



Welcome to the CLU-IN Internet Seminar

Practical Models to Support Remediation Strategy Decision-Making - Part 1

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

Delivered: October 11, 2012, 2:00 PM - 4:00 PM, EDT (18:00-20:00 GMT)

Instructors:

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Dr. Brian Looney, Savannah River National Laboratory (Brian02.looney@srl.doe.gov)

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Moderator:

Jean Balent, U.S. EPA, Technology Innovation and Field Services Division (balent.jean@epa.gov)

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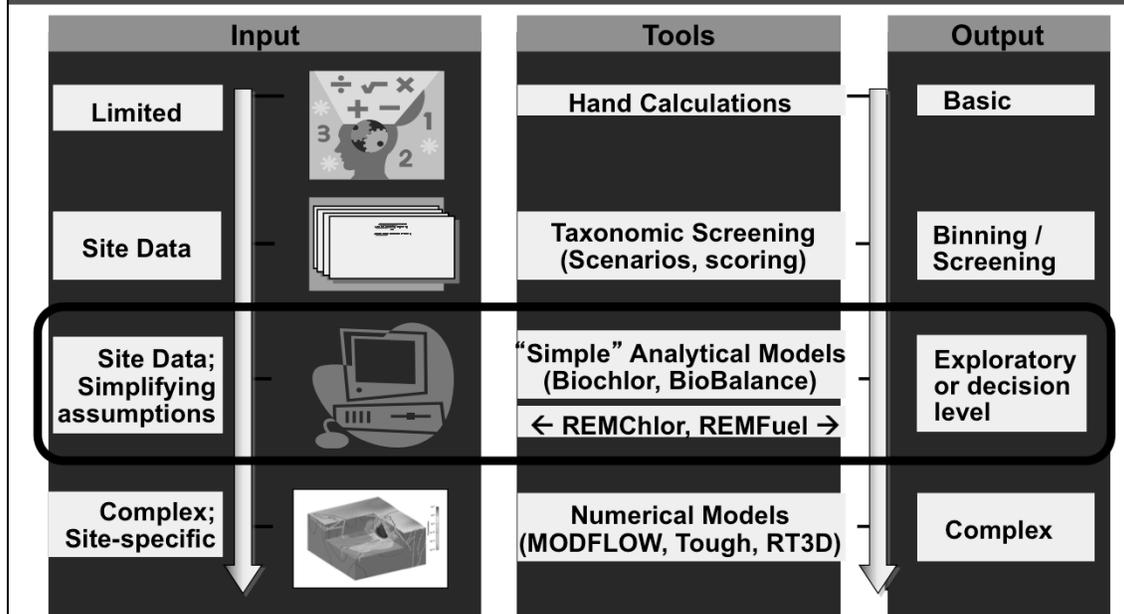


October 2012

Seminar Disclaimer

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

Continuum of Tools Available to Support Environmental Cleanup



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

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

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

Agenda

➔ *Class Objectives*

- **What Tools are Out There?**
- **What Are the Key Questions?**
 - 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?
- **Wrap-Up**

Enabling Objectives

- ▶ **Introduce publicly available analytical models and tools and how these tools can be used in combination to address questions/issues relevant to remediating chlorinated solvents and hydrocarbon fuel sites**
- ▶ **Present options for developing and diversifying metrics for success in supplementing traditional concentration-based goals**

Enabling Objectives *Cont'd*

- ▶ **Encourage decision processes that match environmental technologies to site specific and time specific conditions, supporting the overarching need to transition activities until the various plume segments (e.g. source to aqueous plume, aqueous plume, and distal plume) achieve remediation goals – Combined Remedies.**
- ▶ **Explore how mass balance and mass flux approaches support plume evaluation, remedial decisions, and understanding remediation performance.**
- ▶ **Provide a glimpse on how REMChlor and REMFuel are applied to solve problems**

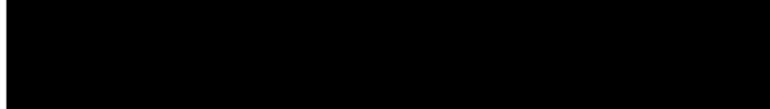
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CLASS OBJECTIVES: *What Do I get from Source and Plume Remediation?*

- ▶ **This is not a simple question; the answer depends on both the site conditions, as well as on the remediation goals.**
- ▶ **Easy to use, mathematically rigorous tools are now available to help answer this question.**
- ▶ **These tools are mainly based on the mass-balance approach, where the source and plume mass and mass fluxes are key variables.**

Related Question:

Is My Groundwater Monitoring System OK?



- **Is the plume growing, shrinking, or stable?**
- **Is most of the contaminant mass in the source area or in the plume?**
- **What is the mass discharge (flux) into the plume?**

Administrative Issues

- **How and when to ask questions**
- **Three types of learning:**
 - ***Slides***
 - ***Homework exercises***
 - ***Demo of running the Models***

Agenda

- **Class Objectives**

-  **What Tools are Out There?**

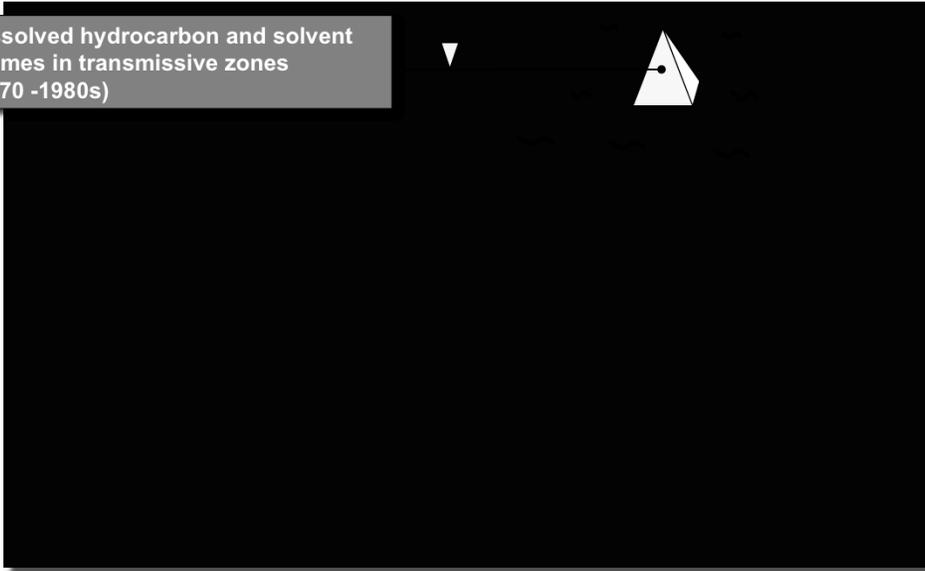
- **What Are the Key Questions?**

- Will Source Remediation Meet Site Goals?
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- **Wrap-Up**

