DNAPL Source-Zone Remediation:
How Much Cleanup & Which Performance Metrics?

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Scope of the Problem

- ~20,000 sites @$5M/site; cost ~$100 billion
- Several source mass depletion technologies have been successfully field tested, but not widely adopted
- Need to link DNAPL source treatment with dissolved plume behavior
- Need new conceptual framework for site assessment, remediation endpoints & technology integration

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Questions Considered by the EPA DNAPL Expert Panel

- What are the benefits of partial source depletion?
- What are the appropriate performance metrics for assessment of source depletion technologies?
- Are available technologies adequate for source characterization to select, (implement), & evaluate mass depletion options?
- What performance can be anticipated from available source depletion technologies?

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Questions Considered by the EPA DNAPL Expert Panel (contd.)

- Are currently available tools adequate to *predict* the performance of source depletion options?
- What are the factors restricting the effective and appropriate adoption of source depletion technologies?
- How should decisions be made on whether to undertake source depletion at a site?
- What are the potential negative impacts of implementing source depletion technologies?

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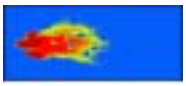
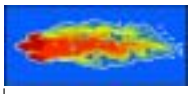
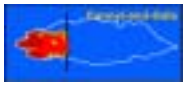
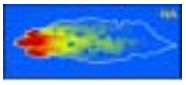
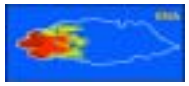
Plume Management as an Alternative to DNAPL Source-Zone Treatment

Contaminated Site		No measures → No NA	Future Situation	
Options				
Technical Complexity	moderate	high	low	high
Investment Costs	low	high	low	moderate
O & M Costs	high	low	low	moderate
Land Use	low	low	high	moderate

Slide courtesy of Dr. Georg Teutsch, University of Tuebingen

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Options for DNAPL Source Zones

- No Mass Depletion
  - Manage only dissolved plume
  - Contain source & monitor plume
- Partial Mass Depletion
  - Reduce source strength & Monitor plume
  - Enhanced attenuation in plume
- "Complete" Mass Depletion
  - Plume hydraulic control

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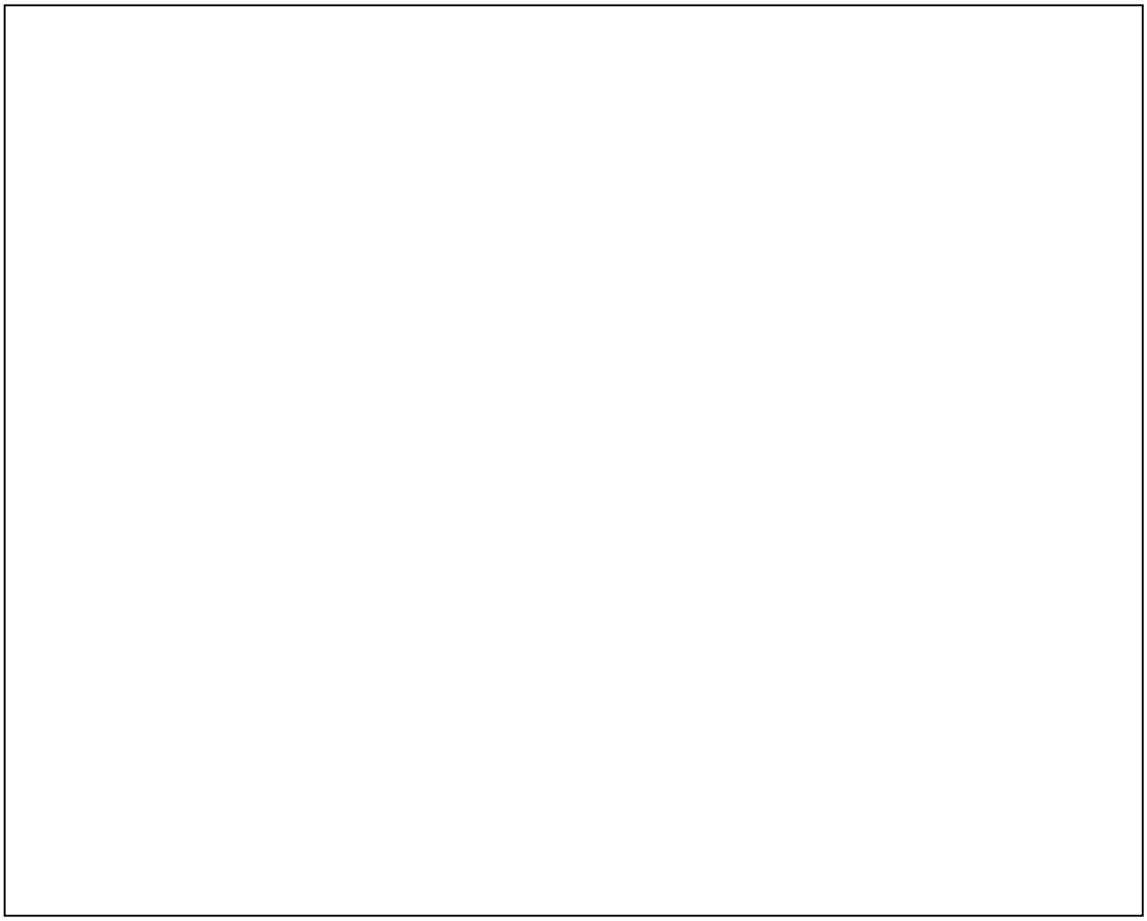
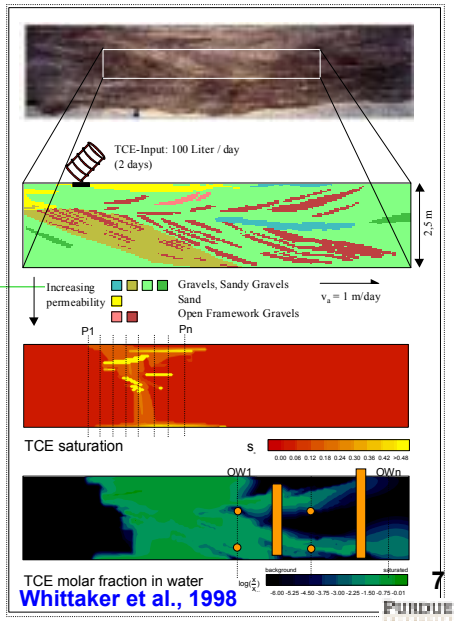


