Welcome to the CLU-IN Internet Seminar

Practical Models to Support Remediation Strategy Decision-Making - Part 5

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

Delivered: November 7, 2012, 1:00 PM - 3:00 PM, EST (18:00-20:00 GMT)

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

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- Entire broadcast offered live via Adobe Connect
  - participants can listen and watch as the presenters advance through materials live
  - *Some materials may be available to download in advance, you are* ***recommended to participate live via the online broadcast***
- Audio is streamed online through by default
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- Q&A – use the Q&A pod to privately submit comments, questions and report technical problems
- This event is being recorded
- Archives accessed for free **http://cluin.org/live/archive/**

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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.

Please mute your phone lines during the seminar to minimize disruption and background noise. If you do not have a mute button, press *6 to mute #6 to unmute your lines at anytime. Also, please do NOT put this call on hold as this may bring delightful, but unwanted background music over the lines and interrupt the seminar.

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

Practical Models to Support Remediation Strategy Decision-Making

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

Module 5 – November 2012

INSTRUCTORS: *Ron Falta, Ph.D.*

CLEMSON UNIVERSITY

- **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

INSTRUCTORS: *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

INSTRUCTORS: *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

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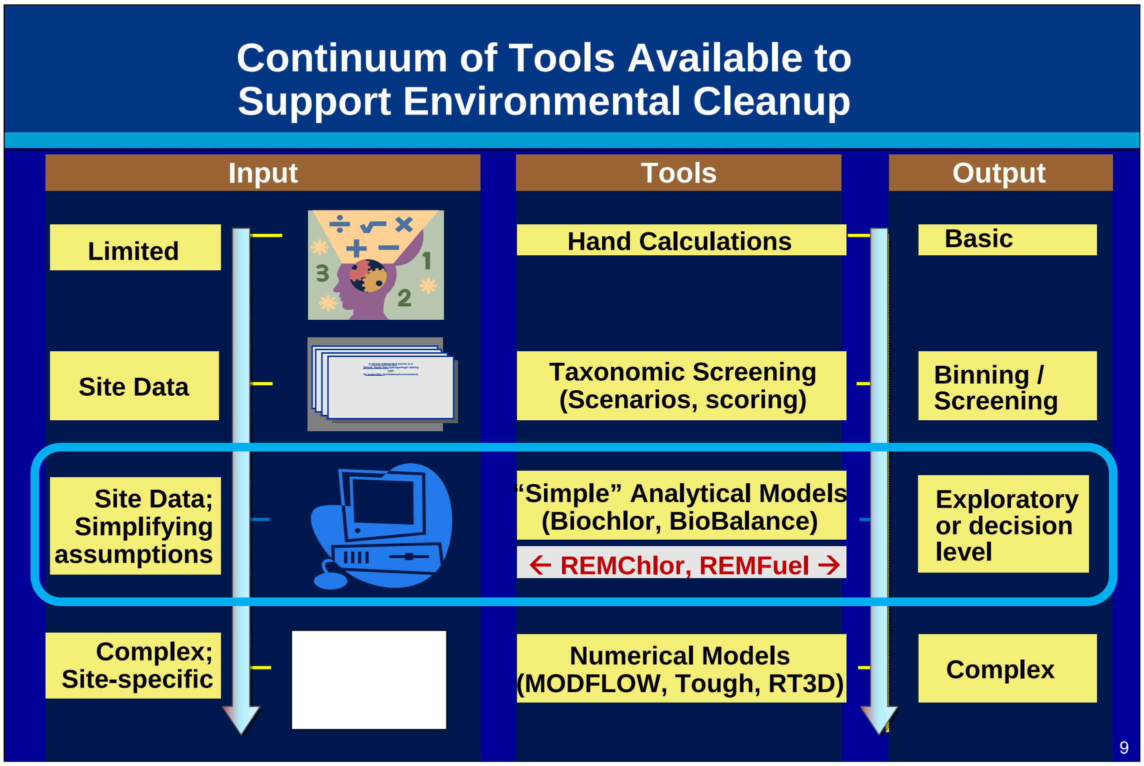
BREAK FOR DISCUSSION OF HOMEWORK EXERCISE 2

AND RESPONSES TO MODULE 4 QUESTIONS FROM PARTICIPANTS


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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A Quick Summary of Modeling Tools

Model	Key Input Data Requirements (approx number of parameters, typical)	Model Type	Output	Advantages	Disadvantages	Best Uses
Scenarios (Chlorinated Solvents)	Site data (<10 with representative data from site)	Screening tool	Conceptual model, downstream inputs	Quick and easy, provides insight into key processes and potential site specific remediation opportunities. Free	Qualitative and insufficient to support final decision and system design.	Early site planning activities, developing consensus among regulators, stakeholders, contractors, and site owners.
RBCA Toolkit	Source concentration, mass, dimensions; Darcy velocity; porosity; dispersion; decay rates and other factors as needed to account for vapor intrusion or other pathways.	Simplified "analytical" model for pathway and risk analysis	Concentration and risk predictions, remedial design and decision support, remediation timeframe	The RBCA Tool Kit modeling and risk characterization software package designed to meet the requirements of the ASTM Standard Guide for Risk-Based Corrective Action (E-2081) for Tier 1 and Tier 2 evaluations. The software combines contaminant transport models and risk assessment tools to calculate baseline risk levels and derive risk-	Reliability of results can be variable and depend on availability of data at proper spacings and/or times -- requires significant judgment to account for geological controls, heterogeneity, etc. -- difficult to simulate complicated and/or changing conditions -- no simulation of electron donor/acceptor -- powerful model that accounts for many exposure pathways and calculates risk (but has the associated learning curve for operation).	This model provides key capabilities that rival more complex numerical models -- provides fairly robust scoping calculations (as above) and reasonable support for remedial decisions and designs -- output follows standard risk assessment protocols and model includes most major exposure pathways..
MODFLOW	Detailed site-specific hydrologic parameters (<20 with data from several locations and times)	Numerical model	Same as "Analytical" model, but more integrated and for more complex or dynamic conditions -- primary output is hydrogeologic (water levels and flow)	Provides flexible and robust simulation of hydrogeology -- can be used for steady-state simulations or for dynamic transient simulations -- can be used to simulate complex pump and treat	Reliability of results can be variable and depend on availability of data at proper spacings and/or times -- requires additional programs and modules to simulate contaminant fate and transport, degradation processes, etc. -- does not simulate	Key exemplar of groundwater models -- widely used and accepted and a powerful tool when used in combination with other models to simulate source and contaminant scenarios and remediation. Many similar

