DNAPL Source Zones

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Superfund Basic Research Program
University of Arizona

- Funded and administered by the National Institute of Environmental Health Sciences (NIEHS), an institute of the National Institutes of Health (NIH)

- Hazardous wastes investigated include: arsenic, chlorinated hydrocarbons, and mine tailings contamination

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The DNAPL Problem

- Primary Source of Contaminant Mass
- Site Characterization
- Remediation

3

The Source-Zone Issue

To Remediate or Not To Remediate---
that is the question…

4

Recent Studies

- Interstate Technology and Regulatory Council. 2002. DNAPL Source Reduction: Facing the Challenge.
- Environmental Protection Agency. 2003. The DNAPL Remediation Challenge: Is There a Case for Source Depletion?
- National Research Council. 2004. Contaminants in the Subsurface: Source Zone Assessment and Remediation.

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Summary

- Complete Mass Removal Not Possible
- Is Partial Removal [Mass Reduction] Beneficial?
- Need To Define Objectives
- Cost/Benefit Analysis

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Key Questions

- Expected Degree of Mass Reduction?
- Impact of Specified MR on Mass Flux?
- Impact of Mass Flux Reduction on Risk?

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Answers

- Need to Understand the Impact of Source-zone Architecture and Dynamics on Mass Flux Behavior

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Research Needs

- SERDP/ESTCP Expert Panel Workshop on Research and Development Needs for Cleanup of Chlorinated Solvent Sites. 2001.
  - Focus Research on Source-Zone Issues
  - Source-zone Architecture and Mass Transfer Processes
  - Pore-scale Processes

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Research Needs

- UA/SBRP Expert Panel DNAPL Workshop. 2005.
  - Source-zone mass flux processes, and the relationship between mass reduction and mass flux
  - Distribution and mass-transfer behavior of DNAPLs at multiple (pore, column, intermediate, field) scales
  - Distribution and mass-transfer behavior of DNAPLs in heterogeneous (low-permeability or fractured) systems

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Continued

- Long-term mass flux behavior, including the influence of aging and the relative contributions of trapped DNAPL, sorbed mass, and matrix-associated dissolved mass
- Impact of co-contaminants on phase properties (wettability, interfacial tension) in complex, natural (real-world) settings
- Mathematical modeling at multiple scales, and associated upscaling

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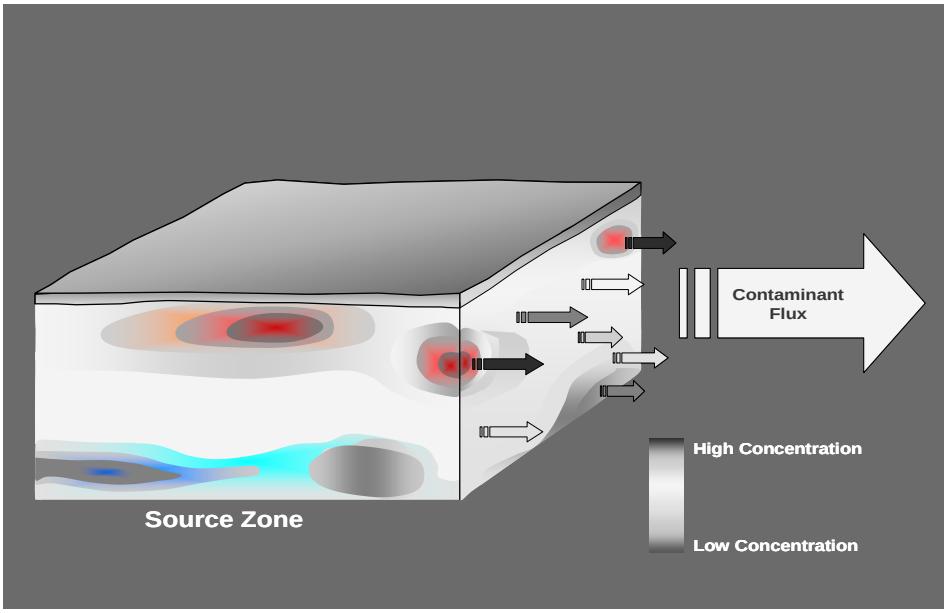
Mass Flux


Contaminant
Flux
High Concentration
Low Concentration
Source Zone

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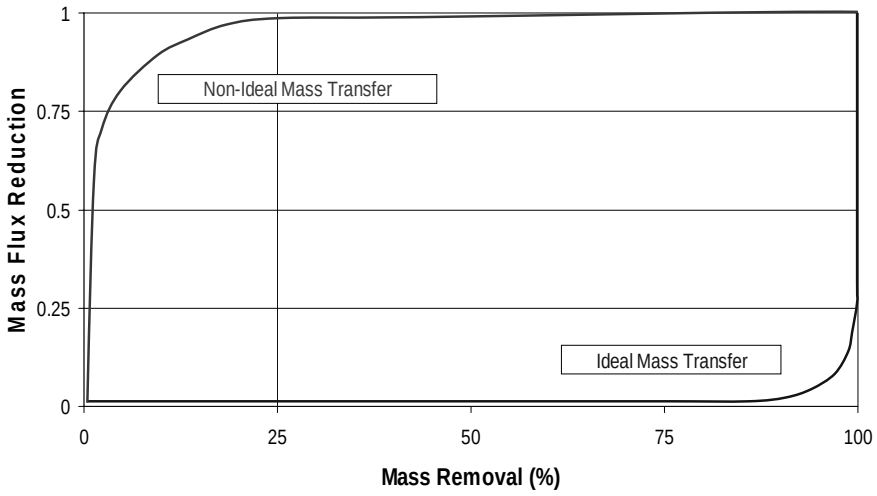
Flux Reduction vs. Mass Removal



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Factors Influencing Mass Flux

- Flow-Field Dynamics
- DNAPL Distribution and Configuration
- Dissolution Dynamics
- Mass Transfer and Transformation Processes

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Measuring Mass Flux

- Measuring Mass Flux in the Field
- Lynn Wood Presentation

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Predicting Mass Flux Reduction

- Flux Reduction-Mass Removal Relationships
- Understand Impacts of Source-zone Architecture and Dynamics on Mass Flux
- Priority Research Need

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Intermediate-Scale Experiments

- Examine Heterogeneous Systems
  - Permeability Variability
  - Non-uniform NAPL Distribution
  - Multiple Mass-transfer Processes
- Controlled/Well-defined Systems
  - Evaluate Flux vs. Mass Removal Behavior

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UA-PNNL Experiments

- Multiple methods to measure aqueous concentrations (mass flux):
  - Depth specific ports [e.g., multilevel sampling ports]
  - Vertically integrated ports [e.g., fully screened MWs]
  - Flow-cell effluent [e.g., extraction well]
- Dual-energy gamma system to measure NAPL saturation in-situ (mass removal)
- Additional characterization methods:
  - Non-reactive tracer test
  - Dye tracer test
  - Visualization of dyed TCE

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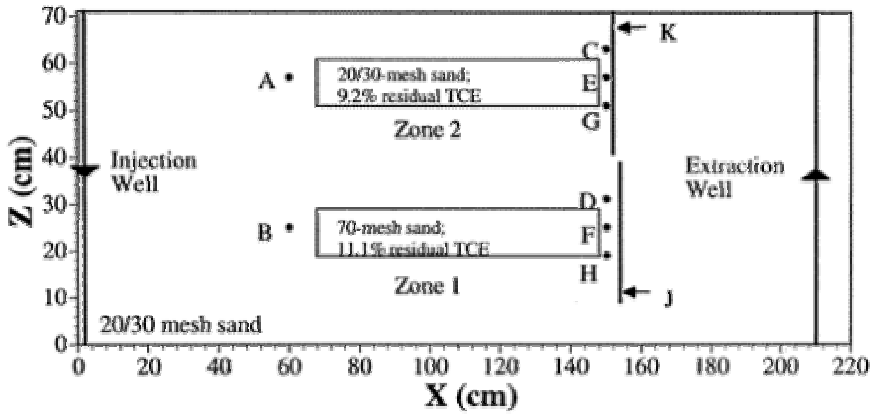
Flow-cell Schematic