Source & Plume Characterization Issues

- How to assess source & plume strength?
  - cores in the source?
  - sample the plume ?
- What is the appropriate scale for assessment?
  - local (point) scale?
  - integral (plume) scale?
  - How frequently should we sample?

Slide courtesy of Dr. Georg Teutsch, University of Tuebingen



Whittaker et al., 1998

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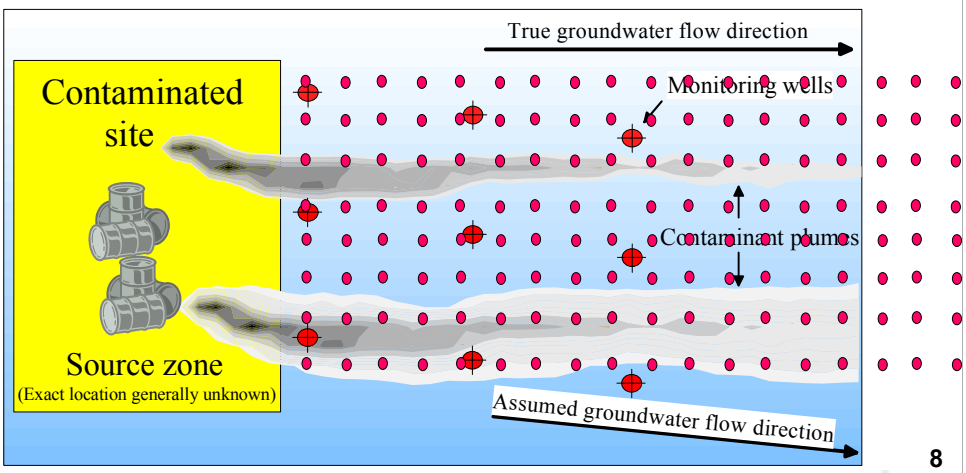
Plume Characterization Issues



Slide courtesy of Dr. Georg Teutsch, University of Tuebingen

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Benefits of Partial Mass Depletion

- Reduction in risks & liability
  - DNAPL mobility
  - source longevity
  - source strength
- Increased attenuation in plume
- Reduction in long-term management & costs
- Better site stewardship

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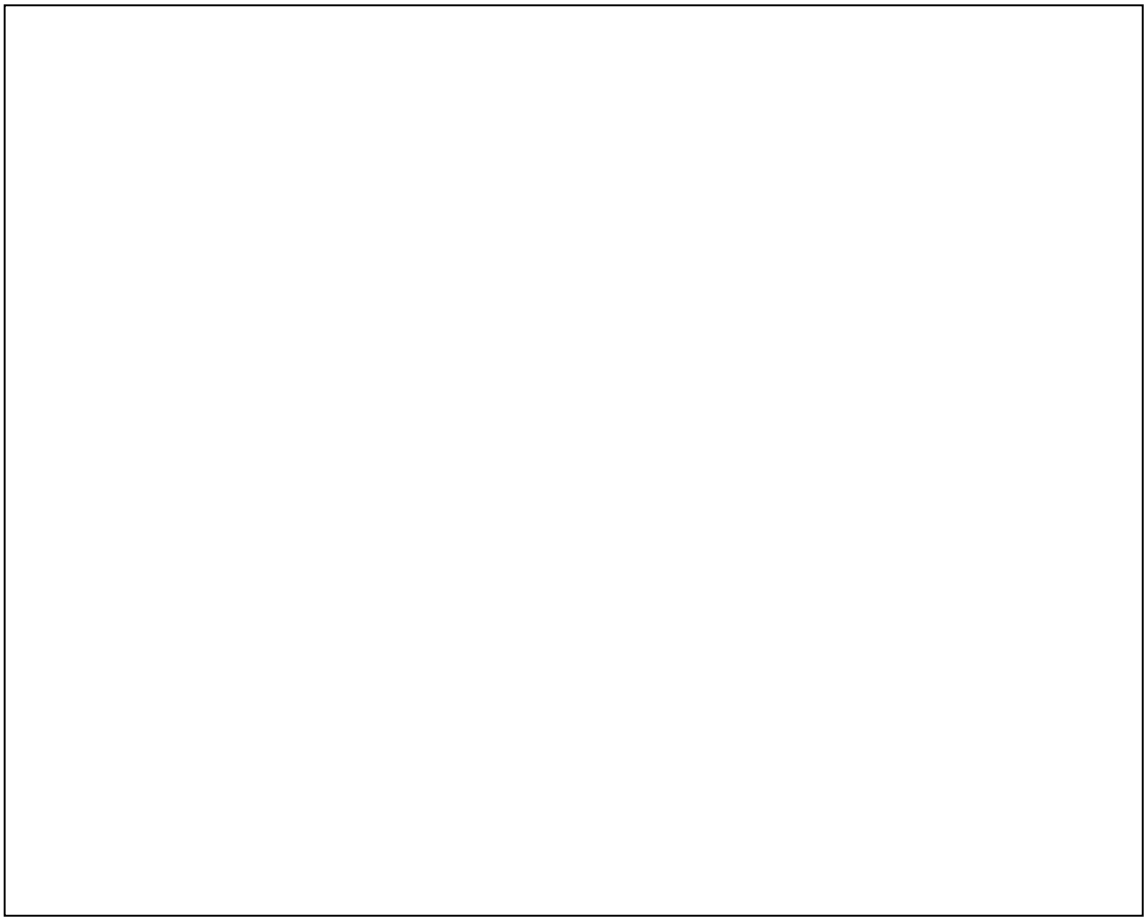


