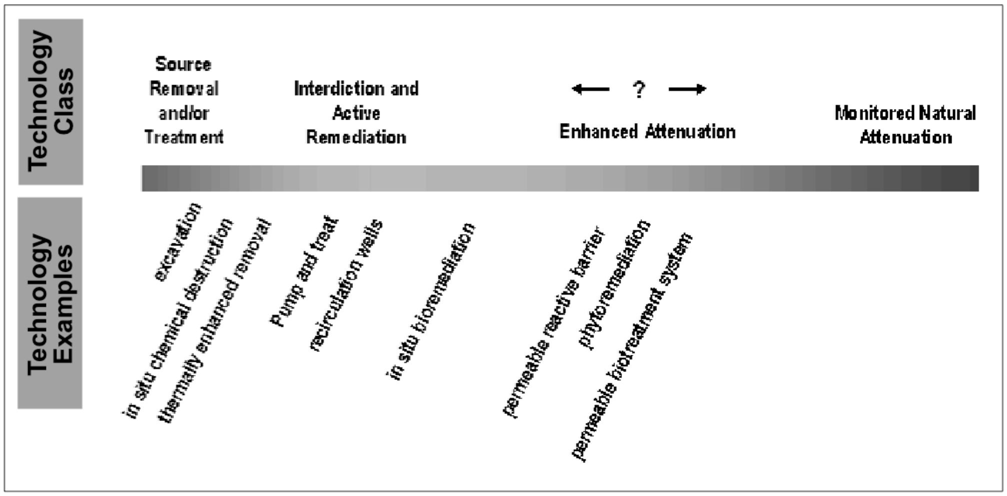
Continuum of Remediation Technologies/ Strategies/Options



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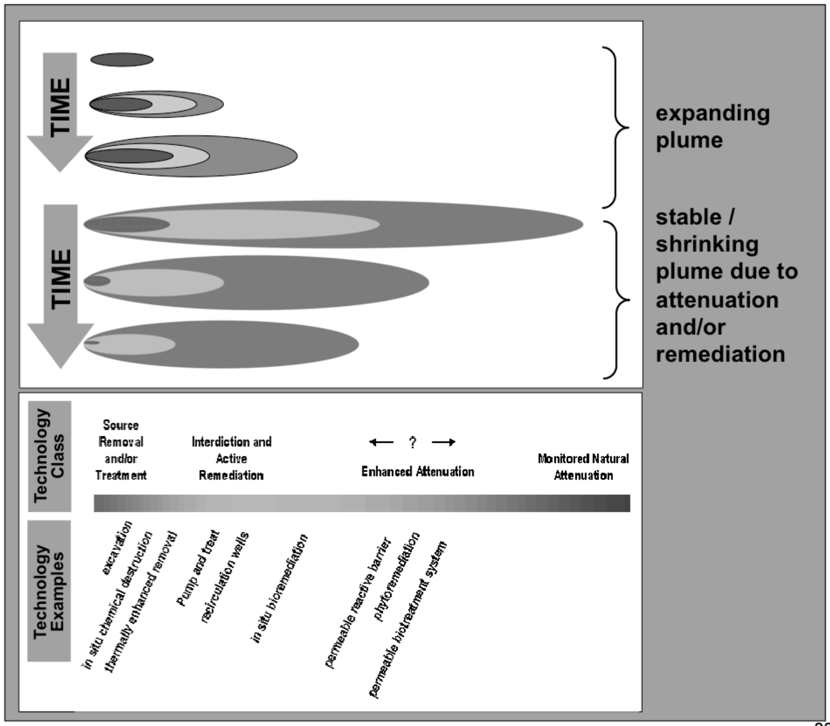
a) Simplified representations of a groundwater plume in space and time

b) Potential remedial technologies



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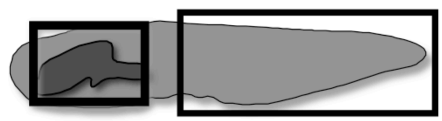
Technology Coupling

- Three types: temporal, spatial, simultaneous
- IDSS team experience most common approaches:
  - Intensive technology followed by passive
  - Different technology for Source versus Plume
  - Any technology followed by MNA
- In past, “opposing” combinations (ISCO then bio) were thought to be incompatible. This has proven to not be *always* the case.