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Flow Cell

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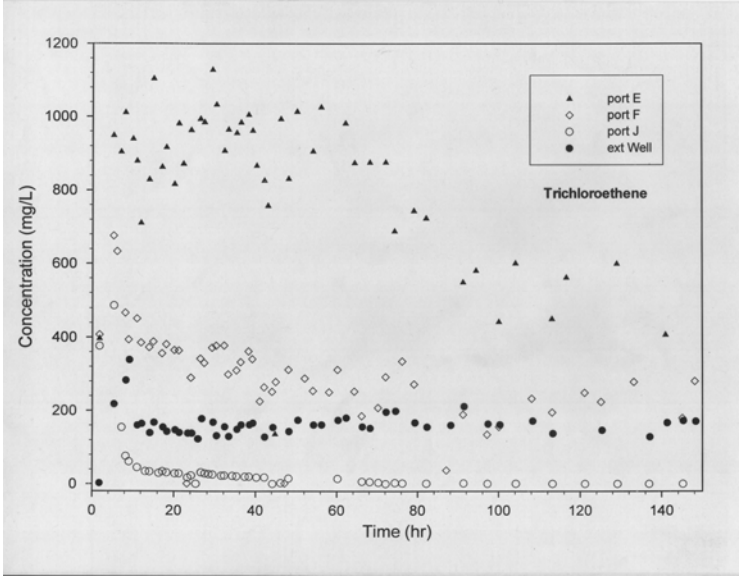
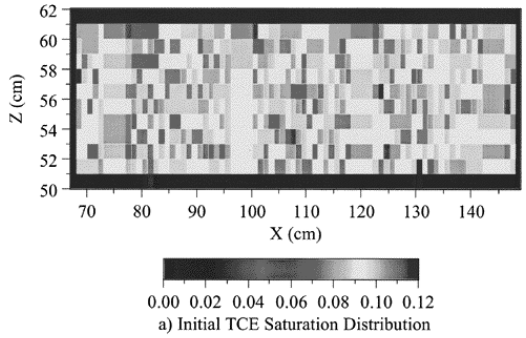
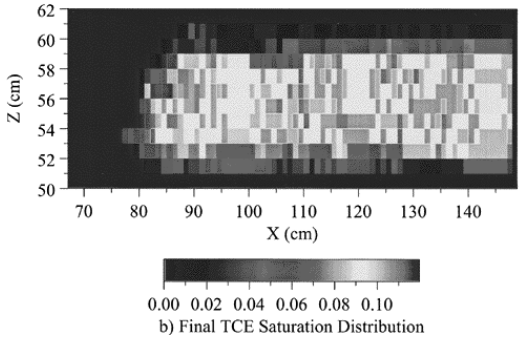
TCE Concentrations





a) Initial TCE Saturation Distribution



b) Final TCE Saturation Distribution

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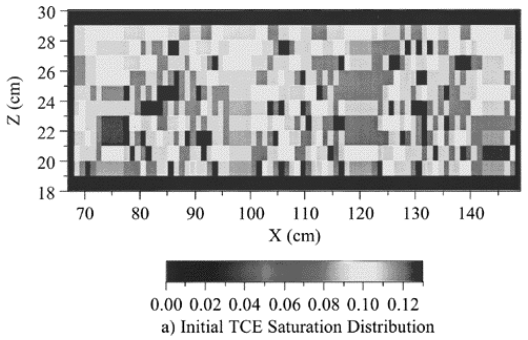
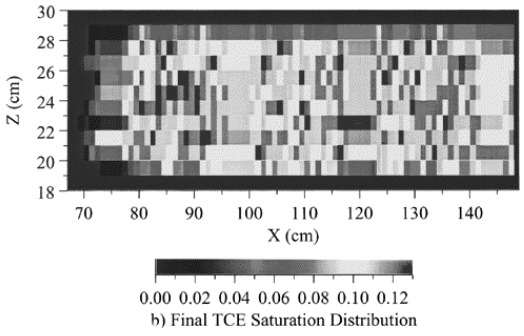


a) Initial TCE Saturation Distribution



b) Final TCE Saturation Distribution

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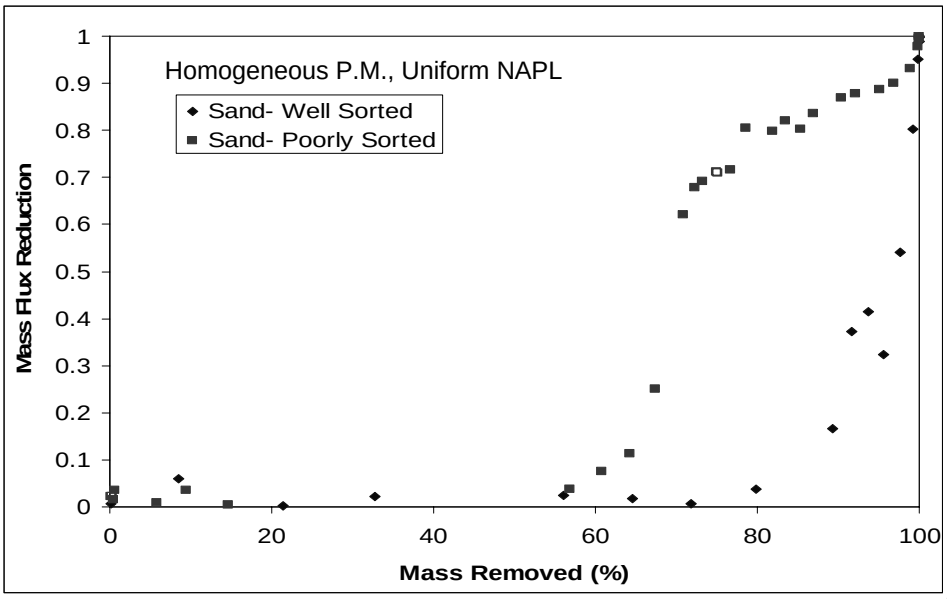
Mass Flux-Mass Removal



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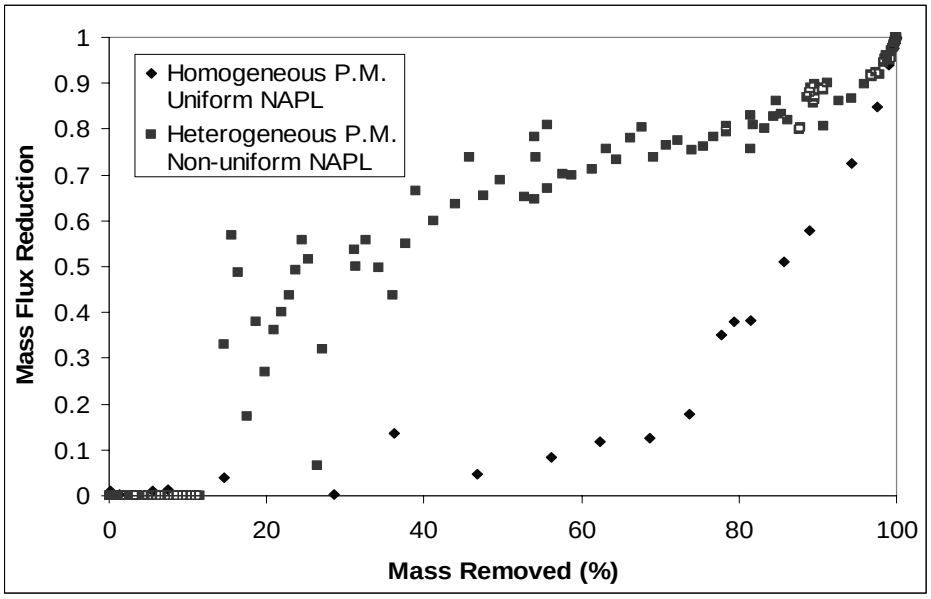
Mass Flux-Mass Removal



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Pore-scale Research

- Topics:
  - Multi-phase Fluid Displacement
  - Wetting/Non-wetting Fluid Distributions
  - Fluid-Fluid Interfacial Areas
  - Mass-transfer Processes

- Methods:
  - High-Resolution Imaging--- MRI/NMR; X-ray
  - Pore-scale Modeling--- Network, Lattice-Boltzmann

GeoSoilEnviroCARS

- Synchrotron-based research facility at the Advanced Photon Source, Argonne, IL
- Supported by NSF, DOE, State of Illinois

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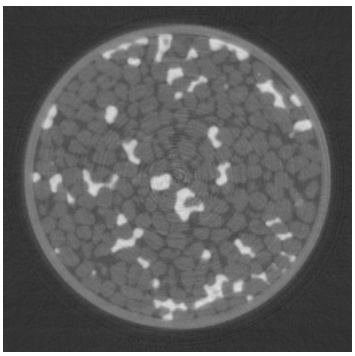
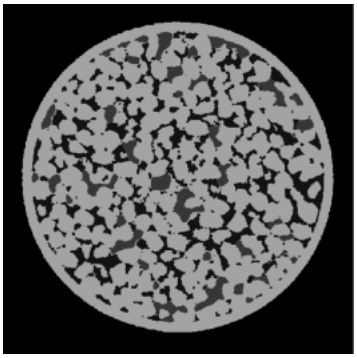
Synchrotron X-ray CT Images