Download Supplementary Table at the CLU-IN resource page for this workshop

A Quick Summary of Modeling Tools - Links

Screening Models	Scenarios (Chlorinated Solvents)	http://www.gsi-net.com/files/papers/SRNL-STI-2011-00459.pdf or http://sti.srs.gov/fulltext/SRNL-STI-2011-00459.pdf
	Scenarios (metals and radionuclided)	http://sti.srs.gov/fulltext/WSRC-STI-2006-00096.pdf
	GW Sensitivity Toolkit	http://www.gsi-net.com/en/software/free-software
	Source Depletion Decision Support System	http://www.gsi-net.com/en/software/free-software
Data Analysis Models	MAROS	http://www.gsi-net.com/en/software/free-software
	SourceDK	http://www.gsi-net.com/en/software/free-software
	Sustainable Remediation Tool	U. S. Air Force Civil Engineer Center
	SiteWise	http://www.ert2.org/t2gsrportal/SiteWise.aspx
	Racer	U. S. Air Force Civil Engineer Center
	Mass Flux Toolkit	http://www.gsi-net.com/en/software/free-software
Analytical Models	BIOBALANCE	http://www.gsi-net.com/en/software/free-software
	BIOCHLOR and BIOSCREEN	http://www.epa.gov/ada/csmos/models/biochlor.html or http://www.epa.gov/ada/csmos/models/bioscrn.html
	REMChlor and REMFuel	http://www.epa.gov/ada/csmos/models/remchlor.html or http://www.epa.gov/ada/csmos/models/remfuel.html
	RBCA Toolkit	http://www.gsi-net.com/en/software.html
	Matrix Diffusion Toolkit	http://www.gsi-net.com/en/software/free-software
Numerical / Hybrid Models	MODFLOW	http://water.usgs.gov/nrp/gwsoftware/modflow.html
	RT3D	http://bioprocess.pnnl.gov/
	T2VOC	http://esd.lbl.gov/research/projects/tough/
	SEAM3D	http://el.erdc.usace.army.mil/elpubs/pdf/trel00-18.pdf
	GMS	several USGS / Aquaveo / EMS-I e.g., http://www.aquaveo.com/gms
	Visual MODFLOW	http://www.swstechnology.com/groundwater-modeling-software/visual-modflow-flex
	PETRASIM	http://www.rockware.com/product/overview.php?id=148
	TECPLOT	http://www.tecplot.com/
	SURFER	http://www.goldensoftware.com/

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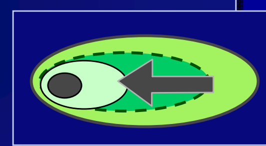
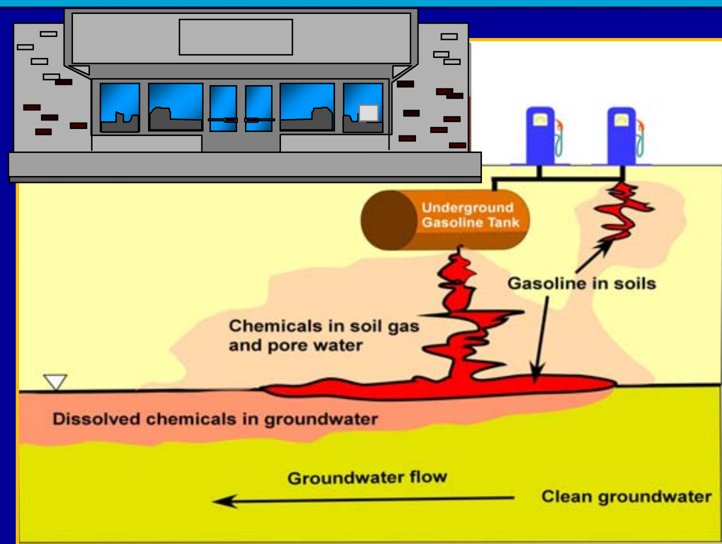
Also on the Supplementary Table at the CLU-IN resource page for this workshop

Add Source and Plume Remediation

- Simulate aggressive source remediation in 2012, assume we can remove 90% of LNAPL
- Also simulate a plume remediation operation (air sparging, chemical oxidation, etc.) between 20 and 100 m, starting in 2012 and ending in 2017
- Assume plume remediation increases benzene decay rate by 4X; no effect on MTBE or TBA



Example: 10,000 gallons of gasoline released in 1997, (unleaded regular with high MTBE). Groundwater pore velocity is 94 ft/yr, moderate degradation in plume



REMFuel Source Term: *Describing How the Source Responds to Weathering, Remediation*

1. Need to pick a gamma (Γ)
2. Thought to range from Γ = 0.5 to Γ = 2.0
3. This is new model, but here is current thinking

Might use Γ < 1.0

- Lots of free product
- NAPL mostly in high conductivity zones
- You are going to do "mass removal" of LNAPL (skimming, LNAPL pumping, etc.)