Control Plane & Source Strength

$$M_d = \Sigma J_i A_i$$

J_i = Local mass flux (ML^2T^{-1})

q_i = Local Darcy flux (LT^{-1})

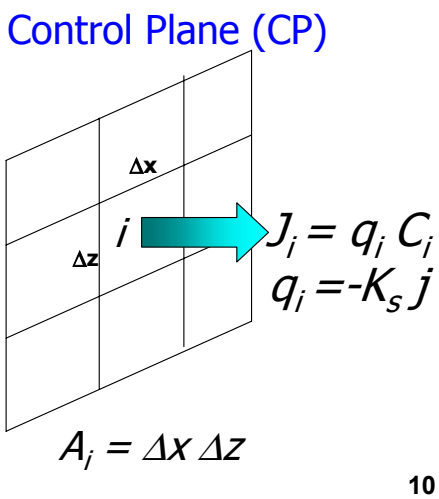
C_i = Local conc. (ML^{-3})

A_i = Area of element i (L^2)

M_d = *Source strength* (MT^{-1})

K_s = Satd. Hyd. Cond (LT^{-1})

j = Hydraulic gradient (-)



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What are the Criteria for Specifying Source Strength Reduction?

- Reduced source strength must
  - Modify the dissolved plume behavior
  - Be less than or equal to the "attenuation capacity" within the plume
  - Be small enough so that *flux-averaged* concentrations at a down-gradient sentinel well or compliance control plane are below the regulatory limits

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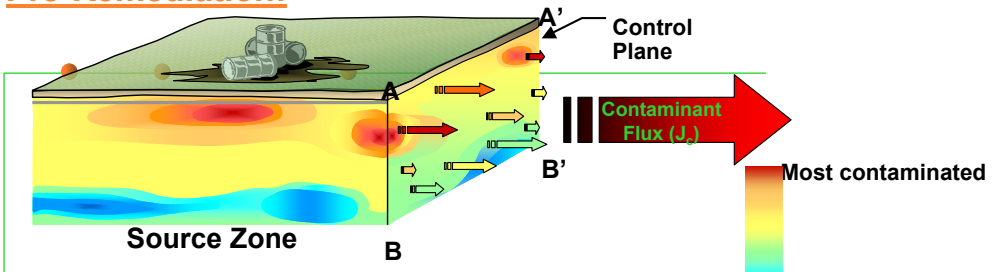
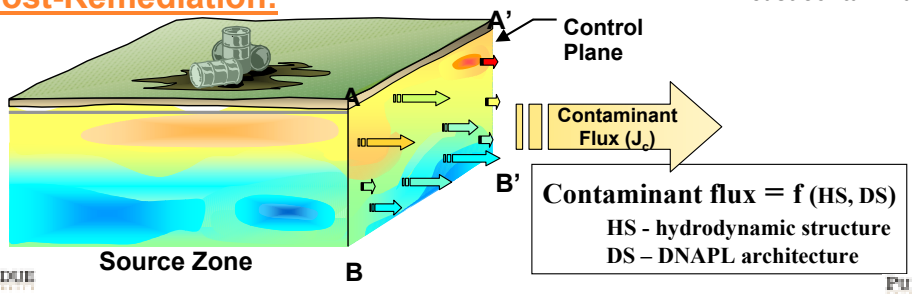
Source Management Strategies

Pre-Remediation:



Post-Remediation:



Contaminant flux = f (HS, DS)