From ITRC Integrated DNAPL Site Strategy training materials

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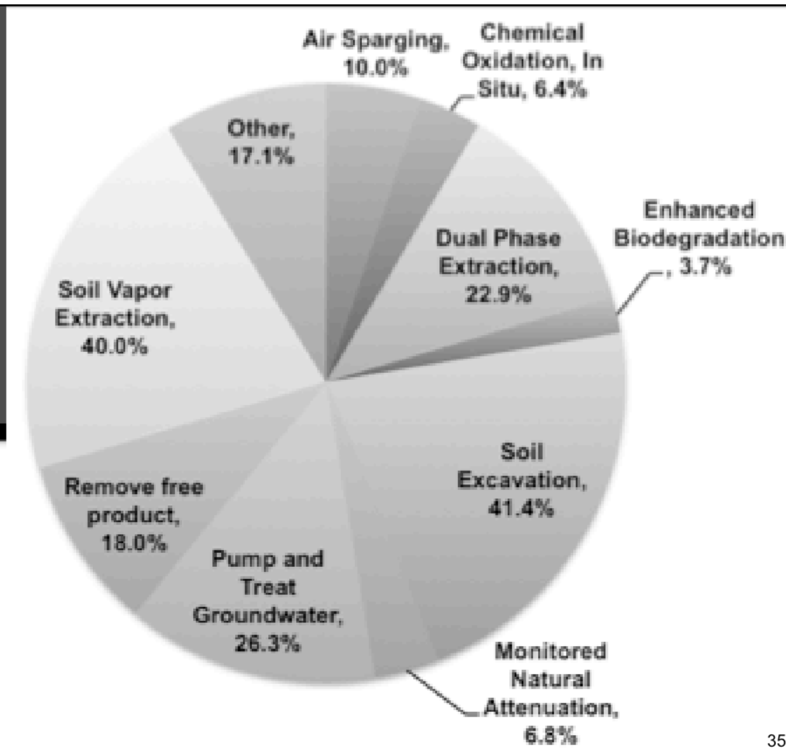
Remediation Technologies Used at California Benzene Sites Based on Geotracker Database

N=1323 Sites



Data: McHugh et al., 2012

Multiple Site Performance Studies
(This and next 3 slides apply to chlorinated solvent sites)

Strong point about these studies …

- **Strong point about these studies…**
- **Independent researchers, careful before/after evaluation**
- **Repeatable, consistent comparison methodology**
- **Describes spectrum of sites**
- **Real data, not anecdotal**
- **Several studies described in peer reviewed papers:**

Ground Water Monitoring&Remediation

Performance of DNAPL Source Depletion Technologies at 59 Chlorinated Solvent-Impacted Sites

by Travis M. McGuire, James M. McDade, and Charles J. Newell

Multiyear Temporal Changes in Chlorinated Solvent Concentrations at 23 Monitored Natural Attenuation Sites

Charles J. Newell, P.E., M.ASCE[1]; Iain Cowie[2]; Travis M. McGuire[3]; and Walt W. McNab Jr.[4]

Abstract: Long-term (e.g., 5–15 years) groundwater concentration versus time records were compiled from 47 near-source zone monitoring wells at 23 chlorinated solvent sites (52 total records). Chlorinated volatile organic compound (CVOC) concentrations decreased significantly in most of the 52 temporal records, with a median reduction in concentration of 74%. A statistical method based on a Mann–Kendall analysis also showed that most sites had statistically significant decreasing concentration trends over time. Median point

Ground Water Monitoring&Remediation

ISCO for Groundwater Remediation: Analysis of Field Applications and Performance

by Friedrich J. Krembs, Robert L. Siegrist, Michelle L. Crimi, Reinhard F. Furrer, and Benjamin G. Petri

Ground Water Monitoring&Remediation

State-of-the-Practice Review of In Situ Thermal Technologies

by Jennifer L. Triplett Kingston, Paul R. Dahlen, and Paul C. Johnson

From ITRC Integrated DNAPL Site Strategy training materials

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Order of Magnitude are Powers of 10
Why Use OoMs for Remediation?

- Hydraulic conductivity is based on OoMs
- VOC concentration is based on OoMs
- Remediation performance (concentration, mass, Md) can be also evaluated using OoMs ….
  - 90% Reduction: 1 OoM reduction
  - 99.9% Reduction: 3 OoM reduction
  - 70% Reduction: 0.5 OoM reduction
- Example:
  - Before concentration 50,000 ug/L
  - After concentration 5 ug/L
  - Need 4 OoMs (99.99% reduction)

From ITRC Integrated DNAPL Site Strategy training materials

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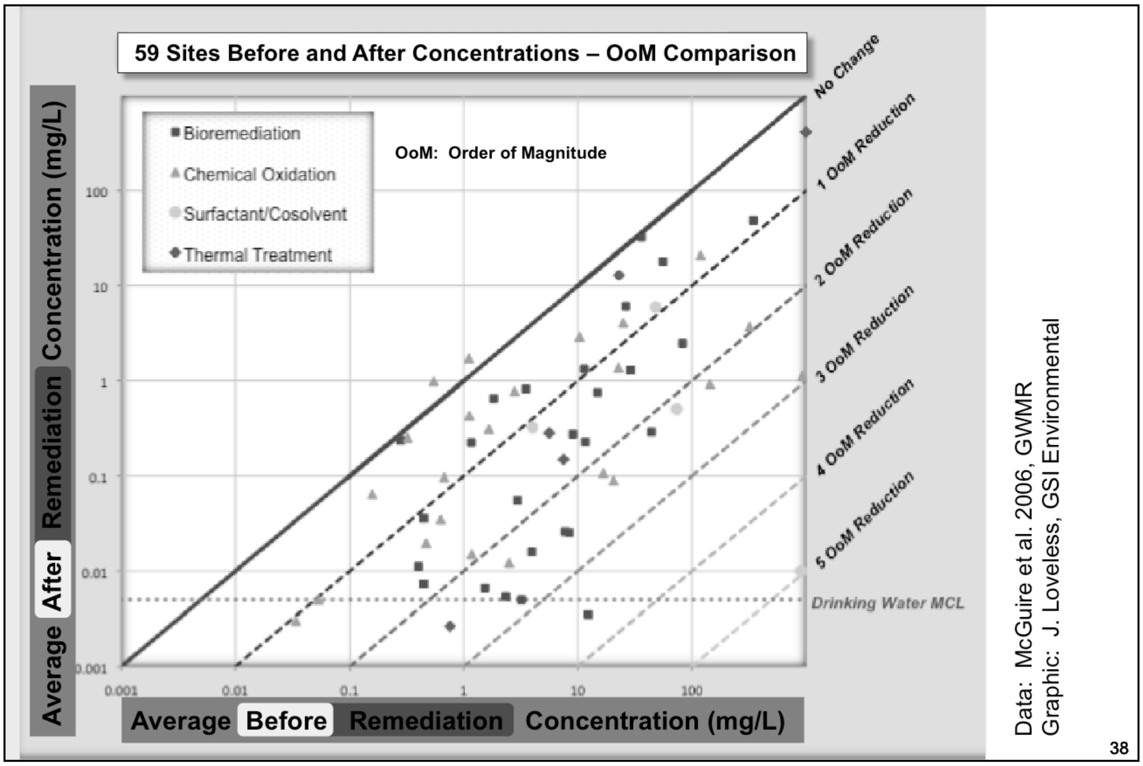