Might use Γ = 1.0

- Multicomponent LNAPL
- You are interested in simulating natural attenuation of source (weathering of LNAPL)
- You want to simulate a "phase change" technology that removes key constituents (such as air sparging for benzene, pump and treat for MTBE)
- Want to use "Middle of Road" value

Might use Γ > 1.0

- Contaminant mass is mostly in low permeability zones

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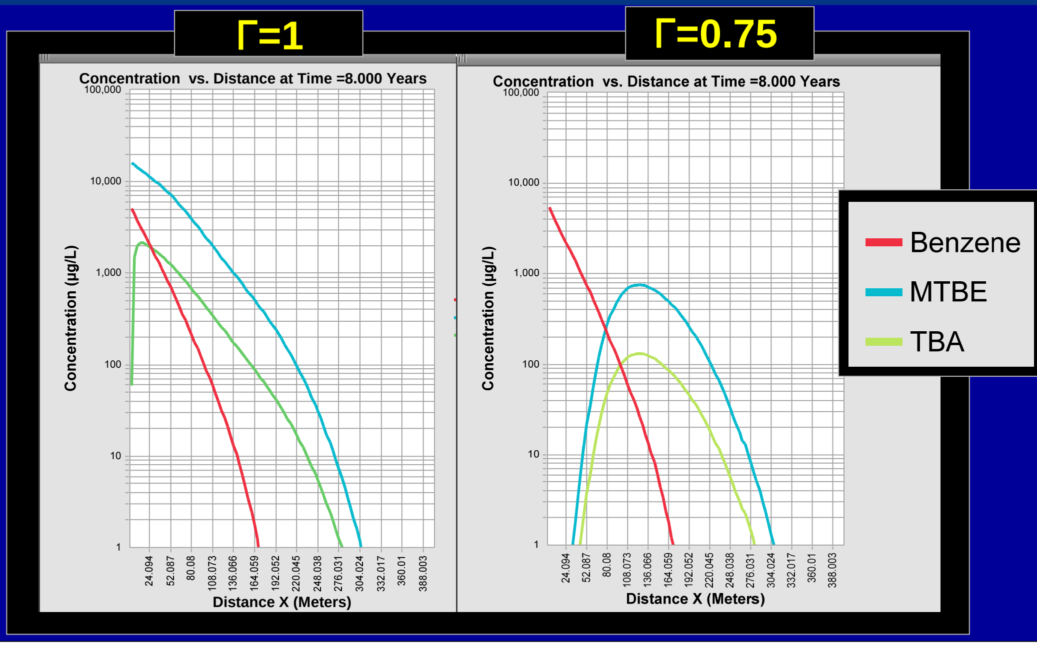
Let's re-run the REMFuel example with Γ = 0.75

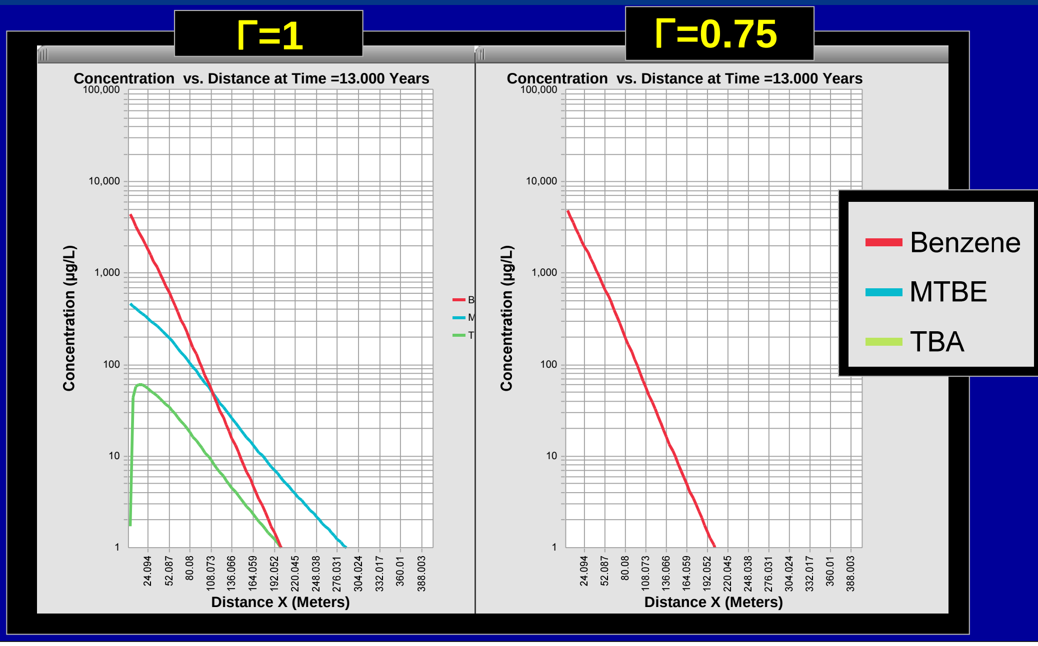
- **With Γ values less than one, source concentrations remain relatively high until the mass is depleted, then they drop rapidly**
- LNAPL components with high solubility (MTBE), will tend to wash out of the LNAPL faster with a small Γ
- LNAPL components with moderate to low solubility will tend to have nearly constant source concentrations until their mass is depleted