Solids = dark gray,
Water = black,
NAPL = white



Solids = gray,
Water = blue,
NAPL = red

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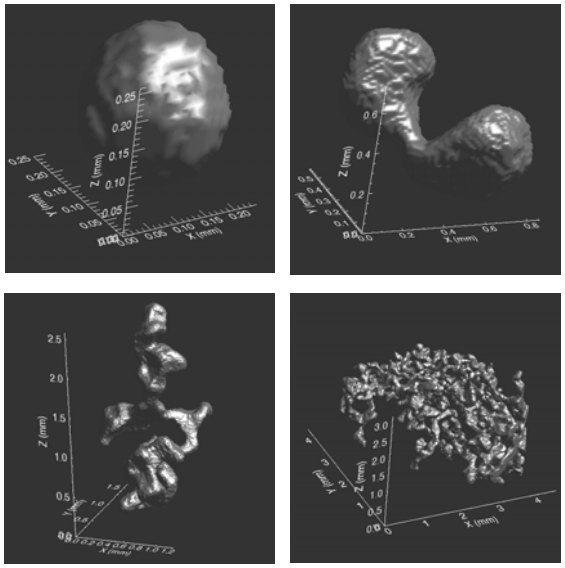
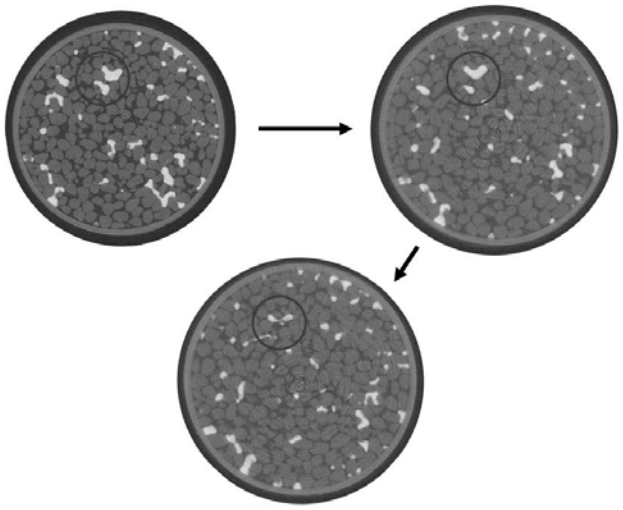
Examples of NAPL Ganglia



Time Series



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Acknowledgements

- NIEHS SBRP

- Greg Schnaar, Justin Marble, Colleen McColl, Michele Mahal, Mart Oostrom

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Measurement and Use of Contaminant Flux as an Assessment Tool for DNAPL Remedial Performance

A. Lynn Wood
Michael C. Brooks

U.S. EPA/ORD/NRMRL

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Measuring Contaminant Mass Flux in the Field

Methods:

- Multi-Level Sampler (MLS) Transects
- Passive Flux Meters (PFM)
- Horizontal Flow Treatment Wells (HFTWs)
- Integral Pumping Test (IPT)
- Modified Integral Pumping Test (MIPT)

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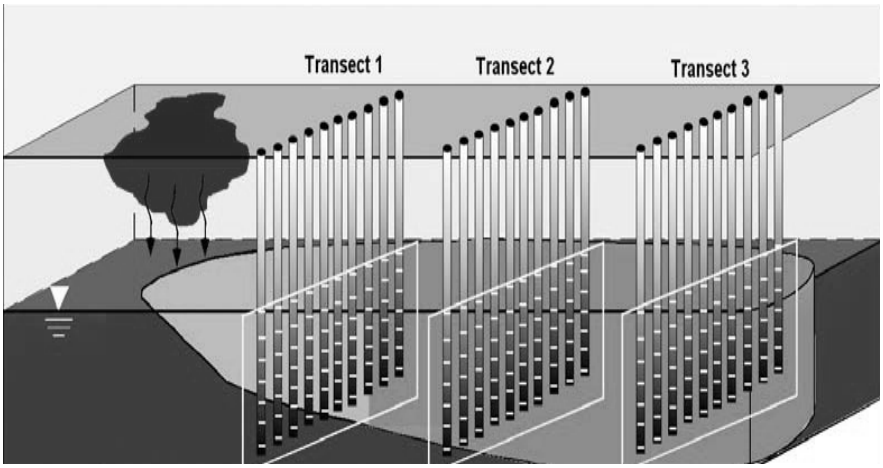
Contaminant Flux Estimates by MLS Transects

(from Newell *et al*., 2003)



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MLS Transect Method

- Advantages:
  - Generates spatial information on concentration distributions
  - Methods exist to estimate uncertainty
  - Small waste volumes produced
  - Conventional
- Disadvantages:
  - Requires independent estimation of water flux
  - Contaminant measures are instantaneous
  - Interrogates small volumes of aquifer
  - Data must be spatially integrated to obtain contaminant mass flows

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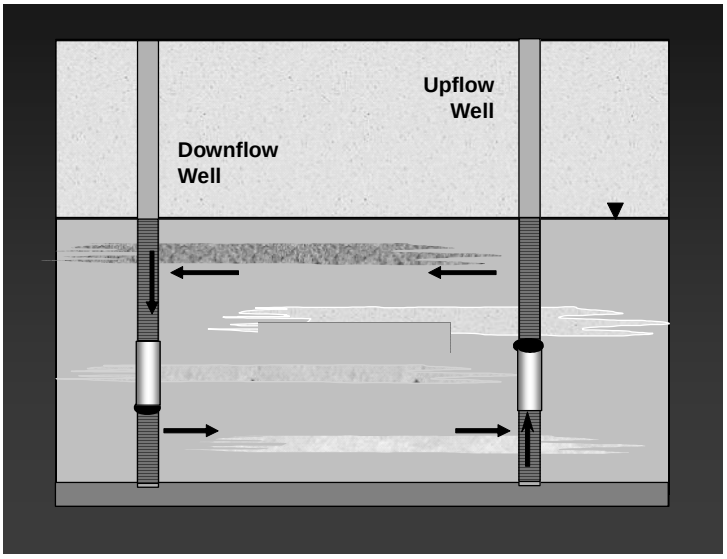
Contaminant Mass Flux Measurements by Horizontal Flow Treatment Wells (HFTWs)

(from Huang *et al.* 2004 and Goltz *et al.* 2004)



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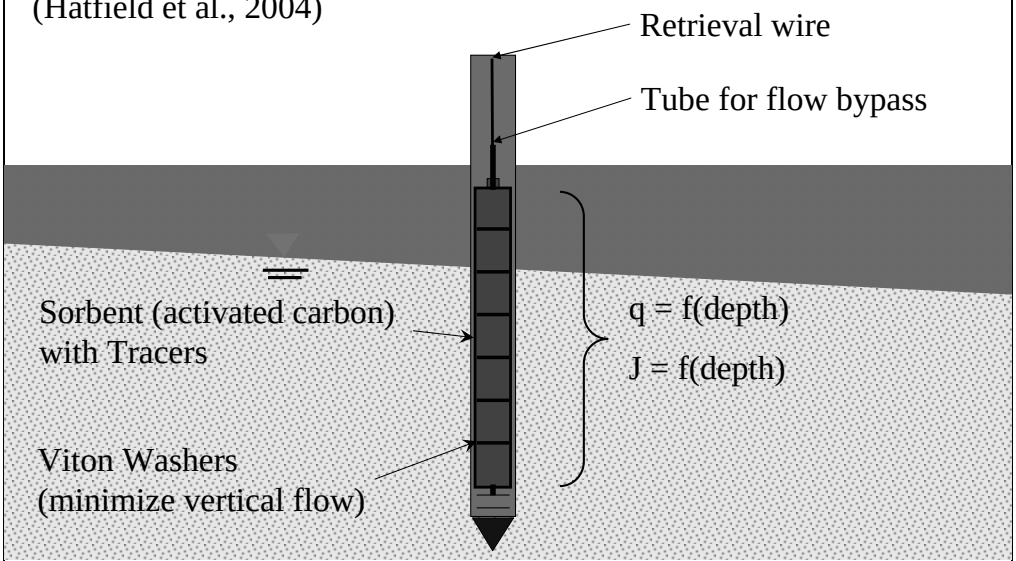
Horizontal Flow Treatment Well (HFTW) Method