59 Sites Before and After Concentrations – OoM Comparison
Bioremediation
Chemical Oxidation
Surfactant/Cosolvent
Thermal Treatment
OoM: Order of Magnitude
No Change
1 OoM Reduction
2 OoM Reduction
3 OoM Reduction
4 OoM Reduction
5 OoM Reduction
Drinking Water MCL
Average After Remediation Concentration (mg/L)
Average Before Remediation Concentration (mg/L)
0.001
0.01
0.1
1
10
100
Data: McGuire et al. 2006, GWMR
Graphic: J. Loveless, GSI Environmental
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Others Say Use Caution….

- Not site specific
- Some lump pilot scale, full scale
- May not account for intentional shutdowns (i.e. they stopped when they got 90% removal)
- Don't account for different levels of design/experience
- We are a lot better now….

From ITRC Integrated DNAPL Site Strategy training materials

BREAK FOR QUESTIONS FROM PARTICIPANTS

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How to Use REMChlor and REMFuel

1. Collect input data.
2. Determine things you don't know and make best estimate.
3. Run model and compare results to available data (such as most recent sampling event).
4. Adjust model parameters to fit data (plume length is most common calibration parameter). Typical things to adjust are parameters in Step 2 above, particularly:
   - Initial source concentration
   - Source mass
   - Biodegradation rate in plume
   - Seepage velocity
5. Run sensitivity analysis (vary several parameters and see which ones are important).

Show Me How It Works

NUMBER 1

REMChlor and the TCE Plume

♦

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REMChlor Case Study: TCE Plume at a Manufacturing Plant in North Carolina

- **Plant in eastern NC, currently produces Dacron polyester resin and fibers.**
- **TCE contamination of groundwater discovered in the late 1980's; ~ stable plume about 1250 ft long (380 m).**
- **Release date unknown, but before 1980.**
- **Plume is dominated by TCE; small amounts of cis-1,2-DCE are present and VC is essentially absent.**
- **Groundwater velocity is slow, less than 100 ft/yr seepage velocity.**

from Liang et al., Ground Water Monitoring and Remediation, Winter, 2012

REMChlor Case Study: TCE Plume at a Manufacturing Plant in North Carolina

- Source zone TCE mass estimated at 300 lbs (136 kg), source zone concentrations up to ~6,000 ug/L.
- Source remediation took place in 1999, consisting of ZVI injection throughout the suspected source zone. Although source mass removal was reported as 95%, wells in the source zone have not seen large reductions in concentration.
- A 5 inch thick permeable reactive barrier (PRB) using ZVI was installed 290 ft downgradient of the source in 1999.

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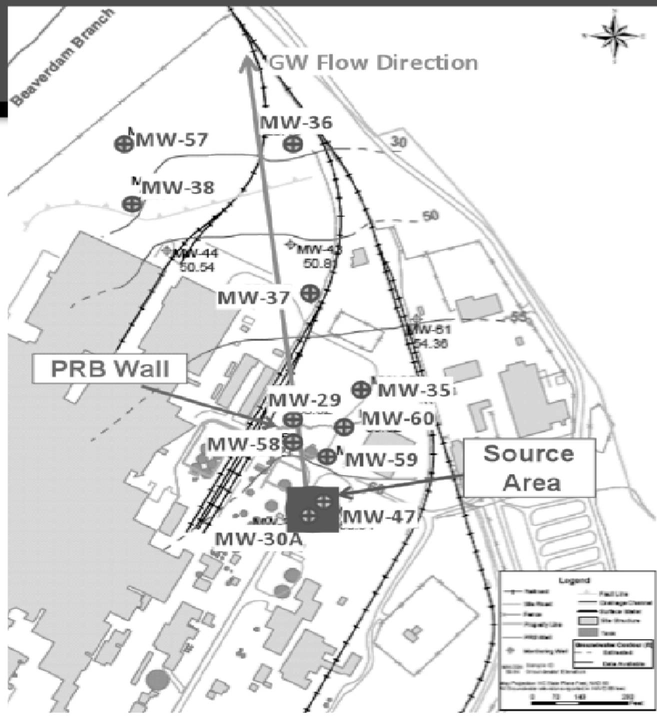
Will Source Remediation
Meet Site Goals?
Should We Combine
Source and
Plume Remediation?