2005 Plume



Γ=1
Γ=0.75
Concentration vs. Distance at Time =8.000 Years
Concentration (µg/L)
Distance X (Meters)
Benzene
MTBE
TBA

2010 Plume

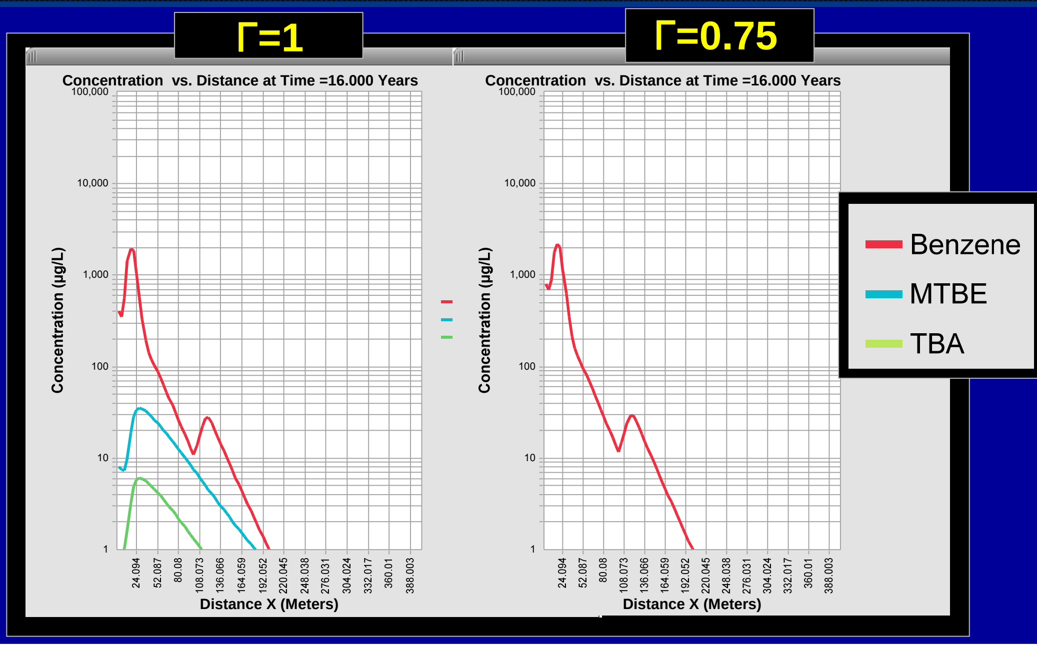


Γ=1
Γ=0.75
Concentration vs. Distance at Time =13.000 Years
Concentration (µg/L)
100,000
10,000
1,000
100
10
1
24.094
52.087
80.08
108.073
136.066
164.059
192.052
220.045
248.038
276.031
304.024
332.017
360.01
388.003
Distance X (Meters)
Benzene
MTBE
TBA

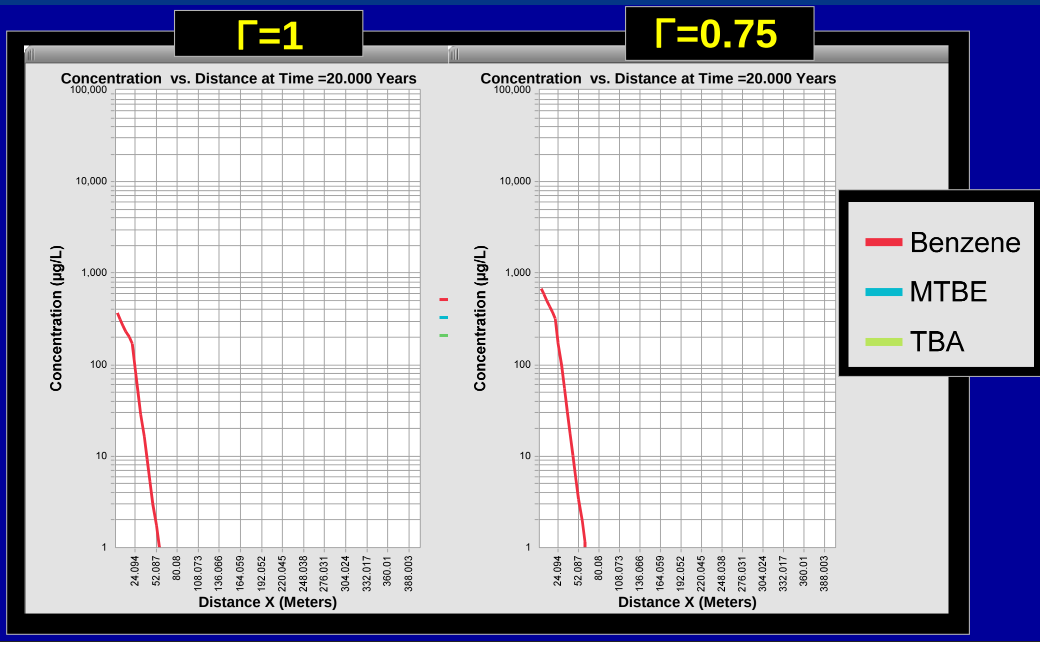
Add Source and Plume Remediation

- Simulate aggressive source remediation in 2012, assume we can remove 90% of LNAPL
- Also simulate a plume remediation operation (air sparging, chemical oxidation, etc.) between 20 and 100 m, starting in 2012 and ending in 2017
- Assume plume remediation increases benzene decay rate by 4X; no effect on MTBE or TBA