- Advantages:
  - Generates water flux and contaminant mass flux estimates
  - Interrogates large volumes of aquifer
  - Can be used in deep aquifers
  - Does not extract groundwater
  - Can estimate horizontal and vertical aquifer conductivities
- Disadvantages:
  - Does not provide spatial information (difficult to quantify uncertainty)
  - Assumes aquifer is homogeneous
  - Uses tracers to estimate interflow
  - Does not function in all wells
  - Underestimates maximum resident contaminant concentrations

Passive Flux Meters

(Hatfield et al., 2004)



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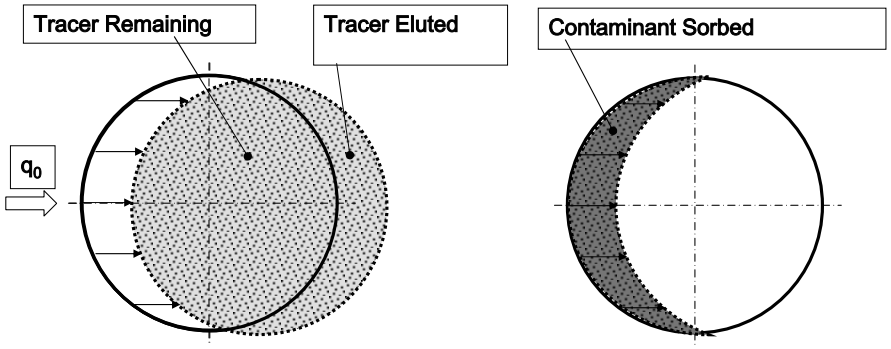
Passive Flux Meter Concepts

Water Flux

Contaminant Flux



(Hatfield et al., 2004)

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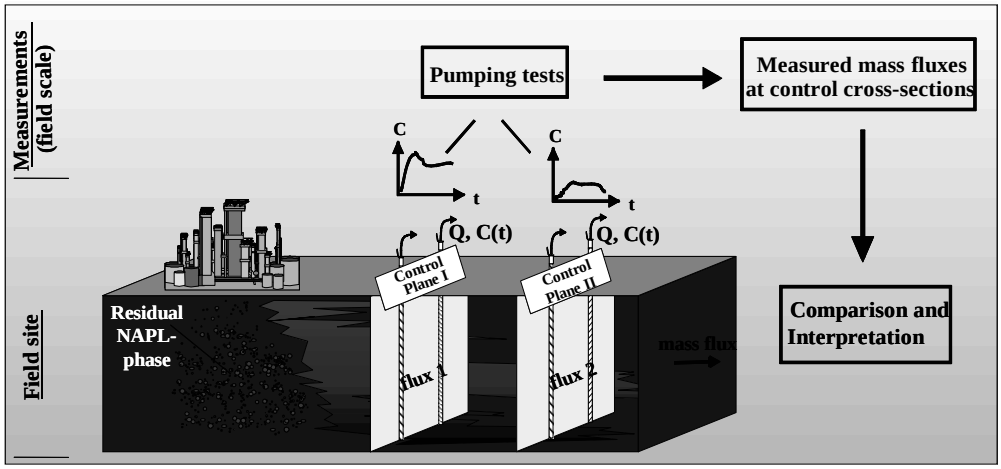
Passive Flux Meter Method

- Advantages:
  - Generates spatial information on cumulative water and contaminant mass flux
  - Methods exist to estimate uncertainty
  - Generates local estimates of horizontal aquifer conductivity
  - Small waste volumes are produced
  - Passive
  - Inexpensive

- Disadvantages:
  - Interrogates small volumes of aquifer
  - Data must be spatially integrated to obtain contaminant mass flows and total water discharge
  - Uses resident tracers to estimate groundwater flux
  - Does not function in all wells

Integral Pumping Test

(Bockelmann *et al.* 2001, 2003; Schwarz et al., 1998; Teutsch et al. 2000; Ptak et al. 2000)



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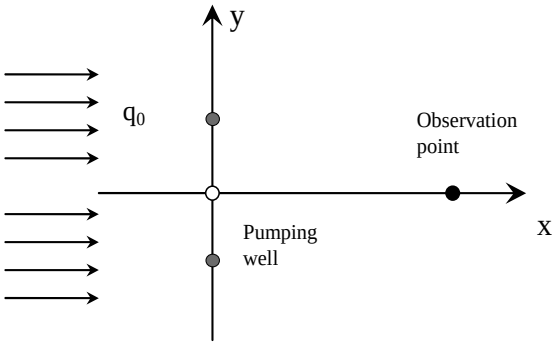
Integral Pumping Method

- Advantages:
  - Generates contaminant mass flow estimates
  - Interrogates large volumes of aquifer
  - Can be used in deep aquifers
- Disadvantages:
  - Costly (wastewater disposal)
  - Requires lengthy time execution
  - Assumes aquifer is homogeneous
  - Does not estimate water flux
  - Does not provide spatial information (difficult to quantify uncertainty)
  - Subject to the limitations of sampling configuration
  - Underestimates maximum resident contaminant concentrations

Modified Integral Pumping Test



$$J = q_0 c$$

Interpreted from concentration –time series

Estimate q_0 directly from IPT results

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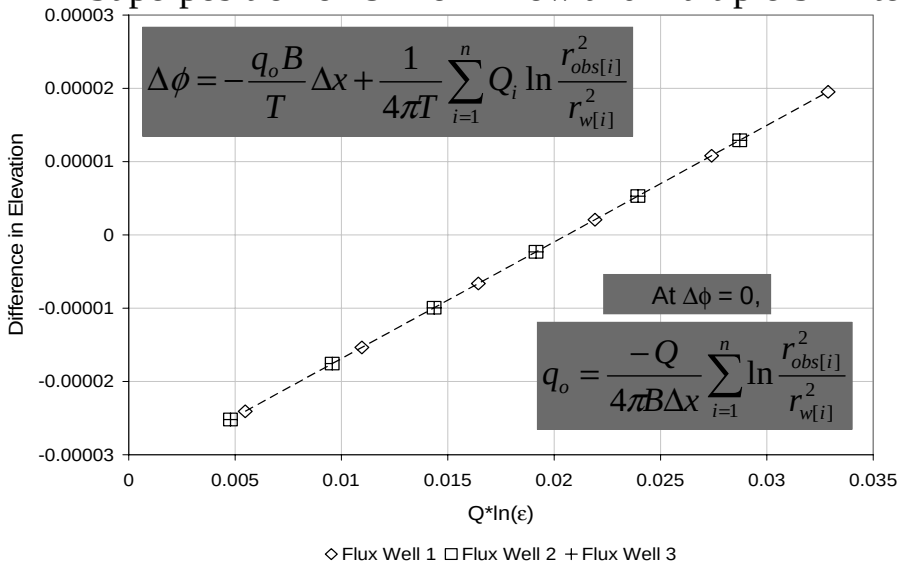
Modified Integral Pumping Test

Superposition of Uniform flow and multiple Sink terms



$$\Delta\phi = -\frac{q_o B}{T}\Delta x + \frac{1}{4\pi T}\sum_{i=1}^{n} Q_i \ln\frac{r_{obs[i]}^2}{r_{w[i]}^2}$$

At $\Delta\phi = 0$,

$$q_o = \frac{-Q}{4\pi B \Delta x}\sum_{i=1}^{n} \ln\frac{r_{obs[i]}^2}{r_{w[i]}^2}$$

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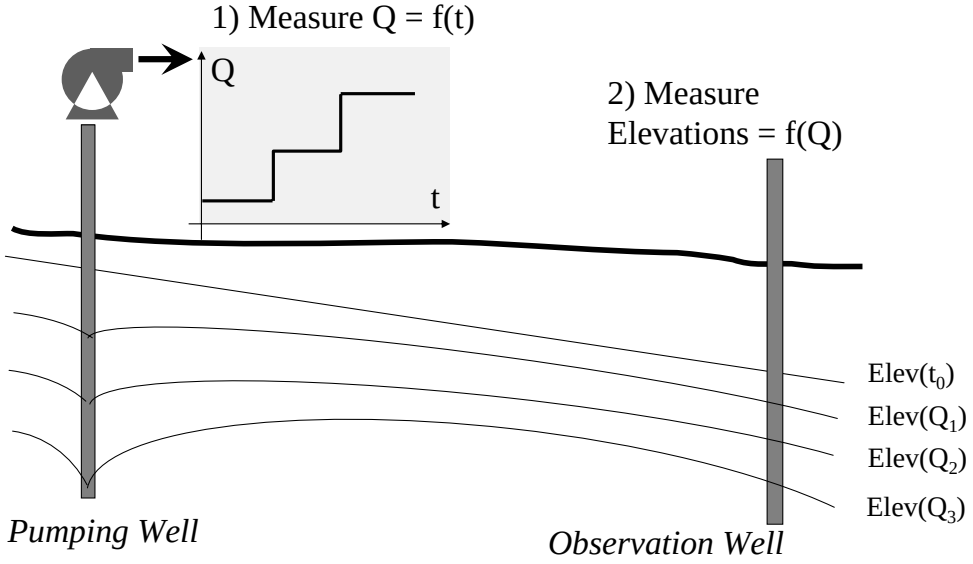
Modified Integral Pumping Test