Emerging Picture of Groundwater Remediation Challenges

Dissolved hydrocarbon and solvent plumes in transmissive zones (1970 -1980s)

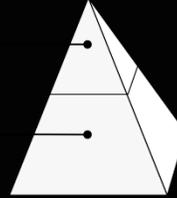


Adapted from: Chlorinated Solvent FAQs

Emerging Picture of Groundwater Remediation Challenges

Dissolved hydrocarbon and solvent plumes in transmissive zones (1970 -1980s)

Plus NAPLs (1990s)



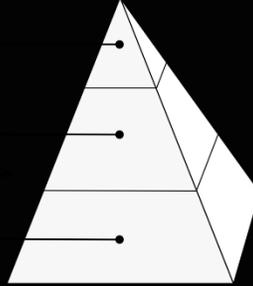
Adapted from: Chlorinated Solvent FAQs

Emerging Picture of Groundwater Remediation Challenges

Dissolved hydrocarbon and solvent plumes in transmissive zones (1970 -1980s)

Plus NAPL in transmissive and low permeability zones (1990s)

Plus dissolved and sorbed phases in low permeability source zones (mid 2000s)



Adapted from: Chlorinated Solvent FAQs

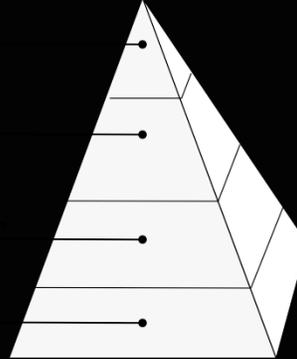
Emerging Picture of Groundwater Remediation Challenges

Dissolved hydrocarbon and solvent plumes in transmissive zones (1970 -1980s)

Plus NAPL in transmissive and low permeability zones (1990s)

Plus dissolved and sorbed phases in low permeability zones in source zones (mid 2000s)

Plus vapor plumes and intrusion into buildings (mid 2000s)



Adapted from: Chlorinated Solvent FAQs

Emerging Picture of Groundwater Remediation Challenges

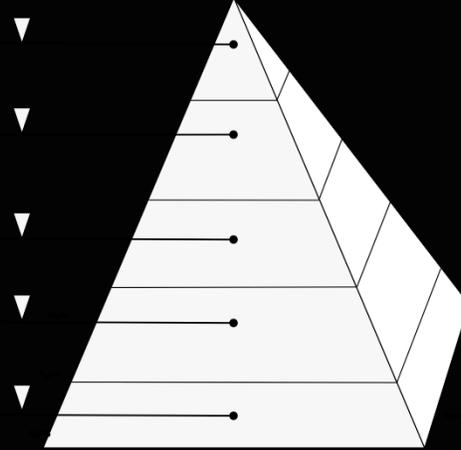
Dissolved hydrocarbon and solvent plumes in transmissive zones (1970 -1980s)

Plus NAPL in transmissive and low permeability zones (1990s)

Plus matrix diffusion in source zones (mid 2000s)

Plus vapor plumes and intrusion into buildings (mid 2000s)

Plus matrix diffusion in some plumes (currently emerging)



Adapted from: Chlorinated Solvent FAQs

Why has Remediation Been Difficult?

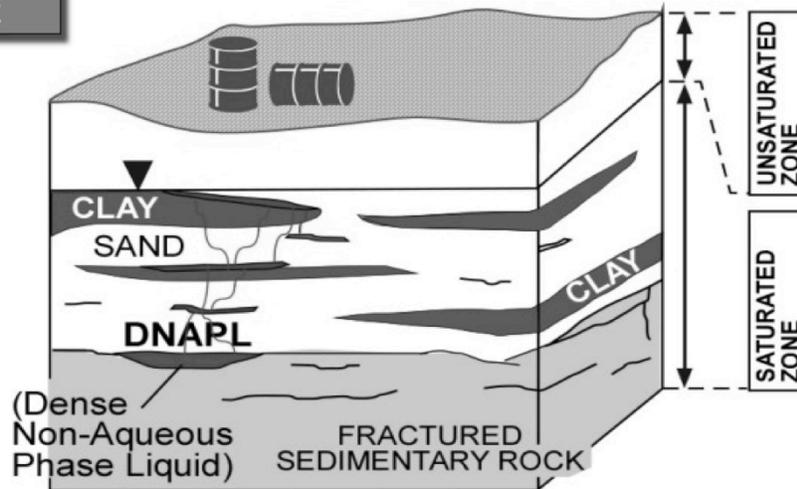


- **Poor design.**
- **Poor understanding of what technologies do.**
- **Misunderstanding the extent / distribution.**
- **Poor recognition of the uncertainties inherent in remediation design.**
- **Remedial objectives that can only be achieved over long periods of time at some sites**

*Source: Chlorinated
Solvent FAQs*

Another Reason, Particularly for Chlorinated Solvent Sites

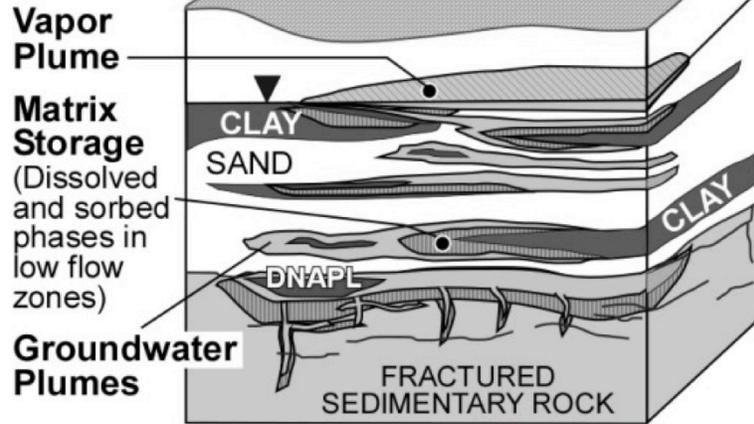
EARLY
STAGE



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Another Reason, Particularly for Chlorinated Solvent Sites