2013 Plume

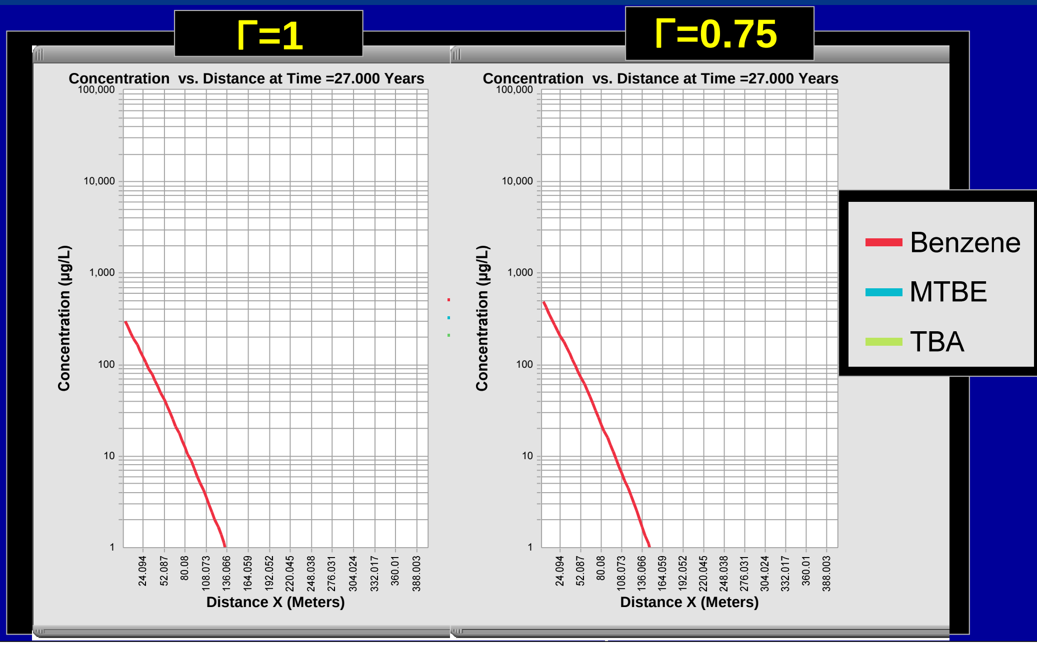

Γ=1
Γ=0.75
Concentration vs. Distance at Time =16.000 Years
Concentration (µg/L)
Distance X (Meters)
100,000
10,000
1,000
100
10
1
24.094
52.087
80.08
108.073
136.066
164.059
192.052
220.045
248.038
276.031
304.024
332.017
360.01
388.003
Concentration vs. Distance at Time =16.000 Years
Concentration (µg/L)
Distance X (Meters)
Benzene
MTBE
TBA

2017 Plume



Γ=1
Γ=0.75
Concentration vs. Distance at Time =20.000 Years
Concentration vs. Distance at Time =20.000 Years
Concentration (µg/L)
Distance X (Meters)
Benzene
MTBE
TBA

2024 Plume


Γ=1
Γ=0.75
Concentration vs. Distance at Time =27.000 Years
Concentration vs. Distance at Time =27.000 Years
100,000
10,000
1,000
100
10
1
Concentration (µg/L)
24.094
52.087
80.08
108.073
136.066
164.059
192.052
220.045
248.038
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304.024
332.017
360.01
388.003
Distance X (Meters)
Benzene
MTBE
TBA

Hands-On Computer Exercise

NUMBER 3

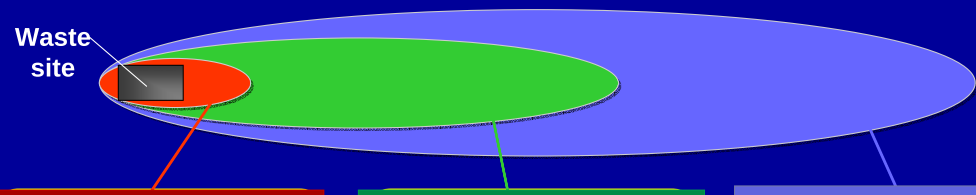
Develop Our Own Plan to Meet Site Goals Using REMChlor (Start With Tutorial 6)

♦

A Final Hands On Exercise: Objectives

- **Develop alternative remedial strategies for a challenging site and refine these based on practical model calculations (e.g., REMChlor)**
- **Demonstrate the simplicity, speed, power and potential usefulness of the approach**
- **Use the models to calculate risks and estimate costs as needed**
- **Examine limitations and issues associated with simplified models**

Anatomy of a Contaminated Site



Source Zone

Characteristics: High conc; significantly perturbed geochemistry

Need: Aggressive technologies to limit long term damage

Examples: Destruction in place or enhanced removal; heat/steam; chem ox or reduction

Primary GW/Vadose Zone Plume

Characteristics: Moderate to high aqueous/vapor phase concentrations

Need: Baseline methods or moderately aggressive alternatives

Examples: Pump (gas or water) and treat; recirc. wells; enhanced biorem

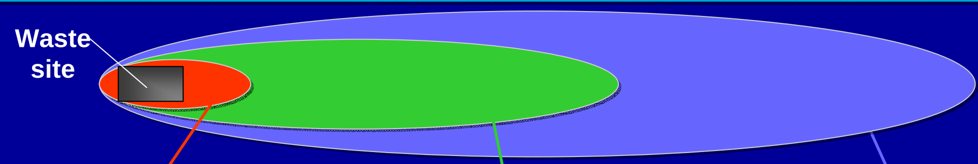
Dilute Plume/Fringe

Characteristics: Low aqueous/vapor phase conc; large water vol

Need: innovative techs - sustainable low energy concepts

Examples: Passive pumping (siphon, barometric, etc.); biorem; phytoremediation, etc.