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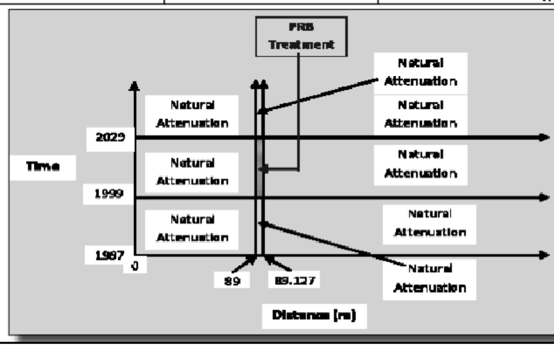
REMChlor Model Parameters for Transport/Natural Attenuation

Parameter	Value	Comment
Initial Source Conc., C_o	6,000 ug/L	Estimated from source wells
Initial Source Mass, M_o	136 kg	From site reports; assume 1967 release date
Source function exponent, Γ	1	Estimated
Source Width, W	8 m	From site reports
Source Depth, D	3.5 m	From site reports
Darcy velocity, V	8 m/yr	Calibrated; reports had estimated 1.5 to 4.6 m/yr
Porosity, φ	0.33	From site reports
Retardation Factor, R	2	Estimated
Longitudinal dispersivity, α_l	x/20	Calibrated
Transverse dispersivity, α_t	x/50	Calibrated
Vertical dispersivity, α_v	x/1000	Estimated
TCE decay rate in plume, λ	0.125 yr^{-1}	Calibrated (equal to $t_{1/2}$ of 5.5 yrs)

REMChlor Model Parameters for Source and Plume Remediation

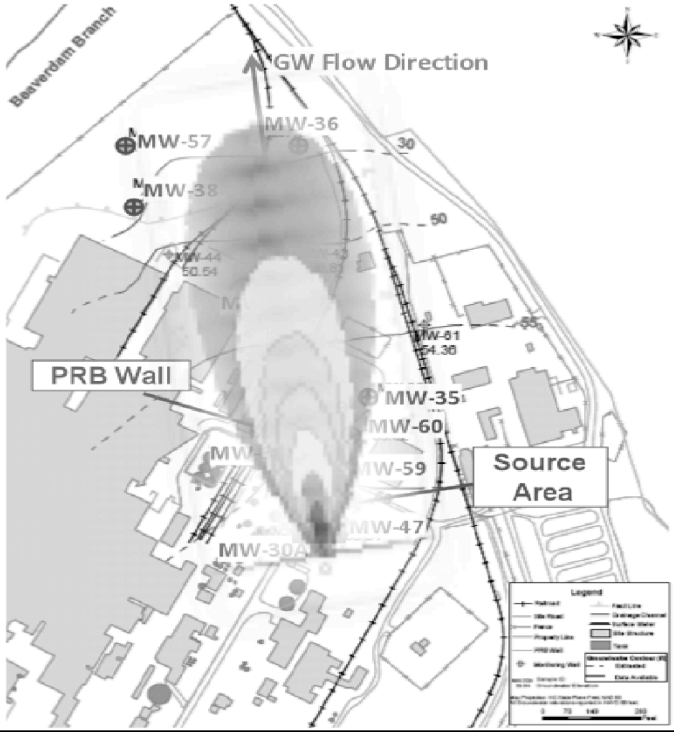
Parameter	Value	Comment
Fraction of source removed in 1999, X	95%	From site reports (but large uncertainty)
PRB wall thickness (after 1999)	0.127m (5")	From site reports
TCE decay rate in PRB	435 yr^{-1}	Estimated from well data (equal to $t_{1/2}$ of 14 hours)



Will Source Remediation Meet Site Goals? Should We Combine Source and Plume Remediation?

Simulated TCE concentrations In 1999 prior to source remediation or PRB wall installation

Contours at 5, 20, 50,100, 200, 500, and 1000 ug/L



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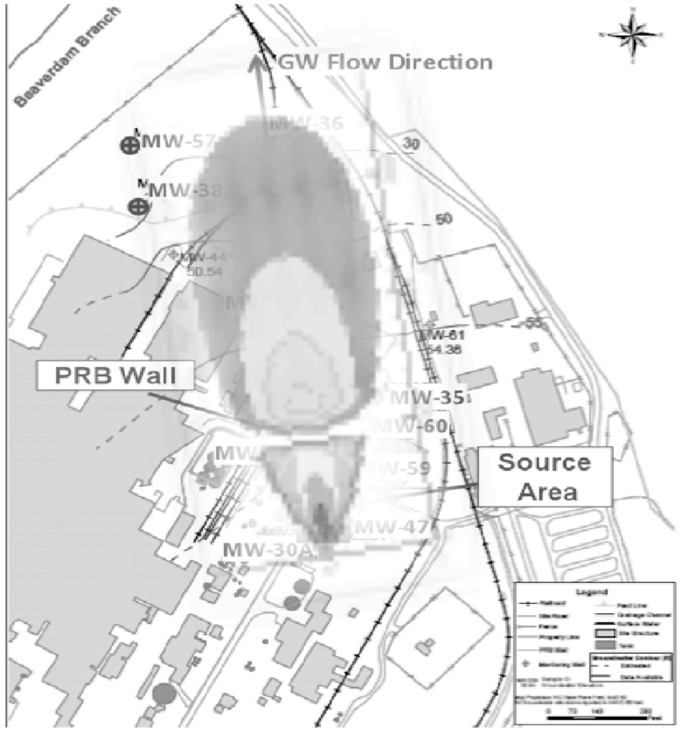
Will Source Remediation Meet Site Goals? Should We Combine Source and Plume Remediation?