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Modified Integral Pumping Method

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  - Subject to the limitations of sampling configuration
  - Underestimates maximum resident contaminant concentrations

Assessing DNAPL Source Remediation Performance

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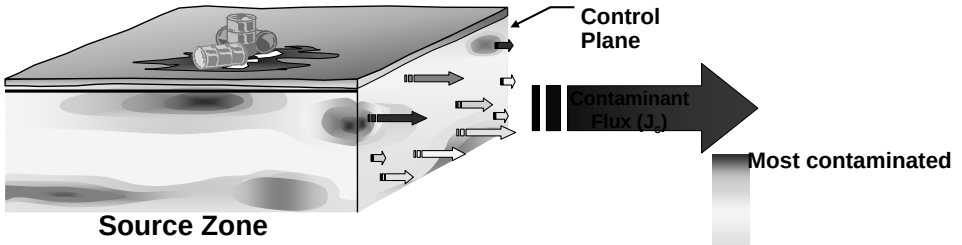
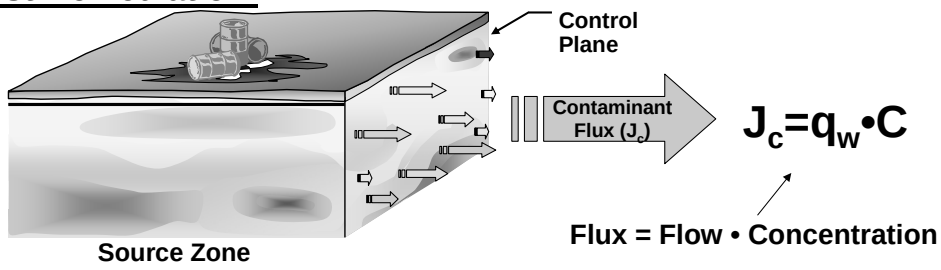
Source Remediation = Contaminant Flux Management

Pre-Remediation:



Post-Remediation:



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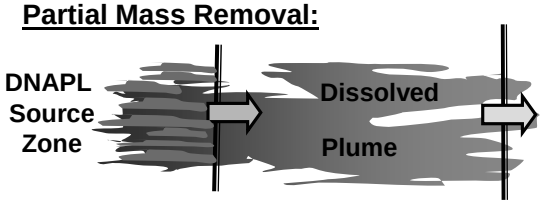
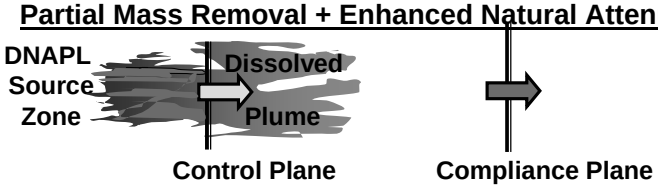
MASS DEPLETION RESPONSE

Pre-Remediation:

Partial Mass Removal:



Partial Mass Removal + Enhanced Natural Attenuation:



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Field Demonstrations

Impacts of DNAPL Source Zone Treatment: Experimental and Modeling Assessment of Benefits of Partial Source Removal

…assess the benefits of aggressive in situ DNAPL source-zone remediation

Laboratory Experiments

Mathematical Modeling

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Project Team

- Mike Annable – University of Florida
- Michael Brooks – EPA/ORD/NRMRL
- Ron Falta – Clemson University
- Mark Goltz – Air Force Institute of Technology
- Jim Jawitz – University of Florida
- Suresh Rao – Purdue University
- Lynn Wood – EPA/ORD/NRMRL

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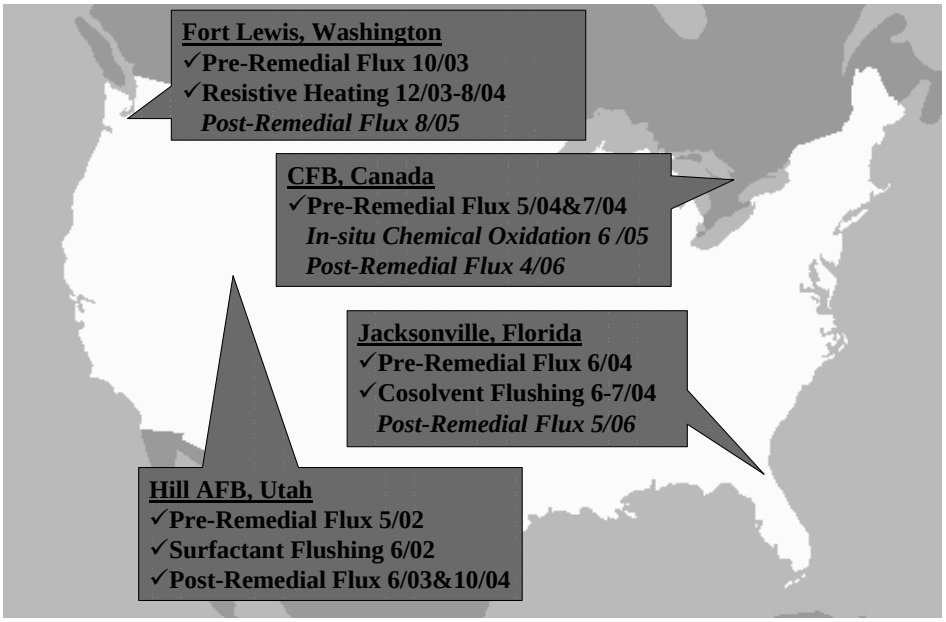
DNAPL Field Sites



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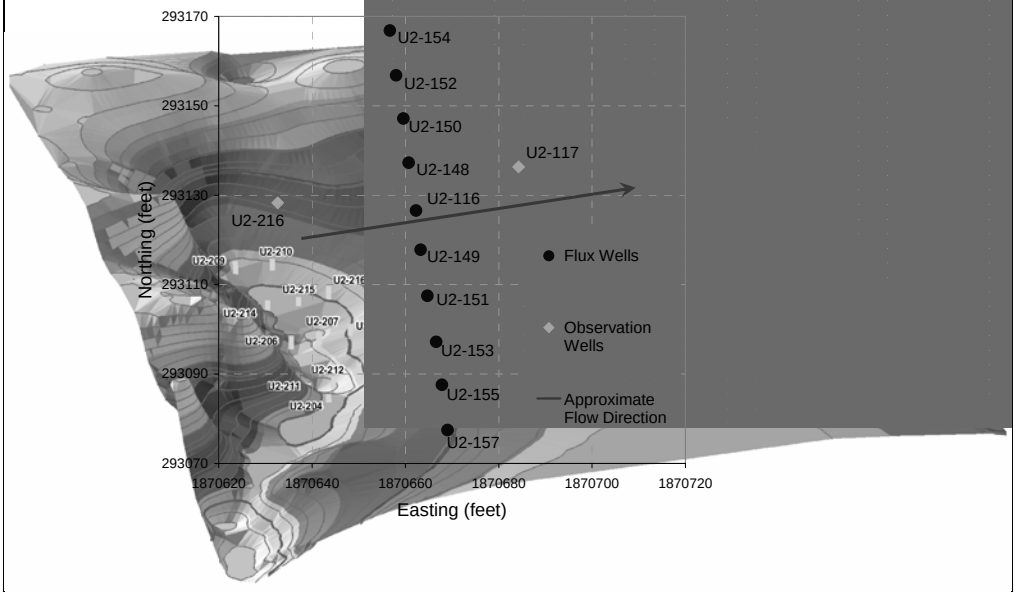
Hill AFB OU2 Layton, Utah