MIDDLE
STAGE



Source: *Chlorinated Solvent FAQs* 24

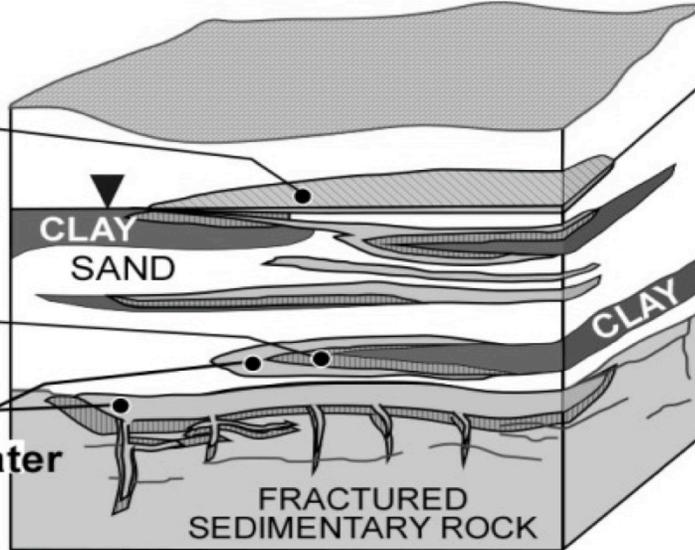
Another Reason, Particularly for Chlorinated Solvent Sites

LATE
STAGE

Vapor
Plume

Matrix
Storage
(Dissolved
and sorbed
phases in
low flow
zones)

Groundwater
Plumes



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Quick Time Out: Matrix Diffusion

Important at certain chlorinated solvent sites.
Maybe less important for BTEX sites?
One recent paper* on matrix diffusion and MTBE



*Rasa et al., 2011

Lee Ann Doner, MS Thesis, Colorado State University

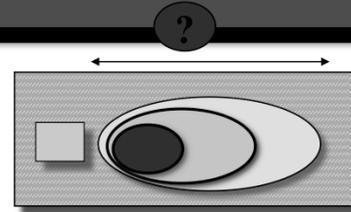
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Colorado State Tank Study – Let's Go to the Movies!

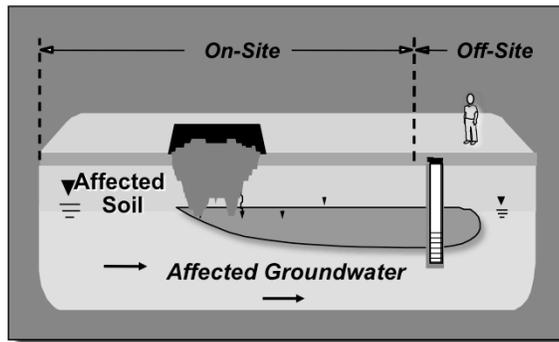


Key Concept 1: Sources

- Most dissolved plumes can be traced back to a concentrated “source area,” where the original release occurred.
- The source area is usually small compared to the plume footprint.
- The source may contain NAPL, and/or it may consist of high concentrations of dissolved contaminants in low permeability zones.
- *The mass of contaminant in the source zone, and the mass discharge of contaminant out of the source zone play a central role in the evolution of dissolved plumes.*



Key Concept 2: **Plumes**



Key Driver

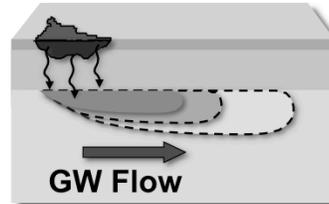
- Discharge from source

Key Processes

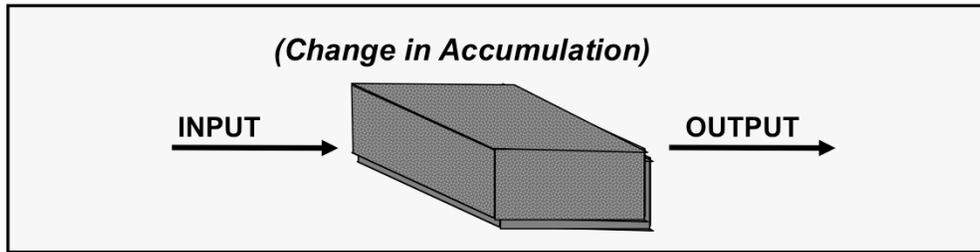
- Advection
- Dispersion
- Adsorption
- Degradation

Key Concept 2: **Plumes**

- Plumes are fed by the source, and move with the groundwater flow with some dispersion.
- The dissolved contaminants may also adsorb or diffuse into aquifer materials.
- The groundwater pore velocity (Darcy velocity divided by porosity) and the rate at which the chemical degrades play a central role the nature of the plume.
- High velocities with low decay rates = large plumes.
- Low velocities with high decay rates = small plumes.



Key Concept 3: Mass Balance

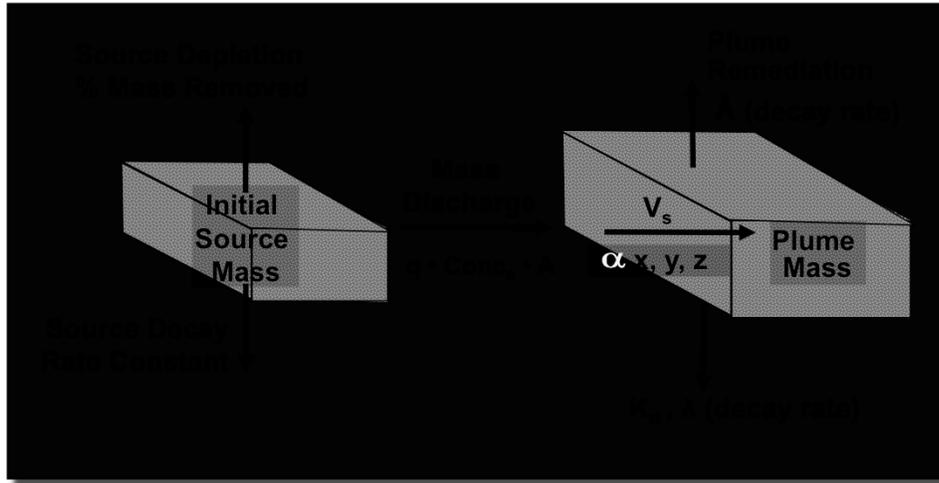


Source: D. Reible

- ▶ First expressed by Lavoisier
- ▶ Also called “material balance”
- ▶ Basic tool for modeling system behavior
- ▶ Used to determine mass flows based on inputs and outputs