Simulated TCE concentrations In 2001, 2 years after source remediation and PRB wall installation

Contours at 5, 20, 50,100, 200, 500, and 1000 ug/L



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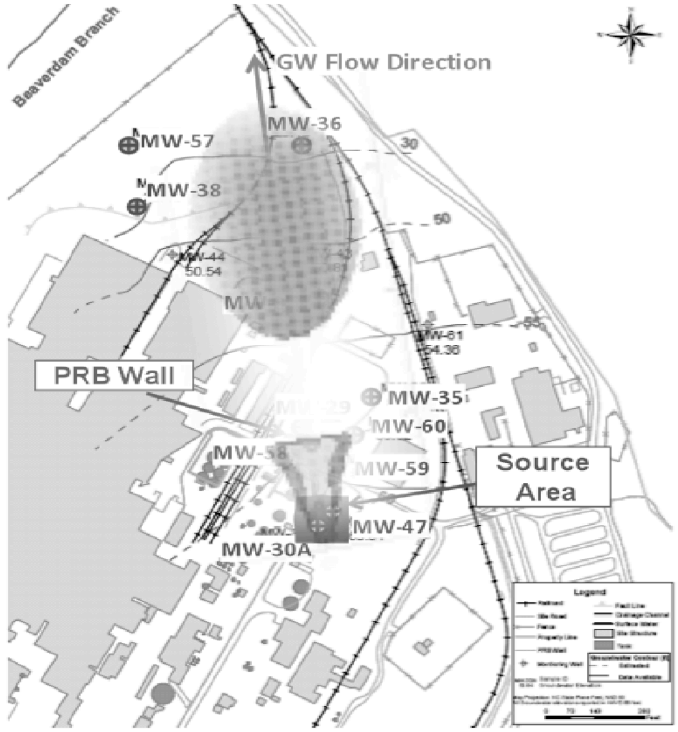
Will Source Remediation Meet Site Goals?
Should We Combine Source and
Plume Remediation?

Simulated TCE concentrations In 2009, 10 years after source remediation and PRB wall installation

Contours at 5, 20, 50,100, 200, 500, and 1000 ug/L



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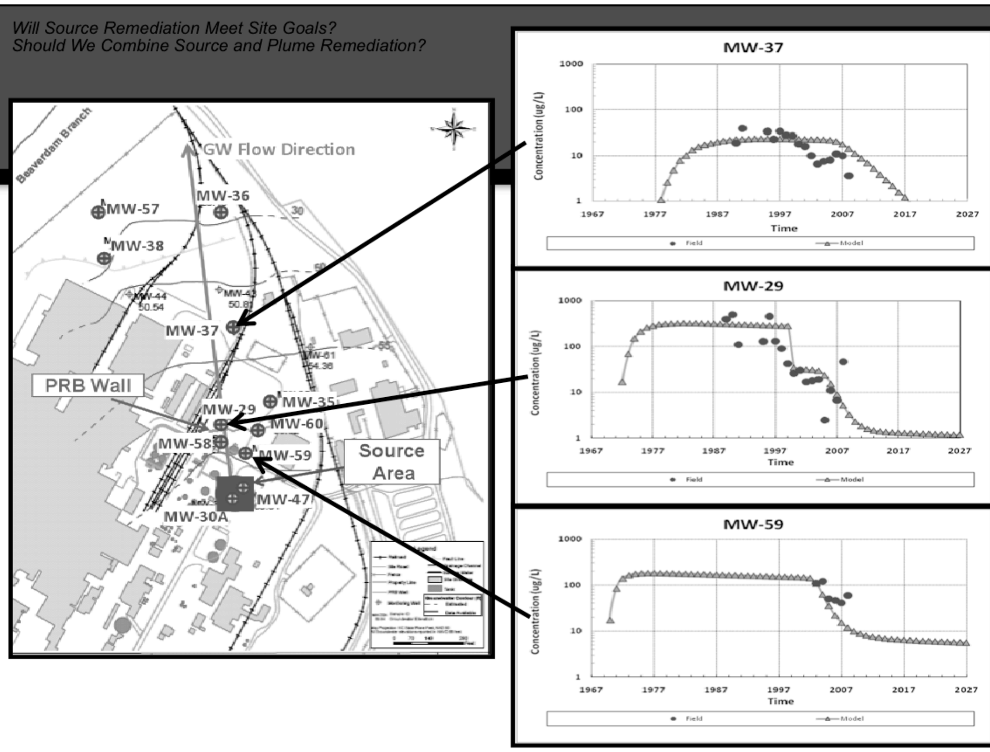
Will Source Remediation Meet Site Goals?
Should We Combine Source and Plume Remediation?