HS - hydrodynamic structure

DS – DNAPL architecture

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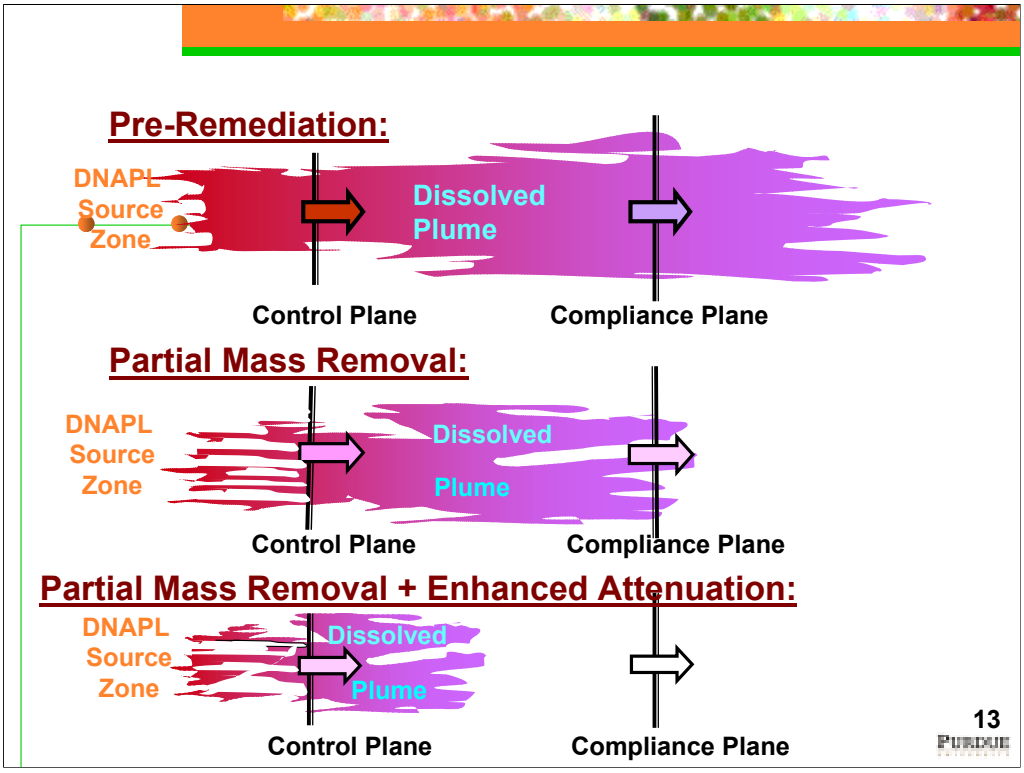
Pre-Remediation:
DNAPL Source Zone
Dissolved Plume
Control Plane
Compliance Plane
Partial Mass Removal:
DNAPL Source Zone
Dissolved Plume
Control Plane
Compliance Plane
Partial Mass Removal + Enhanced Attenuation:
DNAPL Source Zone
Dissolved Plume
Control Plane
Compliance Plane
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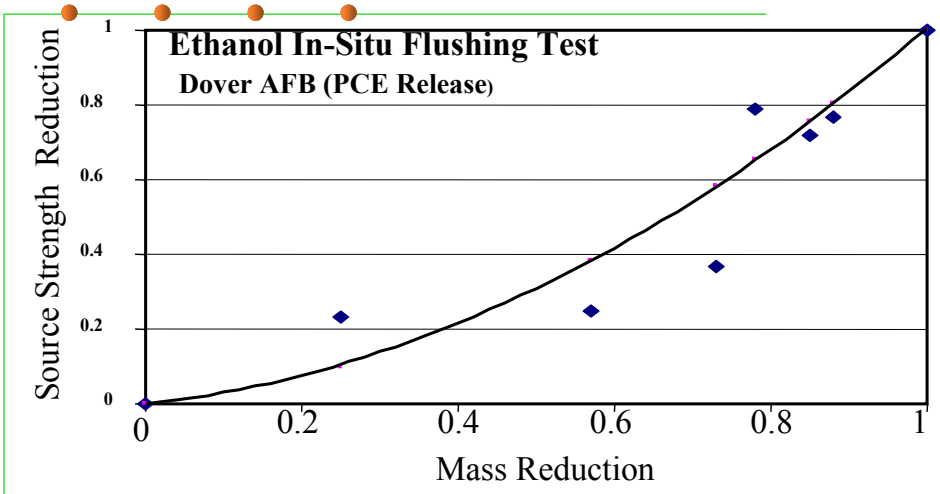
How does Mass Depletion Change Source Strength?

- ***Source strength*** **should be a strong function of DNAPL source architecture, hydrogeologic heterogeneity & correlation between the two.**
- **To date, there are only a handful of controlled experiments to examine this relationship.**
- **Modeling results provide some guidance.**

Dover AFB: Controlled PCE Release



Brooks et al., 2001

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Modeling Approaches Used

- **Analytical** (heterogeneous v; uniform S_n)
  - **Stream-tube Model** (Rao & Jawitz, 2002; Enfield, 2001)
- **Numerical** (heterogeneous v; spatially correlated S_n)
  - **Lagrangian** (Berglund, 1998; Enfield, 2001)
  - **Particle Tracking** (Jawitz & Rao, 2002)
  - **Finite Difference T2VOC** (Falta & Rao, 2001)