Developing the Mass Balance

Label known flows, concentrations, and fate processes



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Questions to be Addressed by Mass Balance Type Modeling

- **What will happen if no action is taken?**
- ***Will source remediation meet site goals?
How effective must the source remediation be?***
- ***Will enhanced biodegradation of the plume meet site goals? How effective (and long-lived) must the plume treatment be?***
- ***Should I combine source and plume remediation?
How much of each do I need before I get to transition to MNA?***
- **What is the remediation time-frame?**
- ***What is a reasonable remediation objective?***

Key Concept 4: Groundwater Modeling

Source

$$\frac{dM}{dt} = -Q(t)C_s(t) - \lambda_s M \quad C_s(t) = C_0 \left(\frac{M(t)}{M_0} \right)^\Gamma$$

Plume

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

**BREAK FOR QUESTIONS
FROM
PARTICIPANTS**

Key Questions

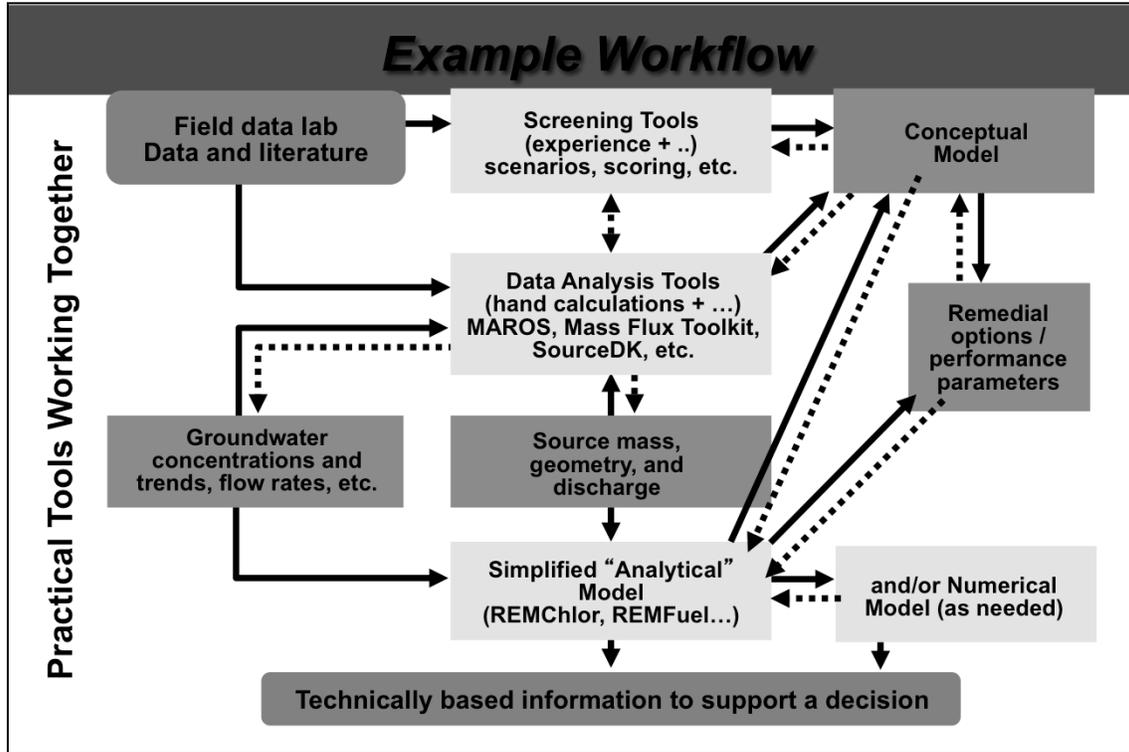
- ***Will Source Remediation Meet Site Goals?***
- ***What Will Happen if No Action is Taken?***
- ***Should I Combine Source and Plume Remediation?***
- ***What is the Remediation Time-Frame?***
- ***What is a Reasonable Remediation Objective?***

How Do We Get Some Answers

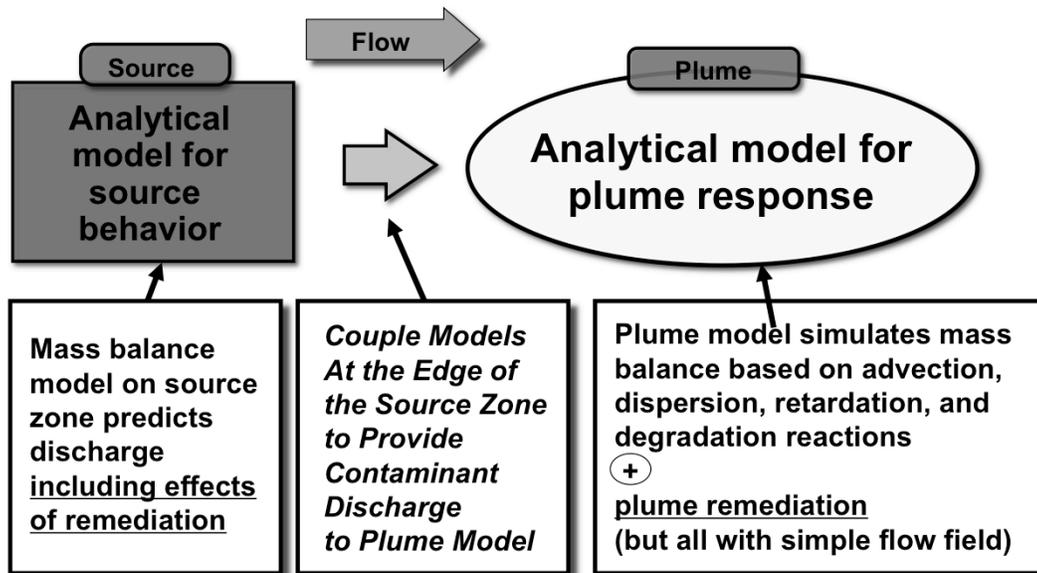
- **We need some source and plume characterization data – the more the better.**
- **We need estimates of the source mass, the source discharge, the groundwater velocity, and plume decay rates.**
- **We need some understanding of source and plume remediation efficiency (% removal, cost, etc.).**
- **We can then run simple models such as REMChlor and REMFuel to test what would happen with source remediation, plume remediation, or some combination of the two.**

How Do We Move Forward?