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REMChlor Key Points

1. REMChlor allows plume to develop for any number of years before remediation (Neat!) (Very Important).
2. You can simulate three natural reaction zones.
3. You can remediate all or part of the plume by increasing degradation rates for three specific time periods (1 year? 5 years? You pick).
4. The plume will respond to all of these factors:

natural attenuation processes
+ plume remediation
+ source decay
+ source remediation (eventually!)

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Hands-On Computer Exercise

NUMBER 1

Now You Try Using REMChlor For a Site

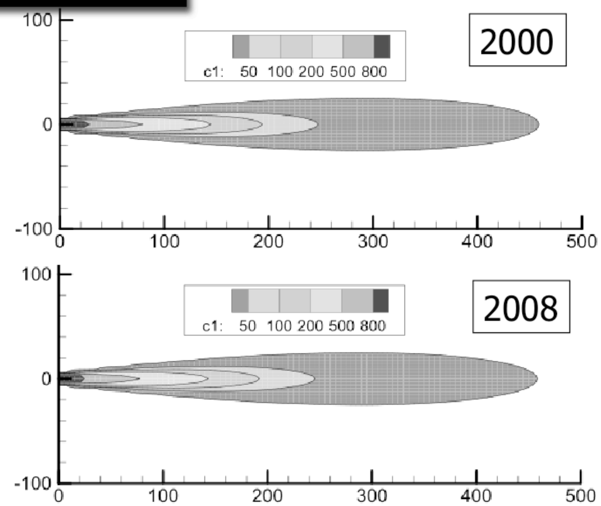
♦

Questions answered:
What will happen if no action taken?
Will source remediation meet site goals?

Will Source Remediation Meet Site Goals?

Case #1

- ***Initial source concentration is 1 mg/L***
- ***Groundwater pore velocity is 60 m/yr***
- ***1,2-DCA plume biodegradation half life is 2 years***
- ***Plume is stable, but not shrinking***



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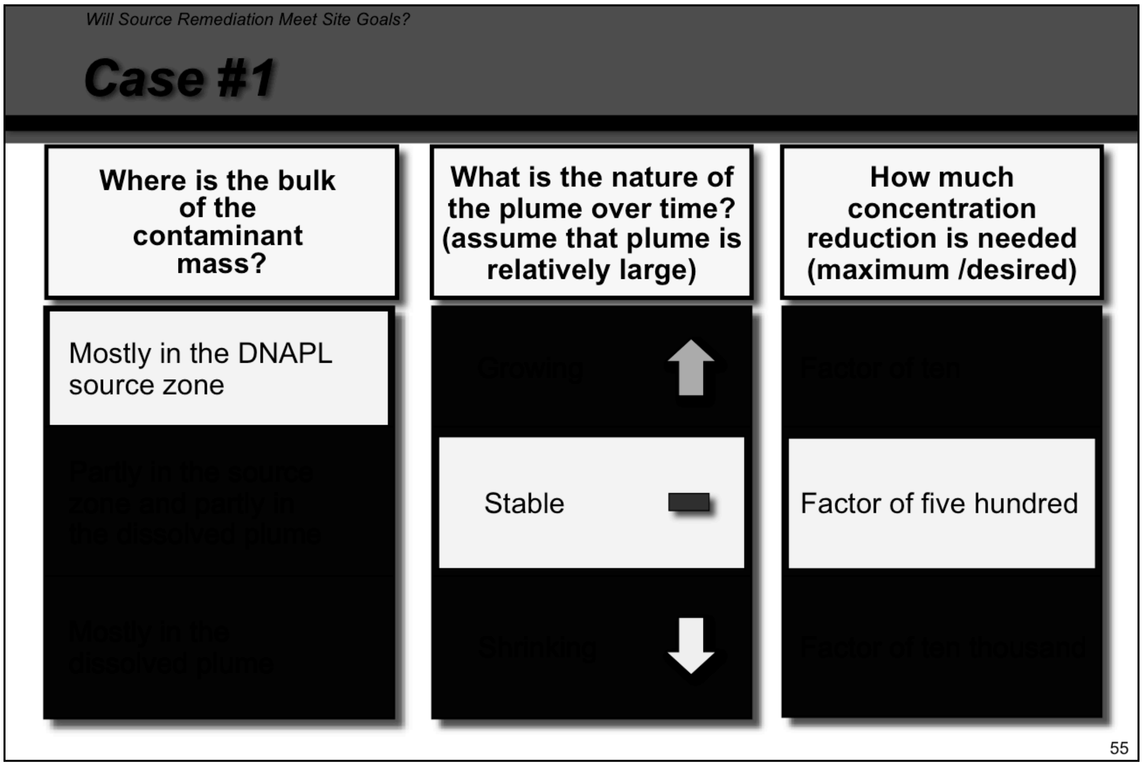
Will Source Remediation Meet Site Goals?
Case #1
Where is the bulk of the contaminant mass?
What is the nature of the plume over time? (assume that plume is relatively large)
How much concentration reduction is needed (maximum /desired)
Mostly in the DNAPL source zone
[redacted]
[redacted]
[redacted]
Stable
[redacted]
[redacted]
Factor of five hundred
[redacted]
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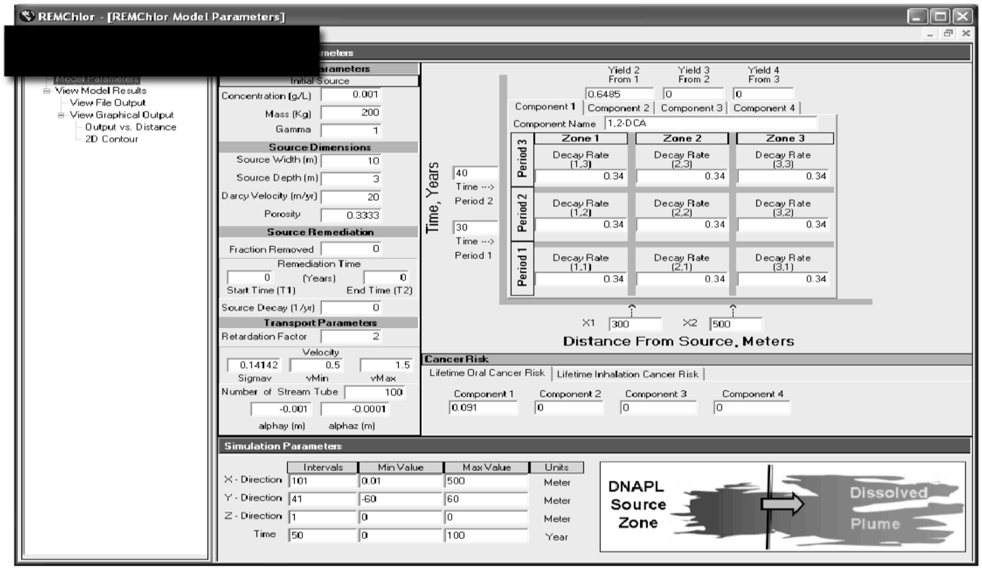
First Step in Analysis