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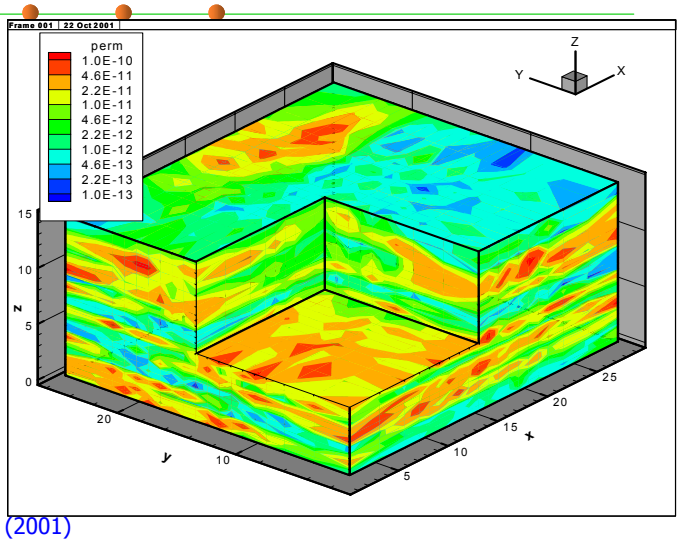
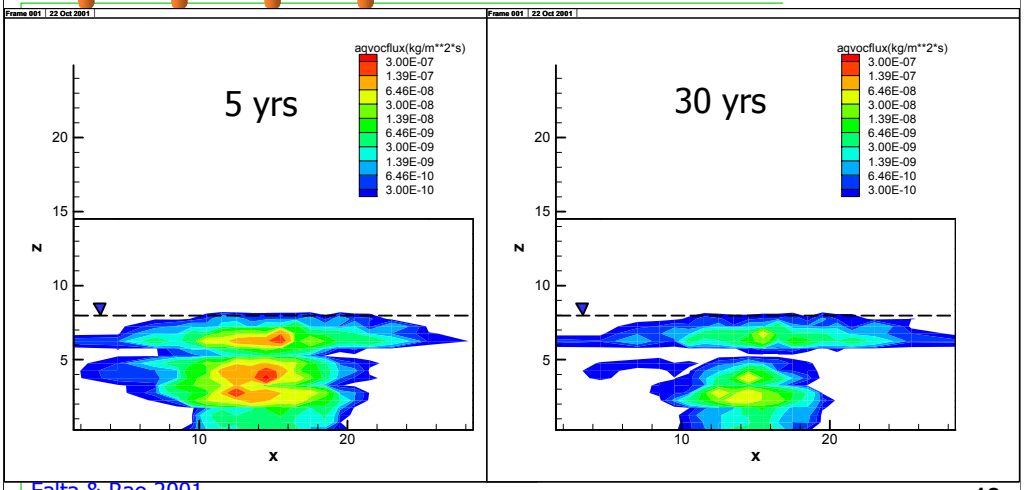
Coastal Plain Geohydrology used in T2VOC Simulations



Falta & Rao (2001)

PCE Source Strength: Positive Correlation Between PCE Content & Permeability



Falta & Rao 2001

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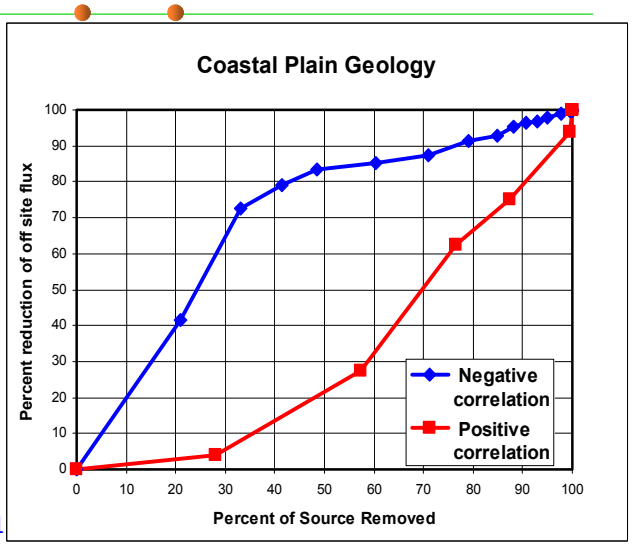
Importance of Correlation: T2VOC Simulations



Falta & Rao 2001

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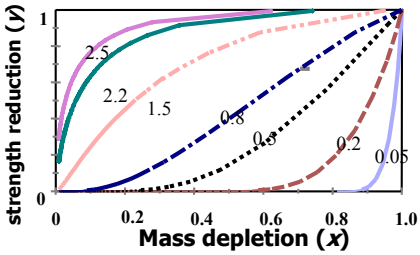
Source Strength Reduction by Mass Depletion in Unconsolidated Media

- Low efficiency (small β) for homogeneous media (e.g., Borden AFB)
- Higher efficiency (larger β) for heterogeneous media (Dover AFB)
- Higher efficiency for negative correlation between permeability & DNAPL content

$$y = x^{1/\beta}$$

$$\beta > 0$$



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Can Source Strength be Measured?

- Traditional monitoring methods have limitations
- Several new approaches are being developed and field tested (Flux Meter; Tuebingen Pump Tests)
- Only limited field data are available to date
- How reliable are these new methods?
- Are the monitoring costs lower?
- What are the alternatives?

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Estimates of Source Strength

Site	Contaminant	(M_d; g/day)
Simpson County, NC	MTBE	0.3 to 2.0
Vandenberg AFB, CA	MTBE	1.2 to 7.0
Port Hueneme, CA	MTBE	150
Elizabeth City, NJ	MTBE	4
Testfeld Sud, Germany	BTEX	1.8
	PAHs	29.5
Landfill Site, Germany	TCE	2.51
Alameda Naval Station, CA	cis-1,2-DCE	31
Nekkar Valley, Germany	PCE	77
Dover AFB, DE	total chlorinated	280
St. Joseph, MI	total ethenes	425

* adapted from: Einarson & Macaky (2001); *ES&T*, 35(3):67A-73A

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Current Options for Measuring Source & Plume Strength

- Transect of fully screened wells for gw sampling & hydraulic tests for *K* and hydraulic head field
- Transect of multilevel samplers for gw sampling along with measured *K* & hydraulic head field
- **Integrated Pumping Tests; steady & unsteady; single & multiple wells (Tuebingen method)**
- **Transect of Borehole Flux Meters (Florida method)**

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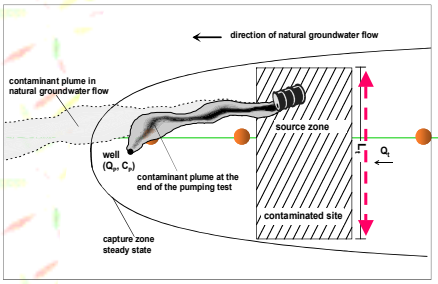
Integral-Scale Flow-Rate Measurement
Tuebingen Integral Pump Tests