- **Look at what has happened at other sites - particularly *multiple - site studies***
- **Practice a flexible, feedback-based decision process (*Observational Approach*)**
- **Use *practical tools* to help understand the site**



What Makes REM-C and REM-F So Special?



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REMFuel and REMChlor

WHAT:

Analytical groundwater transport models that combines source behavior with solute transport in the plume

HOW:

- 1 Enter site data.**
- 2 Try to match existing site data (calibration).**
- 3 Ask questions (up to you!).**
- 4 Change variable and see what happens**
(based on hydrogeology, biodegradation, sorption, source decay, and other key processes at the site).

REMFuel and REMChlor

WHERE:

Free download from EPA Webpage

•<http://www.epa.gov/nrmrl/gwerd/csmos/models/remchlor.html>

•<http://www.epa.gov/nrmrl/gwerd/csmos/models/remfuel.html>

WHEN:

Both available now

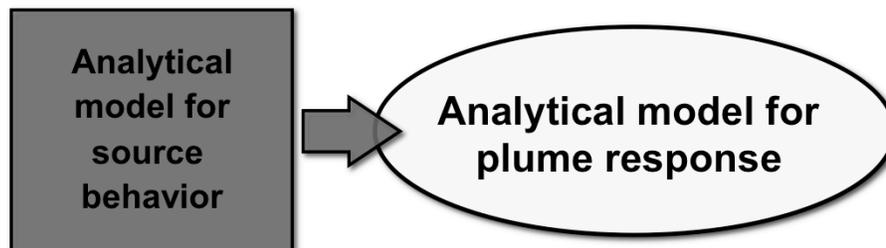
WHO:

Dr. Ron Falta, Clemson University

plus

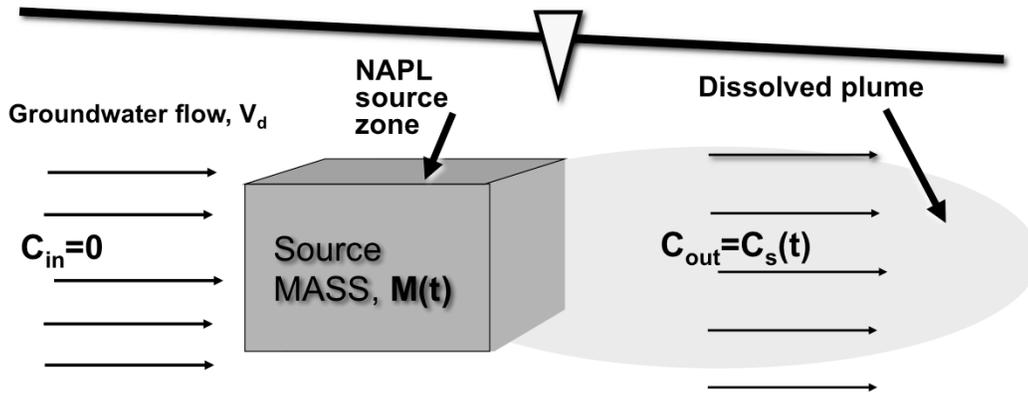
Stacy, Ahsanuzzaman, Wang, Earle, and Wilson
(EPA co-authors - R.S. Kerr Lab, Ada, OK)

**Explanation of How the
Source Term
Works in REMCHLOR and REMFuel**



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The Discharging Concentration (C_s) Depends on the Mass Remaining in the Source Zone, (M)



$$\frac{dM}{dt} = -Q(t)C_s(t) - \lambda_s M$$

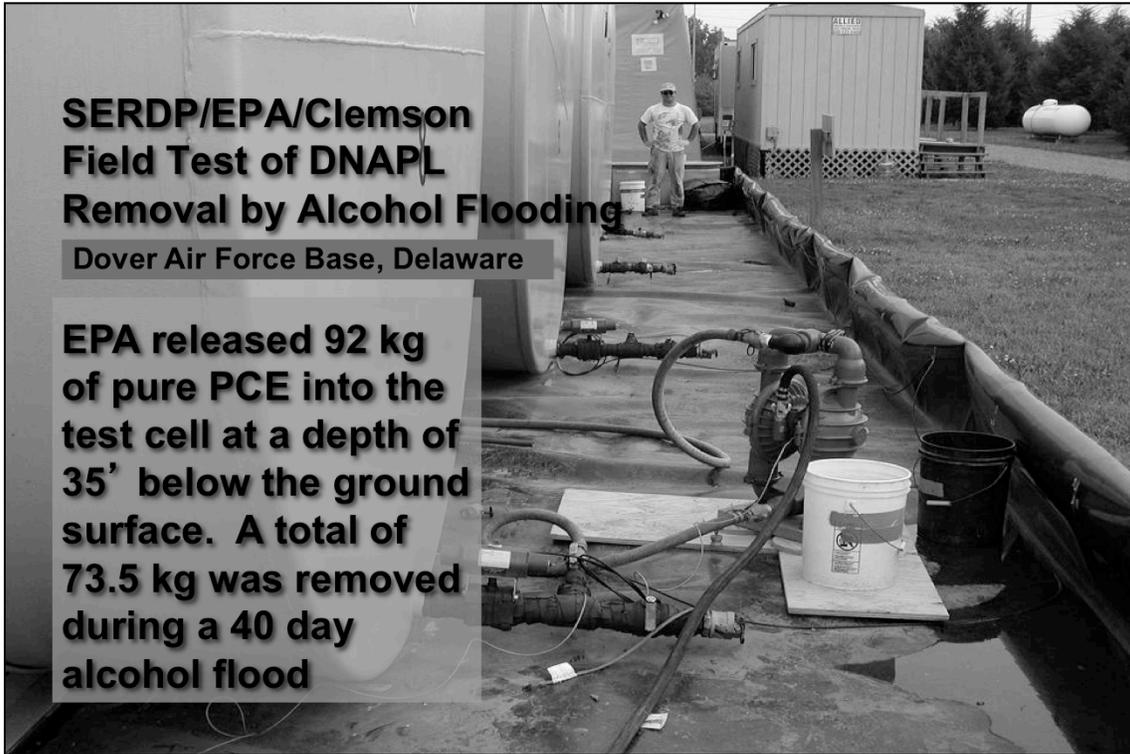
$$\frac{C_s(t)}{C_0} = \left(\frac{M(t)}{M_0} \right)^\Gamma$$

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**SERDP/EPA/Clemson
Field Test of DNAPL
Removal by Alcohol Flooding**