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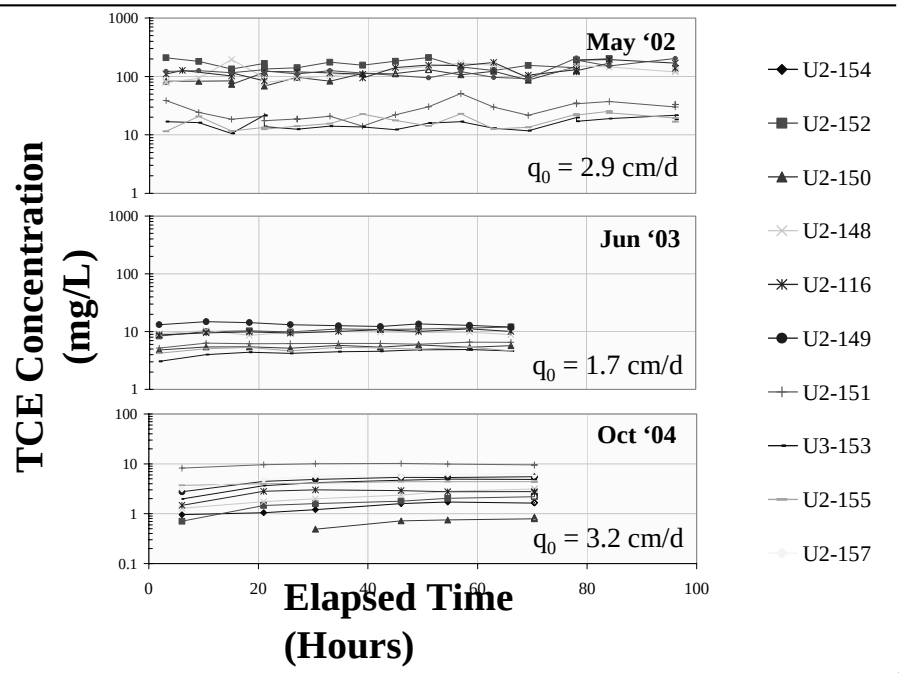
TCE Concentration Time Series



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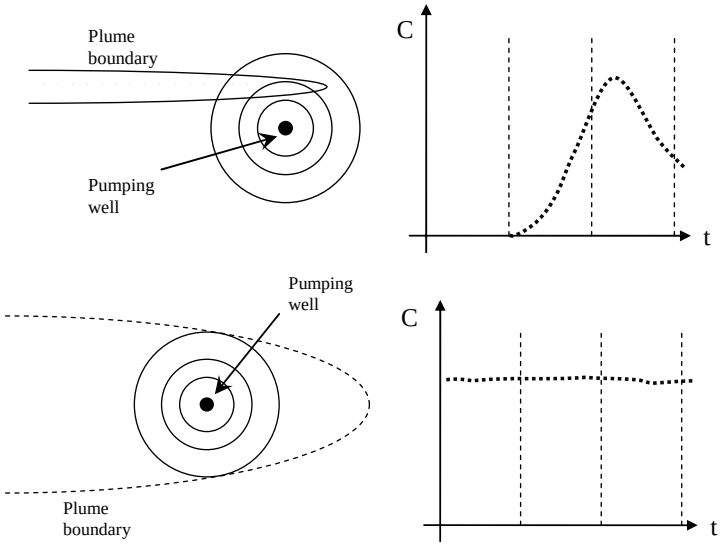
Interpretation of CT series



Adapted from Bockelmann et al. (2003)

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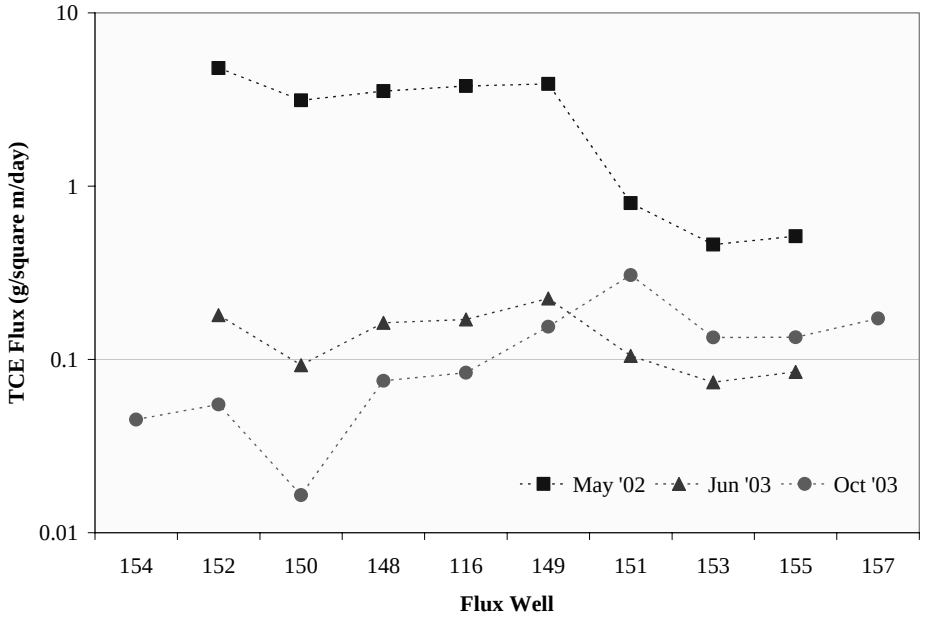
Hill AFB OU2 Layton, Utah TCE Flux Summary



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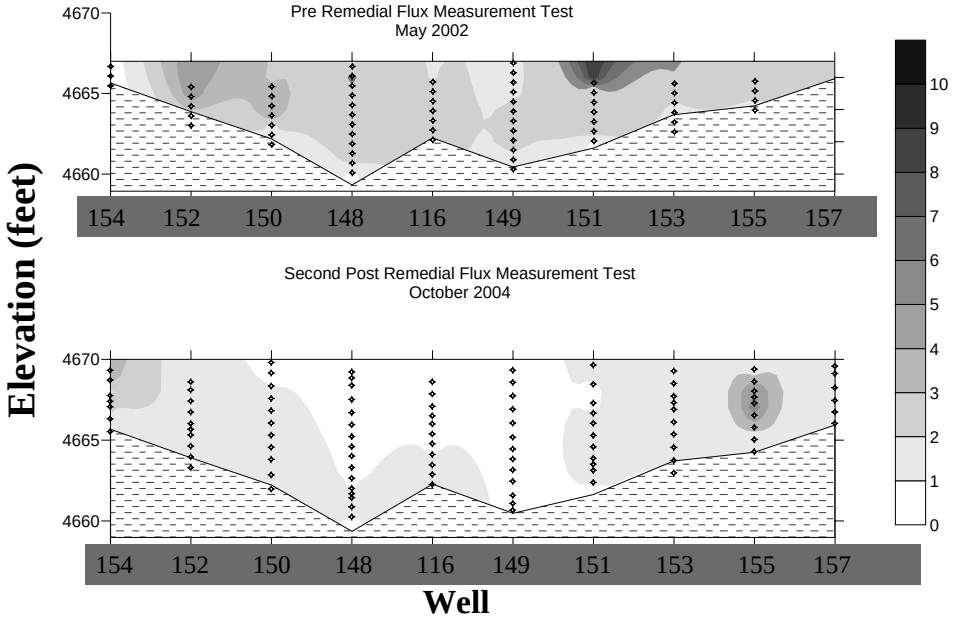
Flux Meter - Darcy Velocity (cm/day)



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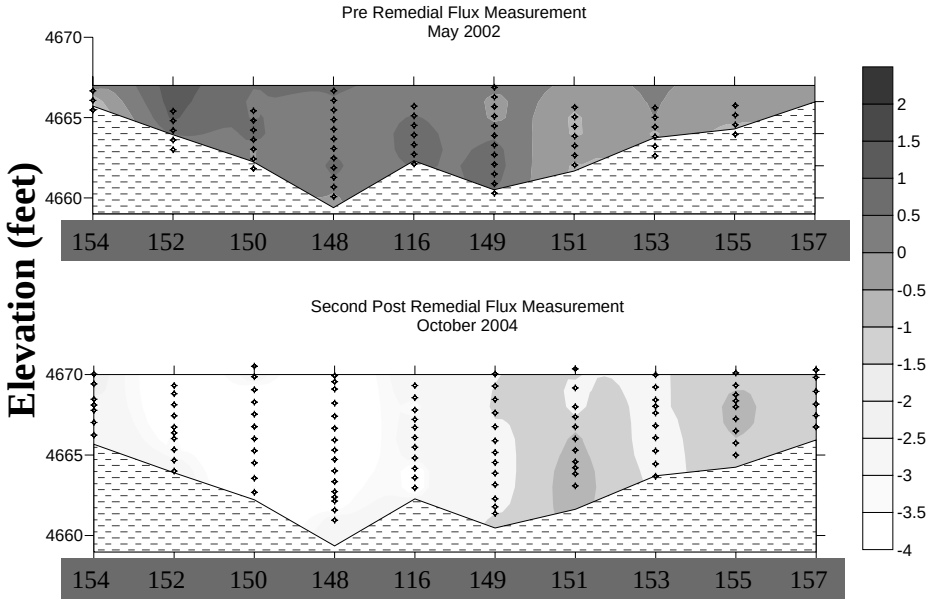
Flux Meter – Log TCE Flux (gram/square meter/day)