Diagnosing and Treating a Contaminated Site



Source Zone

Costs:
$/lb cont or $/cu yd

Removal Examples:
< $50-$100/cu yd or
< $100/lb for chlorinated solvents

hot spot characterization reduces cleanup volume

Primary GW/Vadose Zone Plume

Costs:
$/treatment vol (gal/cu ft)

Removal Examples:
< $0.5-$10 / 1000 gallons

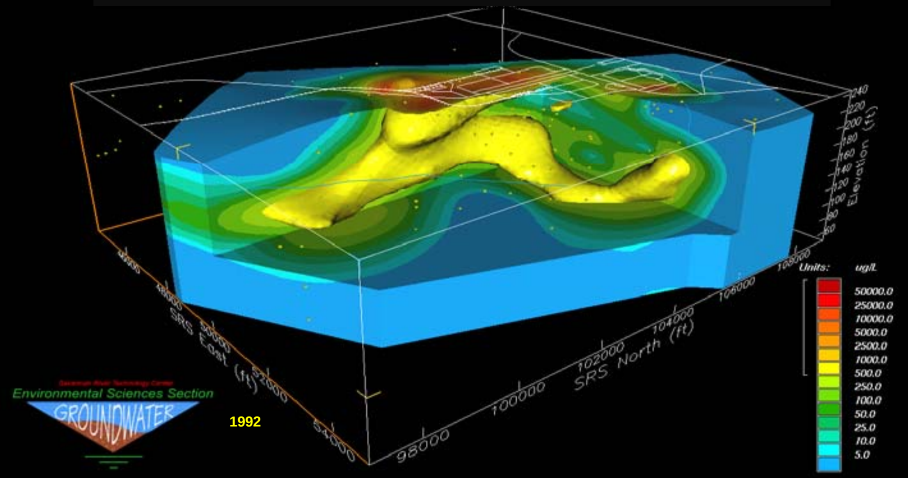
capture zone charac needed, optimize extraction to reduce treatment volume

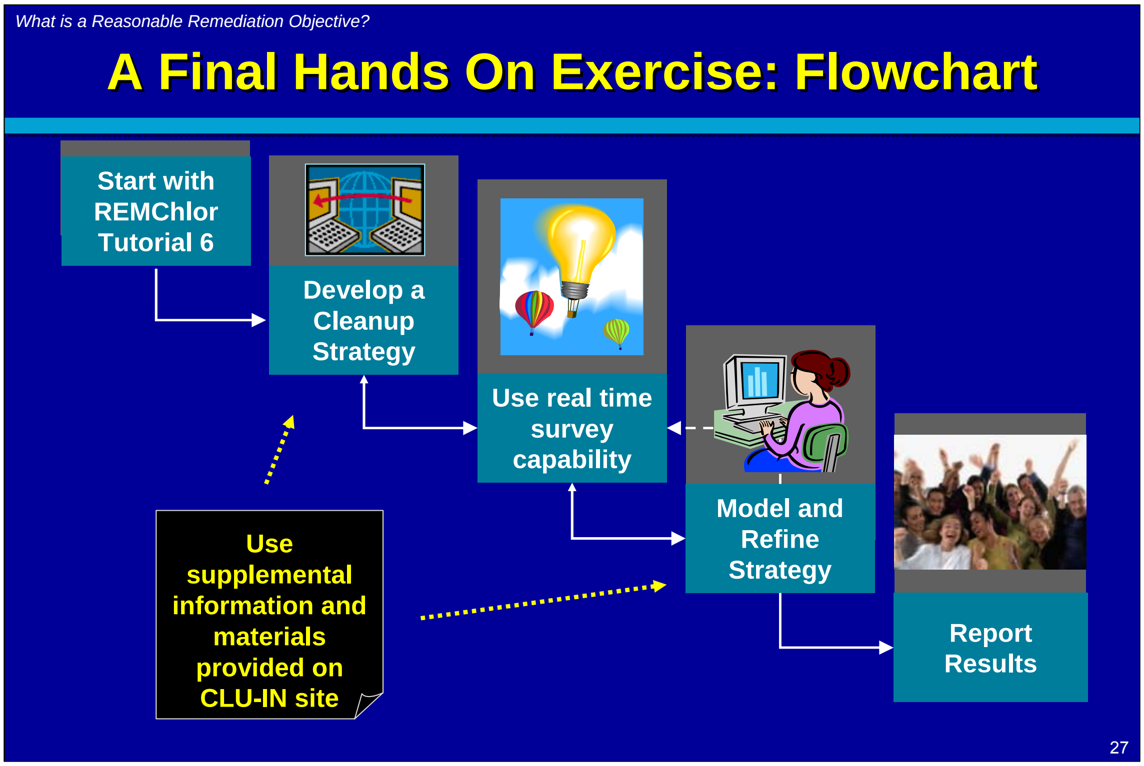
Dilute Plume/Fringe

Costs:
Operation and maintenance costs
$/time

mass transfer and flux characterization needed

Plume of TCE in the groundwater underlying the A/M Area of the DOE Savannah River Site