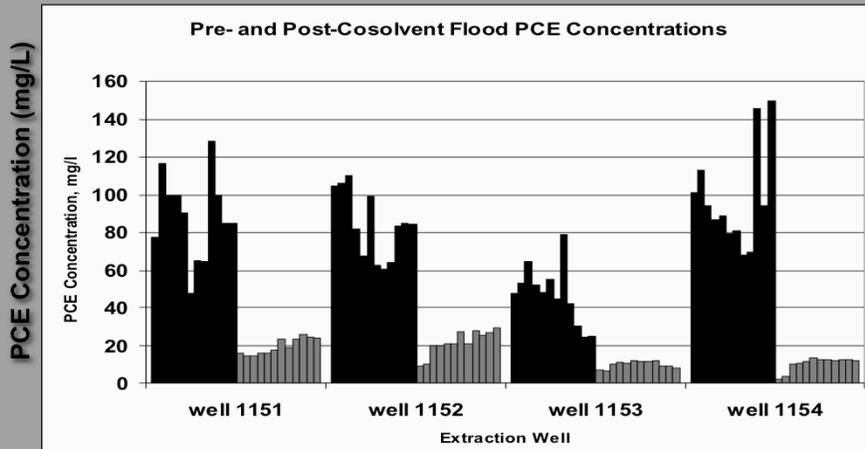
Dover Air Force Base, Delaware

**EPA released 92 kg
of pure PCE into the
test cell at a depth of
35' below the ground
surface. A total of
73.5 kg was removed
during a 40 day
alcohol flood**



80% Source Removal Resulted in 81% Reduction in Groundwater Concentration

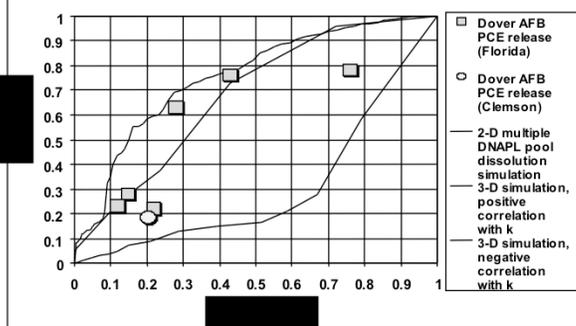
Pre-and Post-Cosolvent Flood PCE Concentrations



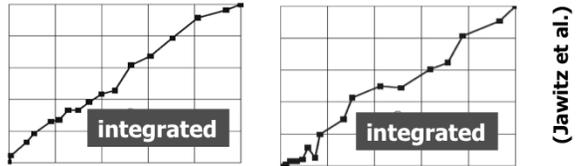
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Source Mass Reduction Leads to Discharge Reduction

Field and Modeling Data

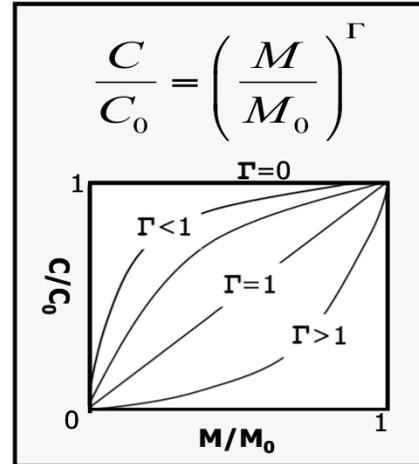


Laboratory dissolution experiments



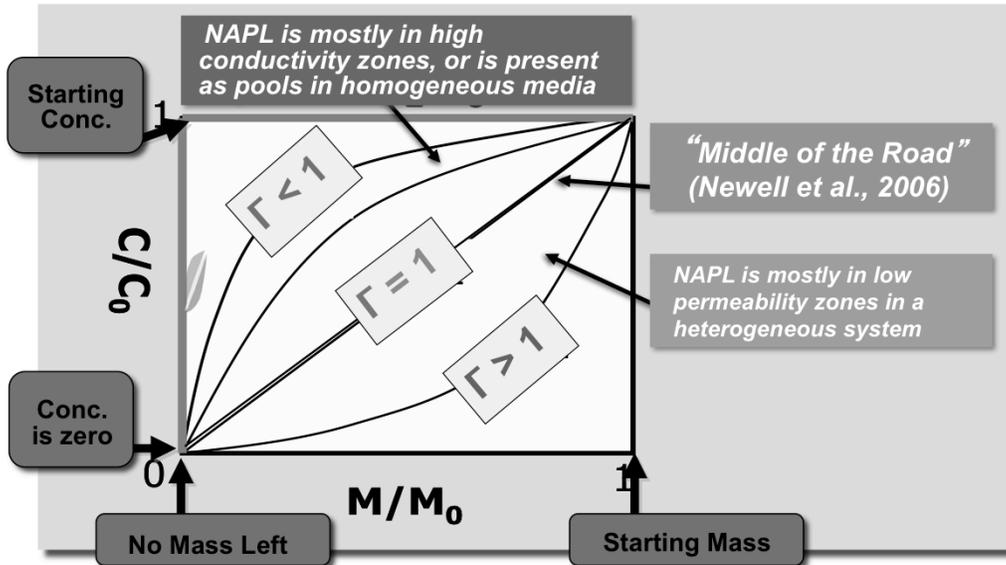
Power function model

[Rao et al., 2001; Parker and Park, 2004; Zhu and Sykes, 2004]



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Source Power Function – What's That?



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LNAPLs are Usually Multi-component NAPLs

The dissolution of components (such as benzene or MTBE) from gasoline can be calculated using partitioning coefficients:

$$C_w = K_{pnw} C_n$$

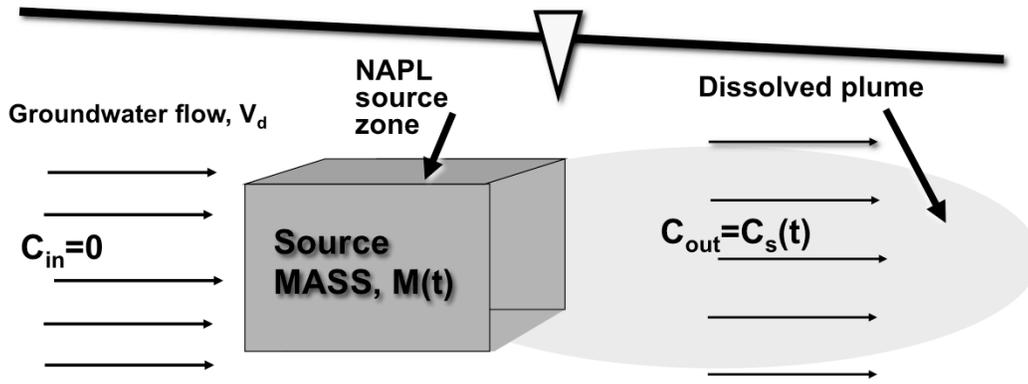
The dissolved concentration in groundwater is equal to the NAPL-water partition coefficient for the component, multiplied by the concentration in the NAPL (this is equivalent to Raoult's Law)