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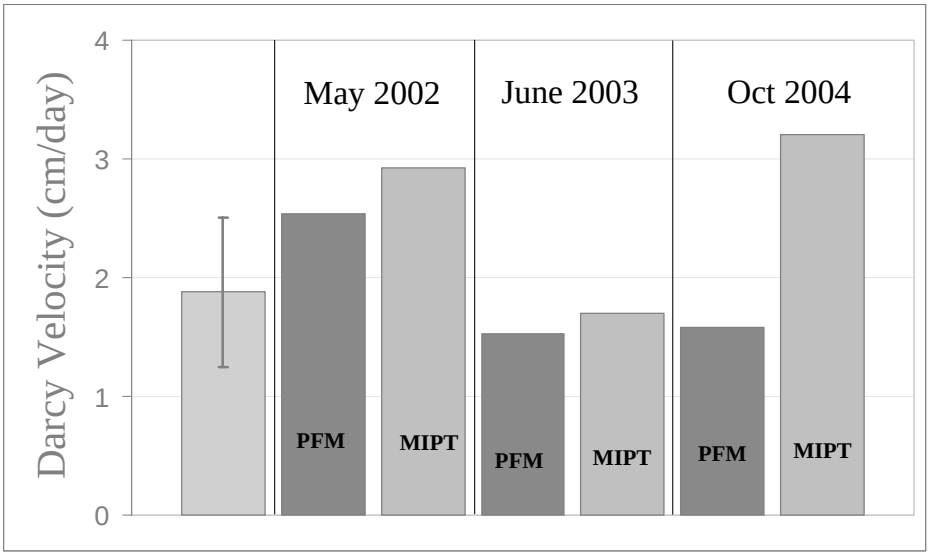
Hill AFB OU2 Layton, Utah
Darcy Velocity Comparison



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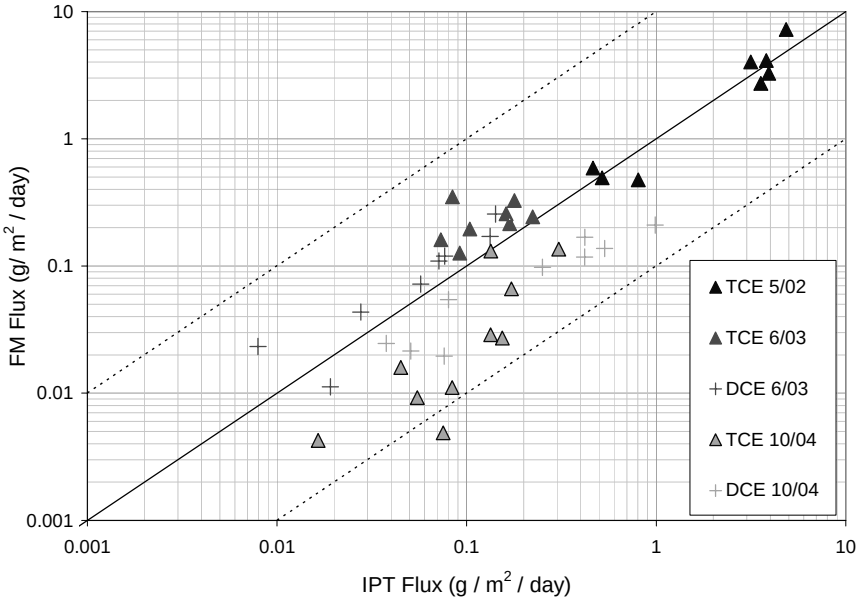
Well-Averaged Flux Summary



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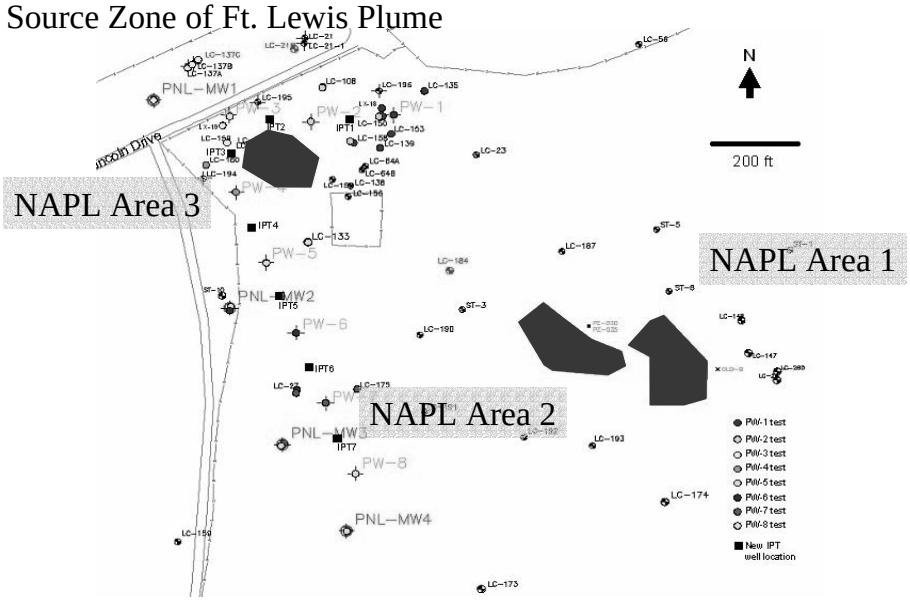
Fort Lewis EGDY Area 1 Tacoma, Washington

Source Zone of Ft. Lewis Plume



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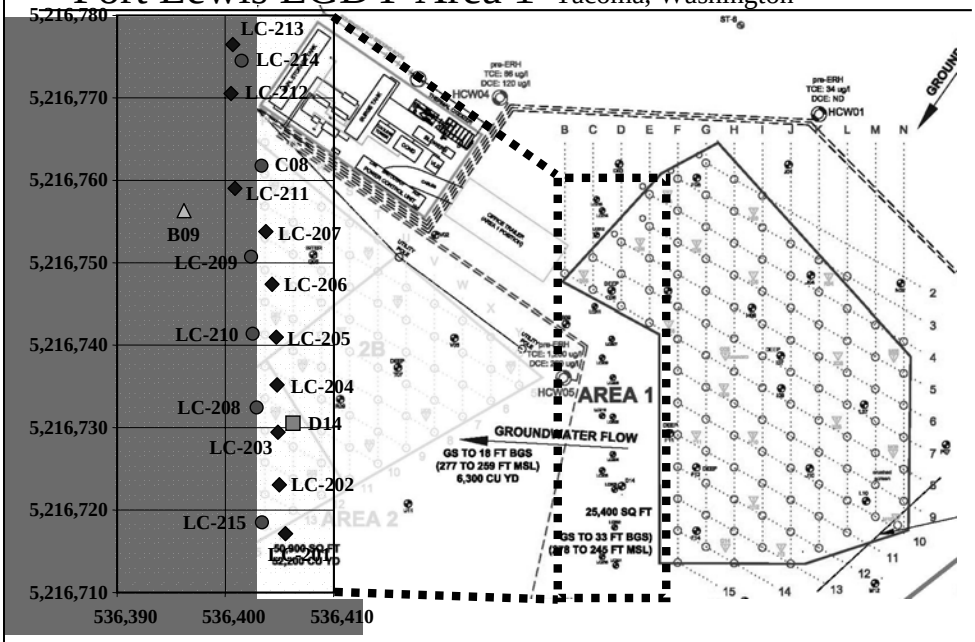
Fort Lewis EGDY Area 1 Tacoma, Washington