Steady state; Single-well

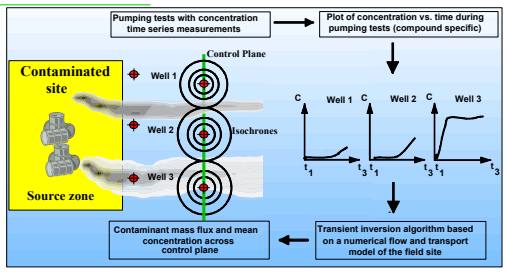


$F_t = C_p Q_p$

$C_{av} = F_t / Q_t$

Teutsch et al., 2000

Unsteady; Multi-well



Slide courtesy of Dr. Georg Teutsch, University of Tuebingen

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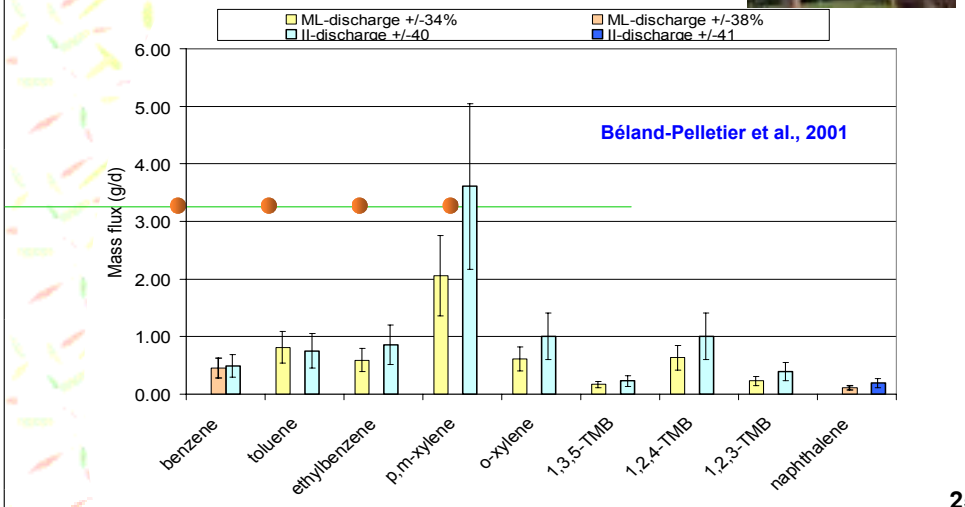
Comparison at Borden CFB



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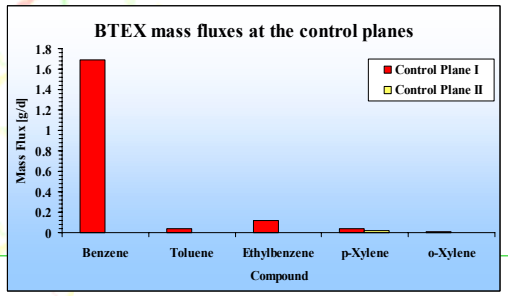
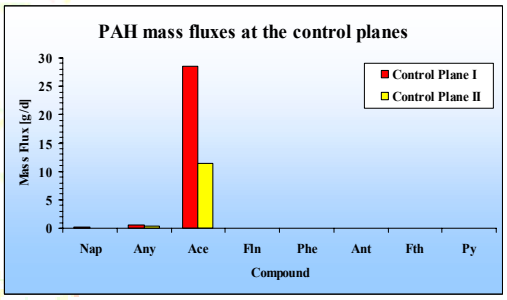
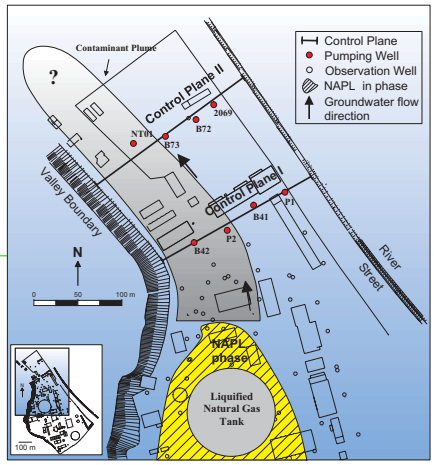
Mass Discharge at Two Control Planes: Field Site in Stuttgart, Germany







Bockelmann et al., 2001

Slide courtesy of Dr. Georg Teutsch, University of Tuebingen

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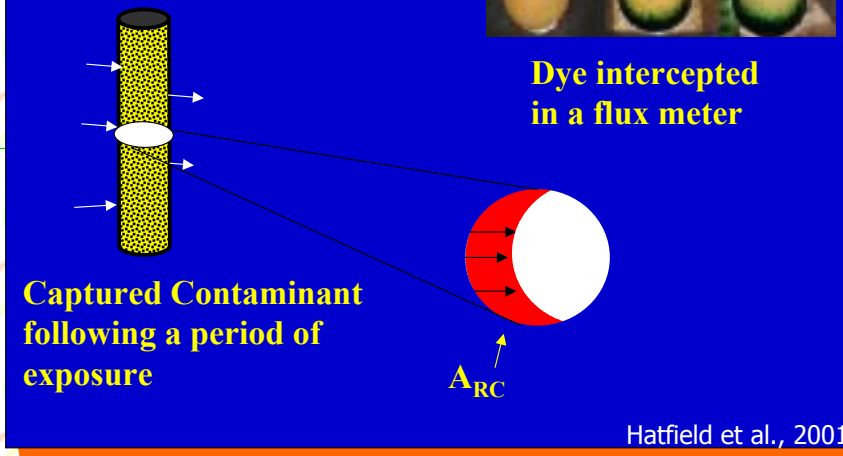
Borehole Flux Meter
Groundwater & Contaminant Fluxes