Assess what will happen if no action is taken.

- Run REMChlor without any source or plume remediation.
- The source still depletes due to water flushing, but the depletion may be very slow.
- If the natural source depletion rate is fast, then source remediation may not be needed.

Will Source Remediation Meet Site Goals? What Will Happen if No Action is Taken?

Case 1, Part A: Simulate Natural Attenuation of Source and Plume



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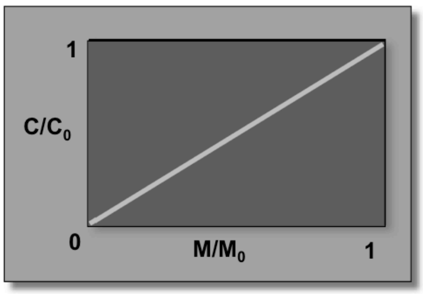
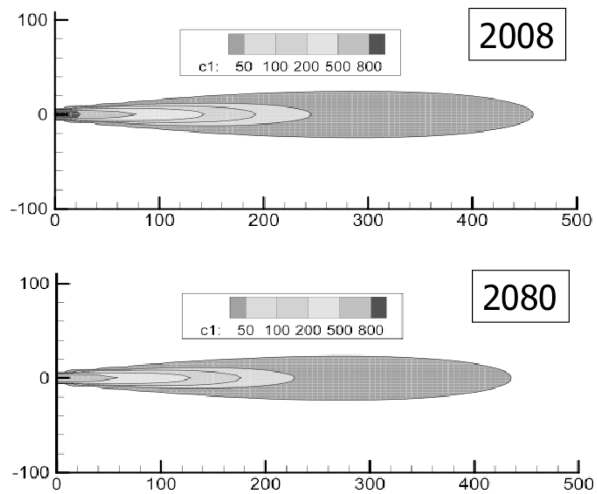
Case 1, Part A: Natural Attenuation of Both Source and Plume

In 2080, plume is nearly the same size, and ~74% of the original DNAPL source mass remains.



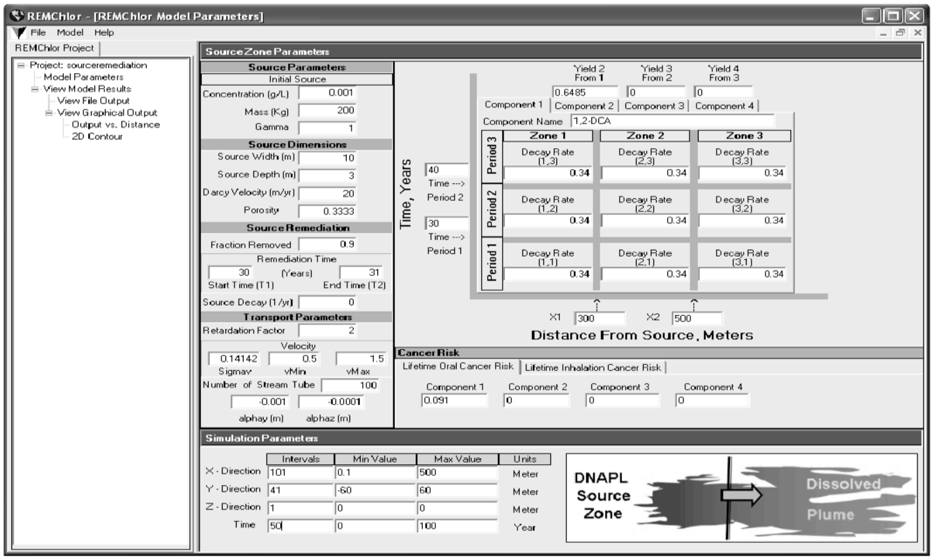


Next Step in Analysis: Run Source Remediation

- Try source remediation.
- We have assumed that we can remove 90% of the source.
- Model source remediation between 2010 and 2011.
- Note that we could combine source and plume remediation, but in this simulation, we look at source remediation alone.