Over time, as the Component Washes Out of the LNAPL, Concentrations Drop

Because the dissolved groundwater concentration is directly proportional to the concentration remaining in the LNAPL, it responds like our power function model, with an exponent of $\Gamma=1$

$$\frac{C}{C_0} = \left(\frac{M}{M_0} \right)^\Gamma$$

The Discharging Concentration (C_s) Depends on the Mass Remaining in the Source Zone, (M)



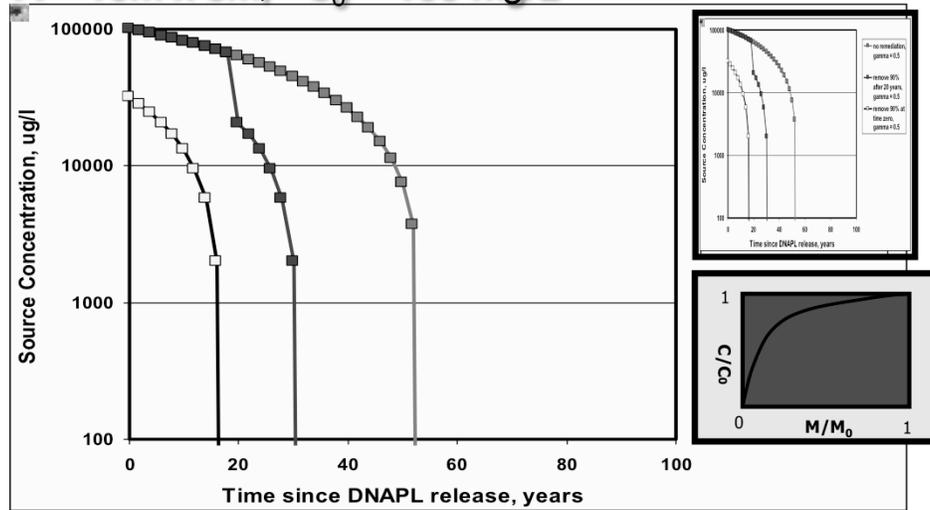
$$\frac{dM}{dt} = -Q(t)C_s(t) - \lambda_s M$$

$$\frac{C_s(t)}{C_0} = \left(\frac{M(t)}{M_0} \right)^\Gamma$$

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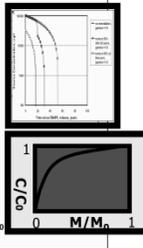
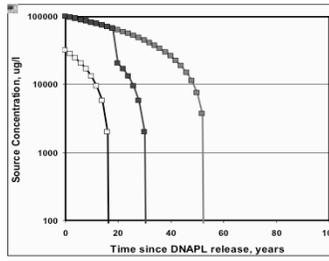
Source Behavior

$\Gamma = 0.5$, $M_0 = 1,620 \text{ kg}$, $V = 20 \text{ m/yr}$,
 $A = 10\text{m} \times 3\text{m}$, $C_0 = 100 \text{ mg/L}$

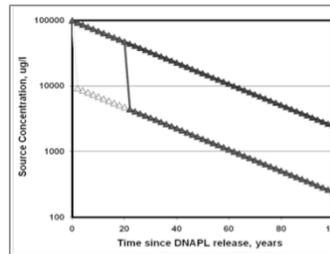


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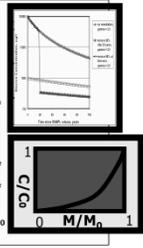
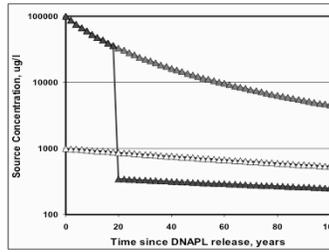
Source Behavior