Dye intercepted in a flux meter

Captured Contaminant following a period of exposure

A_{RC}

Hatfield et al., 2001

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Field Installation and Sampling

Courtesy of Mike Annable, Univ of Florida

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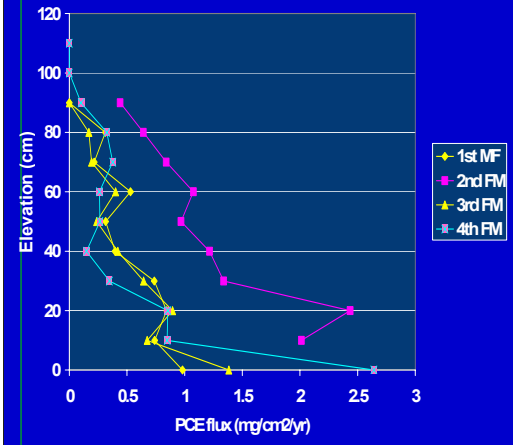
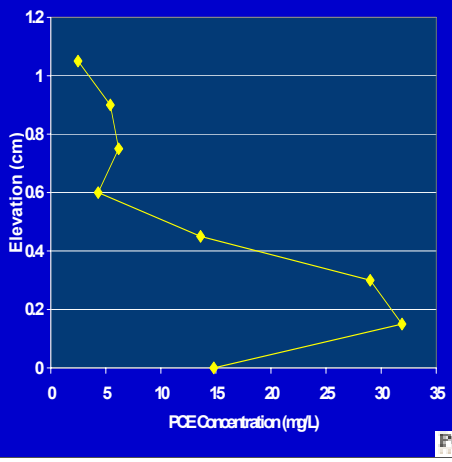
PCE Flux Comparison at Borden CFB





Courtesy of Mike Annable, Univ of Florida

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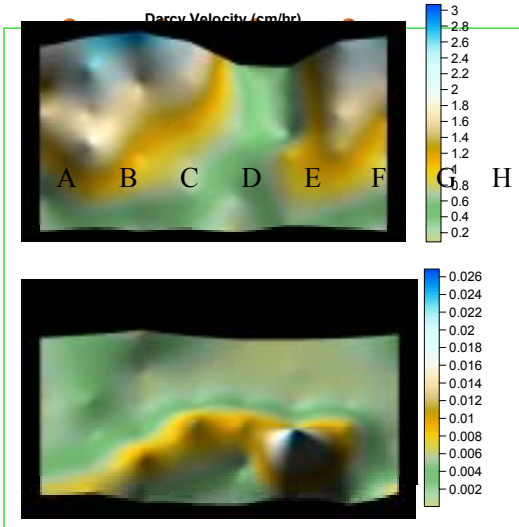
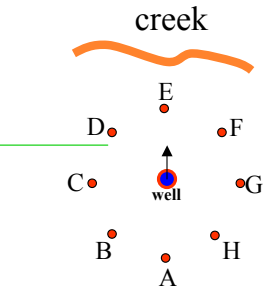
Borden CFB Test Site



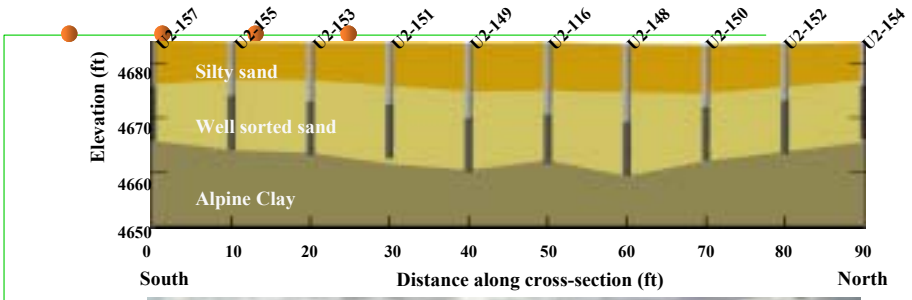


Well Flux
1.12 cm/hr

GW

Courtesy of Mike Annable, Univ of Florida

Hill AFB Test Site



Courtesy of Mike Annable, Univ of Florida

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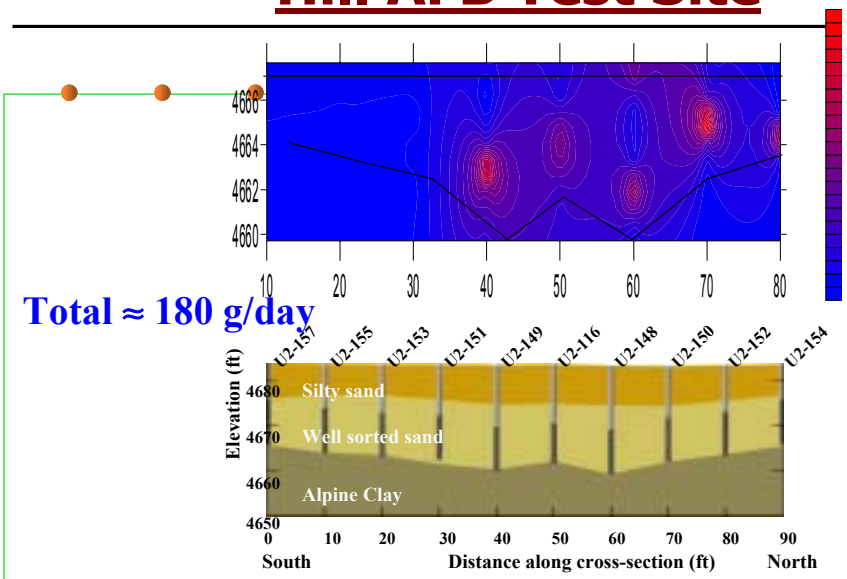
Hill AFB Test Site