What is a Reasonable Remediation Objective?
A Final Hands On Exercise: Flowchart
Start with REMChlor Tutorial 6
Develop a Cleanup Strategy
Use real time survey capability
Model and Refine Strategy
Report Results
Use supplemental information and materials provided on CLU-IN site
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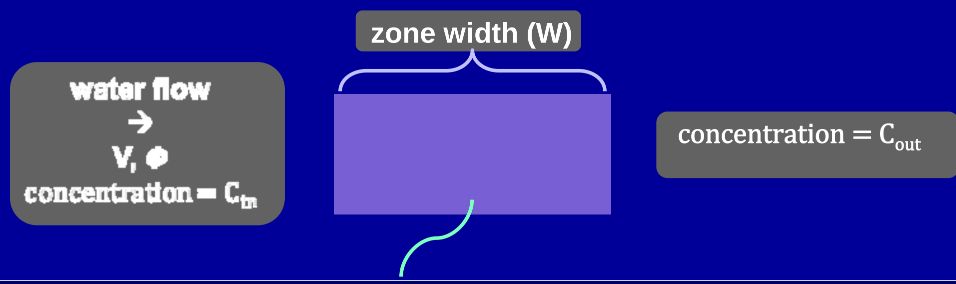
Getting Diverse Remedial Technologies into REMChlor (tips and tricks)

- Each applied technology needs to be able to be modeled as either a fractional source removal/destruction action over a specified period *or* a first order removal process in a specified space time plume zone
- Excavation, Chemical Oxidation, Surfactant/Cosolvent, Thermal
- Bioremediation, Permeable Reactive Barriers, Pump & Treat, etc. (need to calculate an equivalent λ for these technologies)

Calculating λ for a Non-Bioremediation Technology



$$\text{Water residence time} = t_r = \frac{W}{V/\Phi} = \frac{W\Phi}{V}$$

we know that $\frac{C_{out}}{C_{in}} = e^{-\lambda t_r}$ so that $-\lambda t_r = \ln\frac{C_{out}}{C_{in}}$ or $\lambda = \frac{-V}{W\Phi}\ln\frac{C_{out}}{C_{in}}$

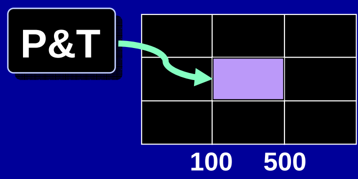
C_{out} = concentration at time = t; C_{in} = concentration at time = 0; V = Darcy velocity; W = treatment area width; Φ = porosity; λ = rate constant

Calculating λ for a non-Bioremediation Technology

NOTES:

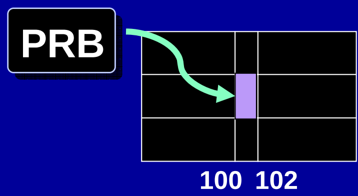
- **Ron's very cool simplified equation to incorporate a wide range of technologies!**
- **This works for any technology that can be represented using an approximate C/C_0 within your designated treatment zone.**
- **Assumes that degradation/removal process is occurring only in the aqueous phase (consistent with EPA guidance and REMChlor operation).**
- **Assumes that technology does not grossly impact overall groundwater flow (e.g., P&T with reinjection).**
- **The resulting □ values are case specific (i.e., dependent on your geometry), actual remediation design needs to be performed to achieve the desired removals and sustainability.**

Examples



For this example, assume:
50% flux reduction
V = 20 m/yr
ϕ = 0.333

P&T $\lambda = [-20 / (400 * 0.333)] * \ln(1-0.5) = 0.1\ yr^{-1}$



For this example, assume:
82% flux reduction
V = 20 m/yr
ϕ = 0.333

PRB $\lambda = [-20 / (2 * 0.333)] * \ln(1-0.82) = 51\ yr^{-1}$

Calculating λ for a bioremediation technology if you only have a half life:
Since $t_{1/2} = 0.693 / \lambda \rightarrow \lambda = 0.693 / t_{1/2}$
e.g. 10 year half life $\lambda = 0.07\ yr^{-1}$

Other tips and tricks

- If the plume crops out into a stream (or is captured by a well)
  - you can use the flux estimates (graphs and output) for the location and estimate blended concentrations based on total flow.
  - In these cases, the plume projections beyond the stream/well distance are not relevant and can be discarded.
- The graphs within REMChlor and REMFuel can be copied and pasted using standard windows commands for use in reports, presentations and “movies”
- The output files from REMChlor and REMFuel can be manipulated in spreadsheet software and are reasonably compatible with a wide range of contouring software.

Rough Cost Factors: *(Source Treatment)*

Source Treatment Technologies: Typical median costs per acre (and per sq m) annotated to indicate range					typical fraction removed
Excavation	-	**$10 million ($2500)**	+	$ 4 million ($1000) to $20 million ($5000)	**< 0.8 to 0.99**
Cosolvent / Surfactant	-	**$10 million ($2500)**	+ +	$ 6 million ($1500) to $40 million ($10000)	**0.6 to 0.9**
Thermal	-	**$5 million ($1250)**	+ +	$ 2 million ($500) to $18 million ($4500)	**0.8 to 0.995**
Chemical Oxidation	-	**$5 million ($1250)**	+	$ 2 million ($500) to $9 million ($2250)	**0.8 to 0.98**
Air Sparging	-	**$1 million ($250)**	+	$ 0.25 million ($65) to $2 million ($500)	**0.1 to 0.6**
Free Product Removal	-	**$0.5 million ($125)**	+	$ 0.1 million ($25) to $1 million ($250)	**0.1 to 0.3**