Will Source Remediation Meet Site Goals? What Will Happen if No Action is Taken?

Case 1, Part B: Source Remediation Simulation



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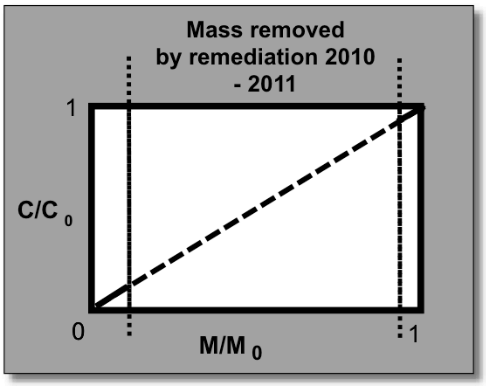
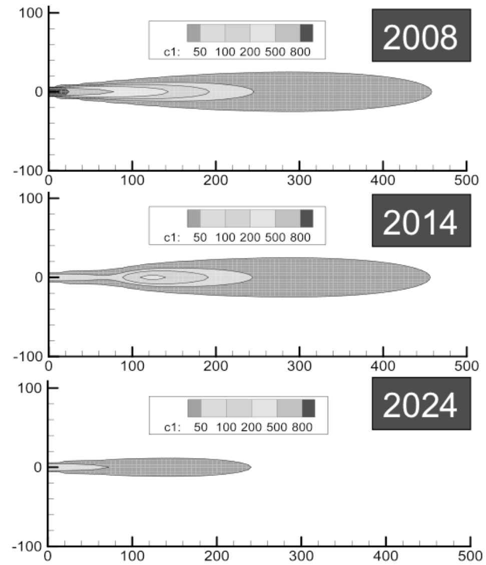
Will Source Remediation Meet Site Goals? What Will Happen if No Action is Taken?

Case 1, Part B: REMChlor Simulation of Source Remediation





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Will Source Remediation Meet Site Goals? What Will Happen if No Action is Taken?

Case 1, Part B: REMChlor Simulation of Source Remediation

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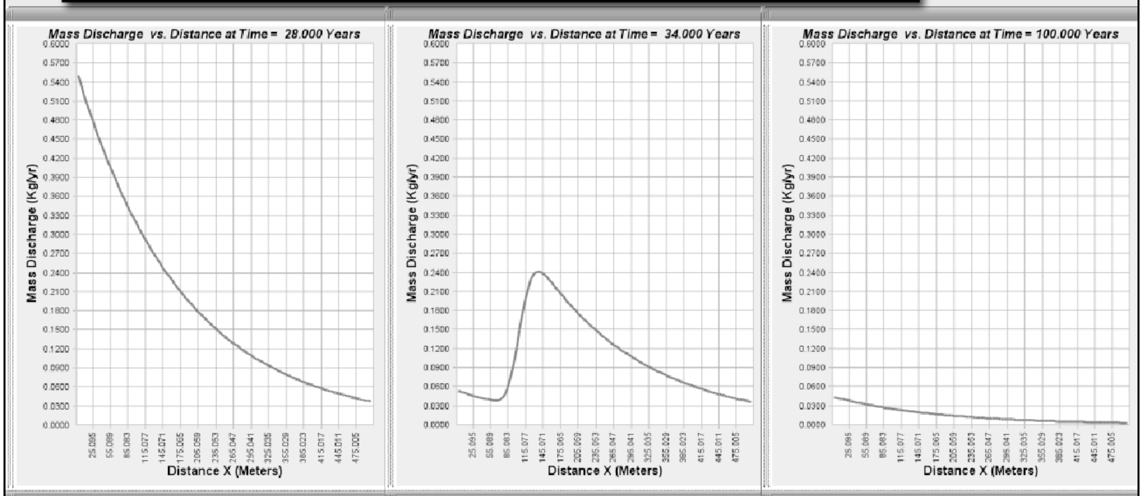

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It Appears that Source Remediation Would Permanently Shrink this Plume

- The plume does not respond instantly to source remediation.
- The beneficial effect of source remediation "washes" downstream until the plume has readjusted to the reduced contaminant discharge.
- Source remediation often results in a detached plume.
- Unless the source treatment is perfect (100%), there will still be a plume, but it will be smaller.
- The degree of plume shrinkage depends not only on the fraction removed, but also on the amount of concentration reduction that is needed.

BREAK FOR QUESTIONS FROM PARTICIPANTS

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Resources & Feedback

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- Please complete the **Feedback Form** to help ensure events like this are offered in the future

Need confirmation of your participation today?

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