Total ≈ 180 g/day

Courtesy of Mike Annable, Univ of Florida

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Planned U.S. Field Tests for Source Strength Measurements

- Dover AFB (test cells) – SERDP
- Jacksonville Sages Site – SERDP
- LC-34 site, Cape Canaveral, FL – SERDP
- Hill AFB, OU2 site, UT – SERDP, ESTCP
- Port Hueneme, CA – ESTCP, SERDP, AFCEE
- Waterville Arsenal, NY – ESCTP
- Fort Lewis, WA – ESTCP
- Alameda Point, CA – ESTCP

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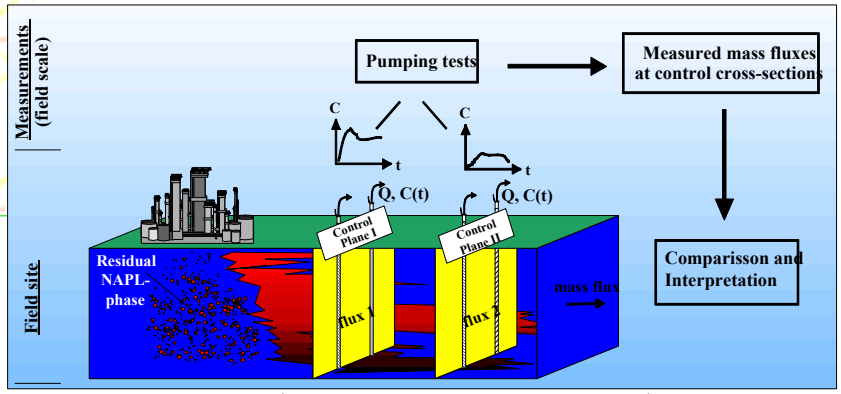
Multiple Control-Plane Approach for Measurement of Contaminant Attenuation



$$NA\ Rate = -\ln\left(\frac{Mass\ Flux\ (ControlPlane\ II)}{Mass\ Flux\ (ControlPlane\ I)}\right) * \frac{1}{\Delta t}$$

Slide coutesy of Dr Georg Teutsch, Univ of Tuebingen

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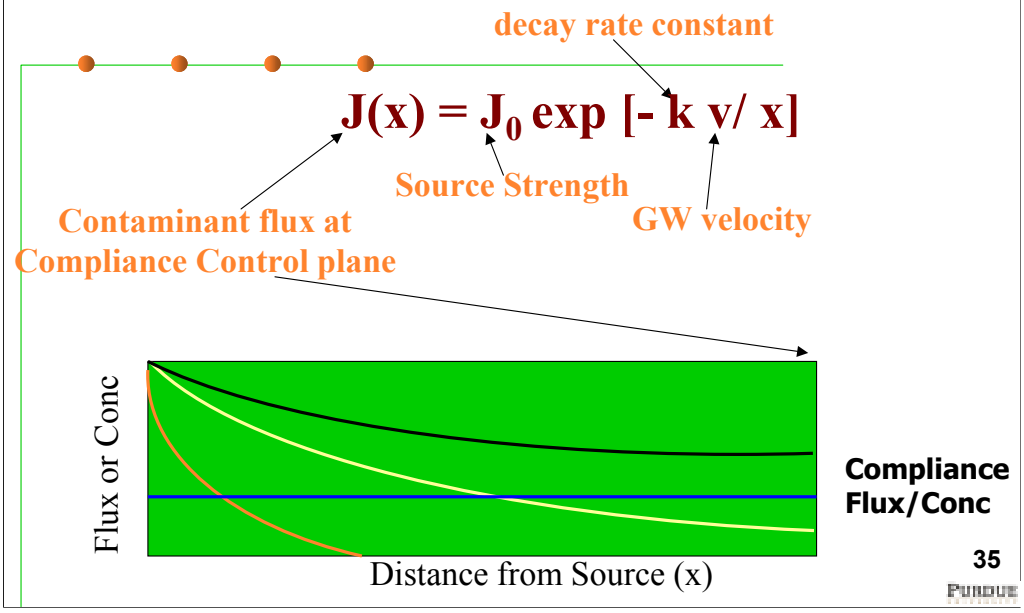
No Further Degradation Approach??



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Conclusions

- The combination of ***flux-averaged concentrations*** and ***source (or plume) strength*** can be useful for the evaluation of risk and remediation performance.
- Robust metrics for site assessment with low resolution (IPT) or high resolution (Flux Meter)
- Field-scale comparisons show good agreement with multi-level monitoring fence; other tests underway.
- Measurements at multiple control planes and times can provide assessment of evolution of source or plume behavior, and attenuation.

Issues in Adopting New Performance Metrics

- Further field-scale validation & map a path to regulatory acceptance for source strength approach
- Discussion of approaches to source strength reduction (depletion vs barriers vs stabilization)
- Large active-use sites vs Smaller, inactive sites
- Unconsolidated vs fractured media
- Evaluation of long-term institutional controls
- Monitoring needs & failure analysis
- Cost-benefit analysis using appropriate financial models

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