$\Gamma = 0.5$

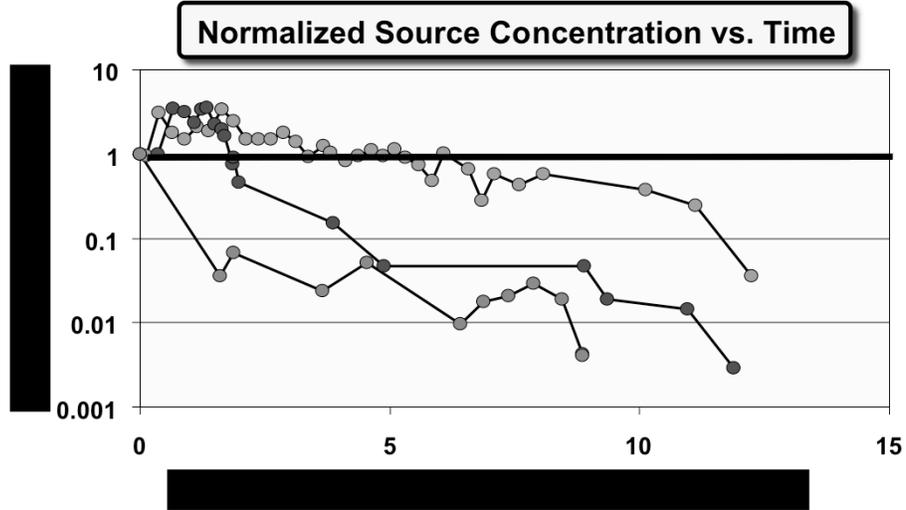


$\Gamma = 1.0$



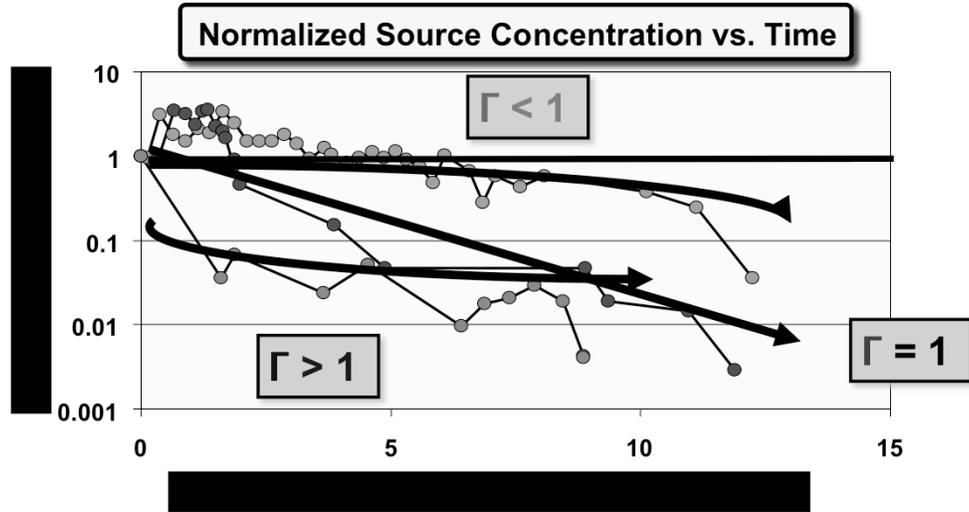
$\Gamma = 2.0$

Take a Look at Data: 3 TCE Sites



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Take a Look at Data: 3 TCE Sites



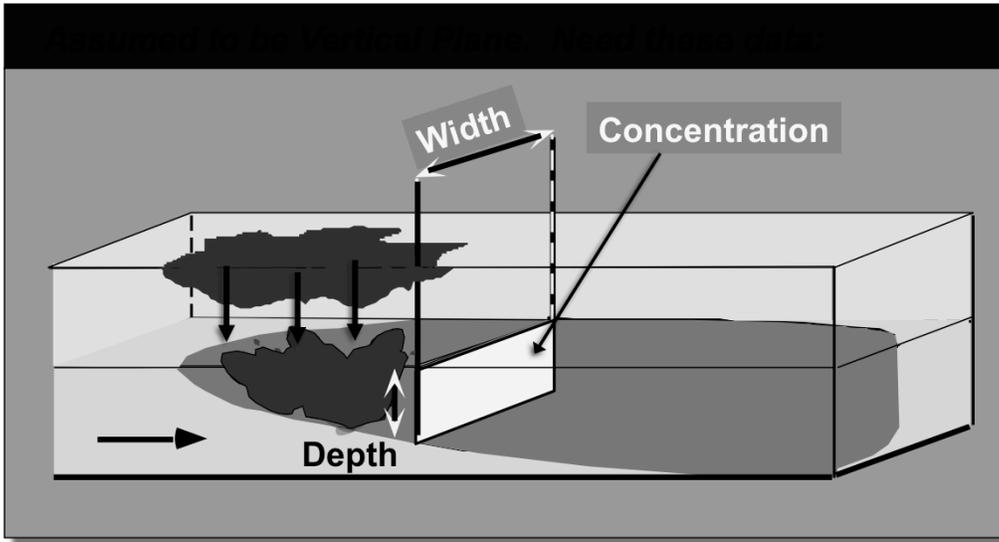
Summary: Describing Your Source Zone ("Source Zone Architecture")

1. Need to pick a gamma (Γ)
2. Thought to range from $\Gamma = 0.5$ to $\Gamma = 2.0$
3. If you think you know something about source architecture, use these rules:

<	=	>
<ul style="list-style-type: none"> - Lots of pools of NAPL - NAPL mostly in high conductivity zones - Concentration vs. time shows long plateau (over many years) 	<ul style="list-style-type: none"> - multicomponent LNAPL - Don't know much about source architecture - Want to use "Middle of Road" value <p style="text-align: center; border: 1px solid black; border-radius: 50%; padding: 5px; display: inline-block;">Most Commonly Used Approach</p>	<ul style="list-style-type: none"> - NAPL is in low permeability zone - There are (or will be) strong matrix diffusion effects (lots of low-permeability material in source zone) - Concentration vs. time shows obvious decline, (over many years)

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Source Term Configuration



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Wrap-Up: Answering Questions About the Source Zone Using REMChlor and REMFuel

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2.

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6.

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Homework Assignment: Download and install REMChlor and REMFuel

- **Download from EPA website:**
- <http://www.epa.gov/nrmrl/gwerd/csмос/models/remchlor.html>
- <http://www.epa.gov/nrmrl/gwerd/csмос/models/remfuel.html>
- **To run these, you will probably need to right-click on the icon, and then “run as administrator”**
- **A complete user’s manual is available as a pdf in the help section**
- **It is always a good idea to print out the manual, and keep it handy**



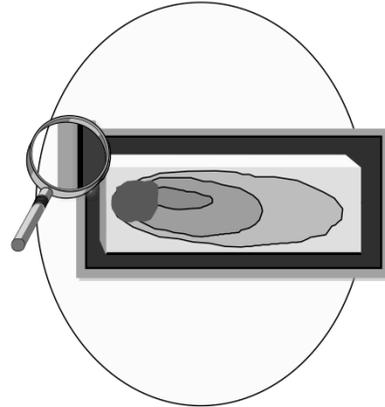
Homework Exercise

NUMBER 1

**Plume gets shorter
by how much?**



Text and Calculations



**BREAK FOR QUESTIONS
FROM
PARTICIPANTS**

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Resources & Feedback

- To view a complete list of resources for this seminar, please visit the **Additional Resources**
- Please complete the **Feedback Form** to help ensure events like this are offered in the future

The screenshot shows a web page for the EPA Technology Innovation Program. The header includes the EPA logo and the text 'United States Environmental Protection Agency' and 'Technology Innovation Program'. Below the header, there is a title: 'U.S. EPA Technical Support Project Engineering Forum Green Remediation: Opening the Door to Field Use Session C (Green Remediation Tools and Examples) Seminar Feedback Form'. The main content area contains a message: 'We would like to receive any feedback you might have that would make this service more valuable. Please take the time to fill out this form before leaving the site.' Below this message are several input fields: 'First Name:', 'Last Name:', 'Daytime Phone Number:', and 'Email Address:'. The email address field is pre-filled with 'baird.zand@epa.gov'. At the bottom of the form, there is a checkbox with the text: 'Please send a copy of my feedback confirmation as a record of my participation to this address'. The form is set against a light background with a dark sidebar on the left containing navigation links like 'Go to Seminar', 'Links', 'Feedback', 'Home', and 'CLU-IN Studio'.

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