Assumes nominal $/ cu yd cost range from the literature and a 1 acre target zone 30 ft thick
Assumes technology is applicable and reasonably designed and reasonably effective
If a very high removal efficiency is desired, the assumed costs would increase

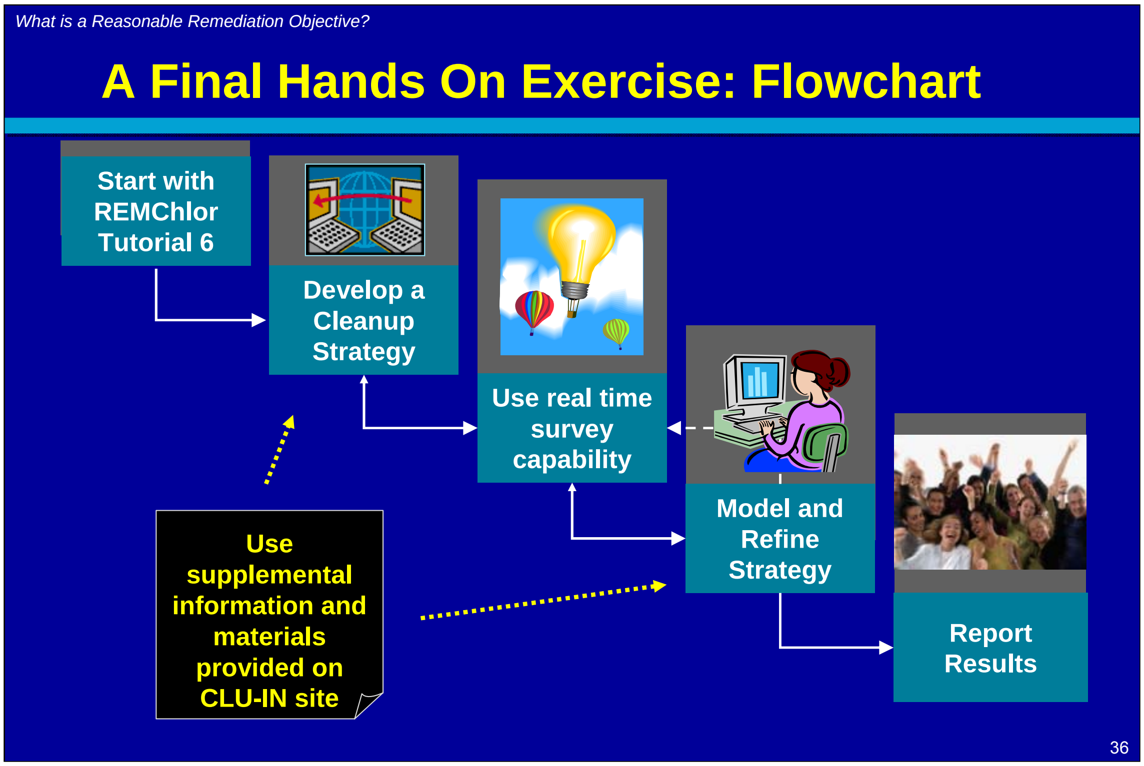
Rough Cost Factors: *(Plume Treatment)*

Plume Treatment Technologies:

Typical median costs 1st year & per plume/application				acre per year (and per sq m per year)		typical performance	
Bioremediation (bulk)	– –	1 million & $0.1 million ($25)	+ +	$ 0.05 million ($12) to $1 million ($250)	–	High	
Pump and Treat	–	1 million & $0.01 million ($2.5)	+	$ 0.005 million ($1.3) to $0.1 million ($25)		Poor / Moderate	+
Typical PRB costs per 100 m transect per year							
Zero Valent Iron	–	$0.5 million	+ +	assumes cost of $5 million and 10 yr longevity		High	+
Mulch / Bio Zone	–	$0.1 million	+ +	assumes cost with upkeep of $1.5 million and 15 yr longevity	–	High	

Assumes nominal cost range from the literature (for PRB assumes about 100 m length and 10 m depth)
Assumes technology is applicable and reasonably designed and reasonably effective
If a very high removal efficiency is desired, the assumed costs would increase

BREAK FOR QUESTIONS FROM PARTICIPANTS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A Final Hands On Exercise: Process

- We will use the – Real Time Survey capabilities of ADOBE Connect to simulate working as a team
- Start with REMChlor Tutorial 6
  - Assume release in year 0 (e.g., 1981) and start remediation in year 30 (e.g., 2010)
- Develop Cleanup Plan
  - Develop remediation goals and performance metrics
  - Develop a strategy that uses one or more technologies to attempt to reach these goals (including source treatment/removal, treatment actions in the plume, and/or MNA)
  - Use information in Supplemental Handouts to assist in developing your strategy and in modeling

A Final Hands On Exercise: Process

- Model the performance of the team's various remediation strategies and refine to best meet the goals
  - Consider concentration, flux, risk and/or cost
  - Refine based on performance
- Report out on strategy, metrics, and results

A Final Hands On Exercise: Misc.

- This is a challenging problem
- There is no "right" answer
- Be creative
- Use the tools and techniques that we have provided to incorporate source actions and remedial technologies into the simplified (space-time and λ) modeling construct of REMChlor
- Record info on strategy, metrics, performance, cost, etc. as you go along
- Pay attention to how much your team accomplishes in an hour (or so)

questions

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

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**
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