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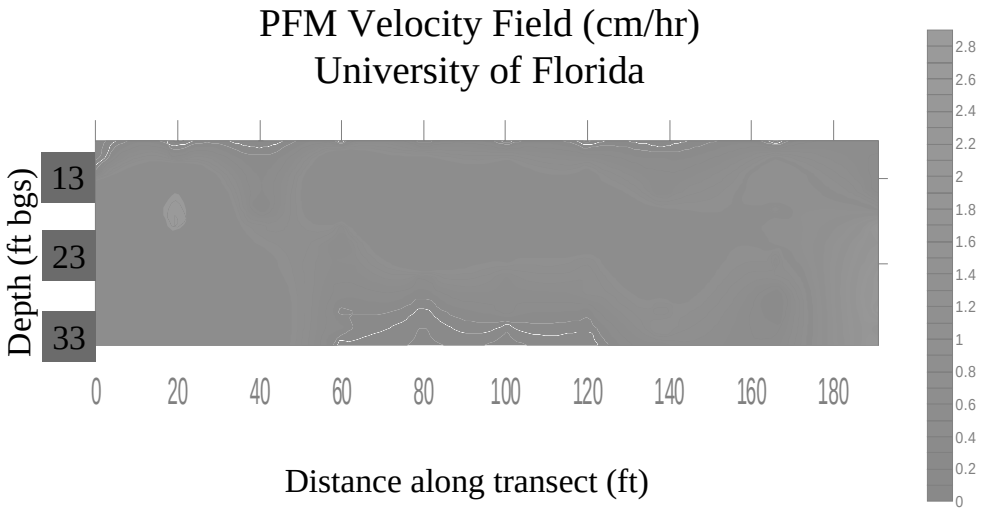
Fort Lewis EGDY Area 1 Tacoma, Washington



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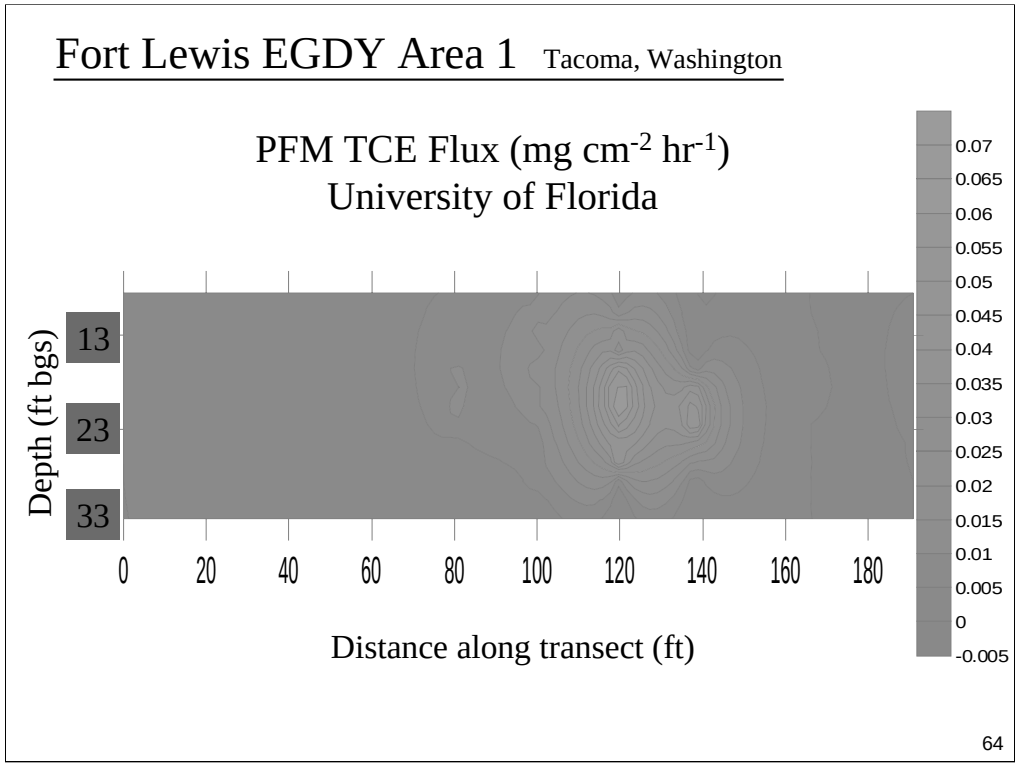
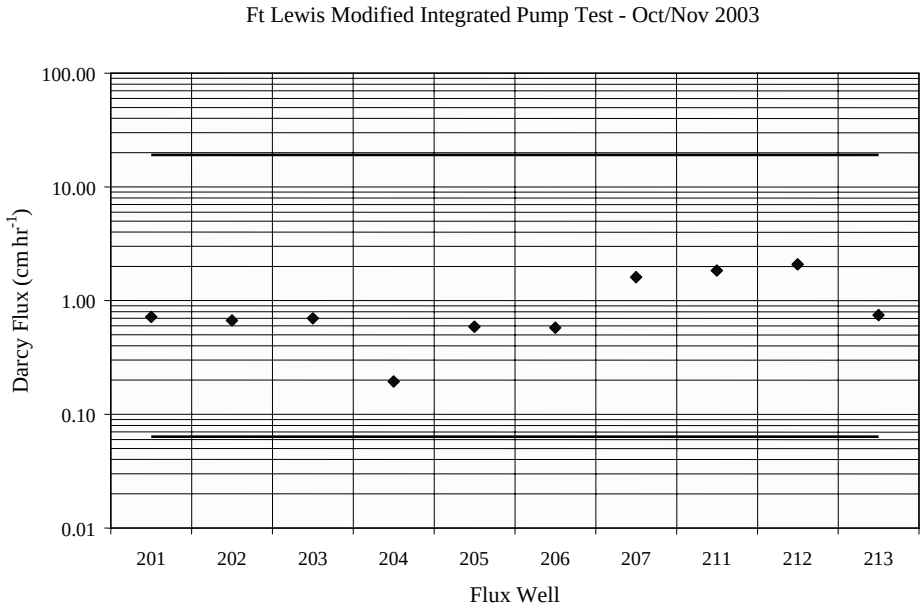


Range: <0.1 to 20 g/ sqm /day; Transect average 2 g / sqm / day.

Fort Lewis EGDY Area 1 Tacoma, Washington



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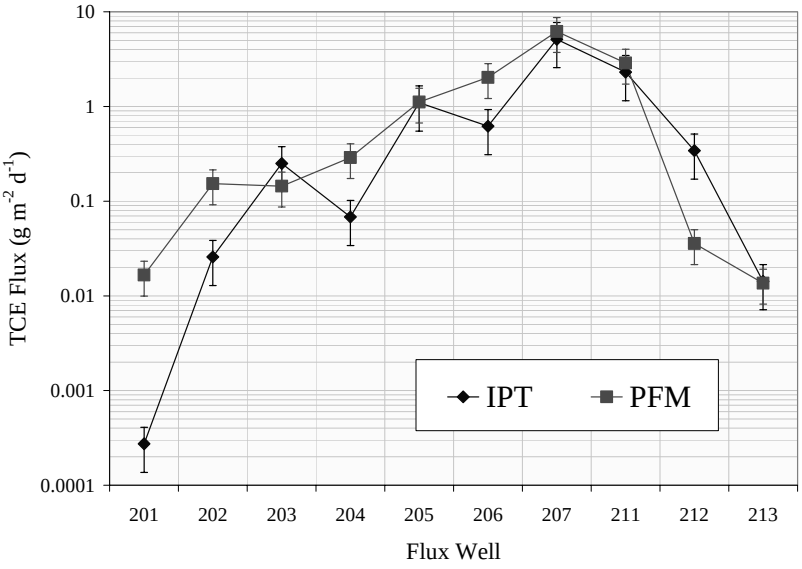
Fort Lewis EGDY Area 1 Tacoma, Washington

Average Pre-Remedial Flux, Oct/Nov 2003



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Summary

- Modified IPT method is being used to measure pre- and post-remedial flux
- Approximately an order of magnitude decrease in flux at Hill AFB
- Flux estimates based on flux meter and IPT methods to date are comparable

Acknowledgements

- Onsite Assistance
  - Hill AFB EMR/URS, Utah
  - LFR, Florida
  - US Army Corps of Engineers Seattle District/Fort Lewis Public Works, Washington
  - University of Waterloo, Canada

- Project Funding: Strategic Environmental Research and Development Program (SERDP)

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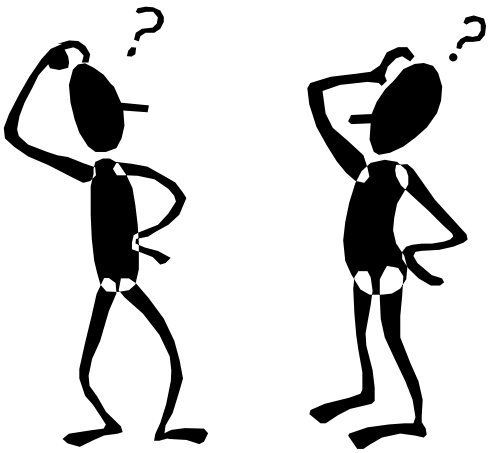

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Thank You

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