DNAPL Source Zones

Mark L. Brusseau
University of Arizona

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

2

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…

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.

5

Summary

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

6

Key Questions

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

7

Answers

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

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

9

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

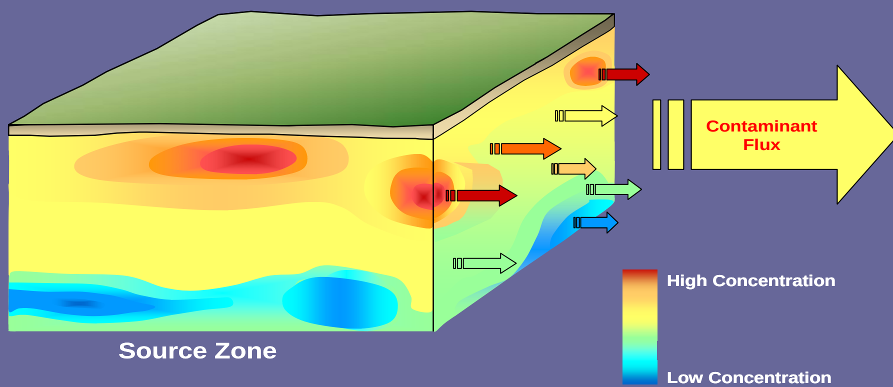
Continued

- 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

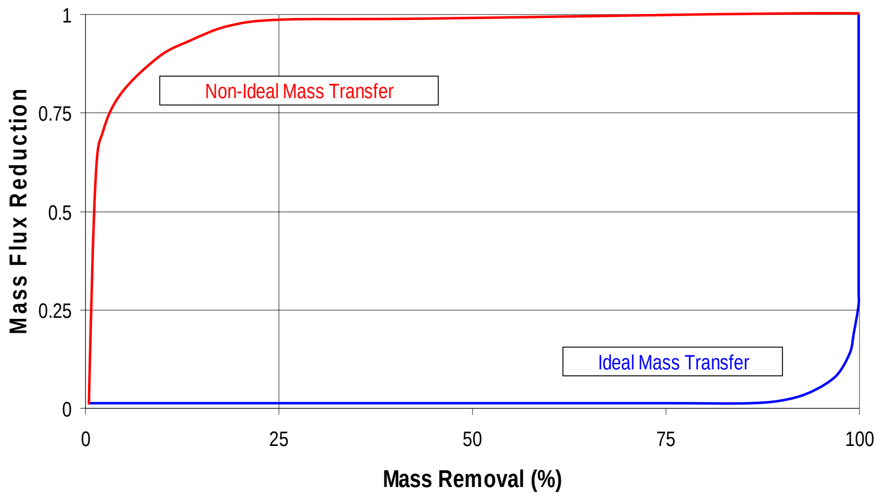
Mass Flux



Contaminant Flux
High Concentration
Low Concentration
Source Zone

12

Flux Reduction vs. Mass Removal



13

Factors Influencing Mass Flux

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

14

Measuring Mass Flux

- Measuring Mass Flux in the Field
- Lynn Wood Presentation

15

Predicting Mass Flux Reduction

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

16

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

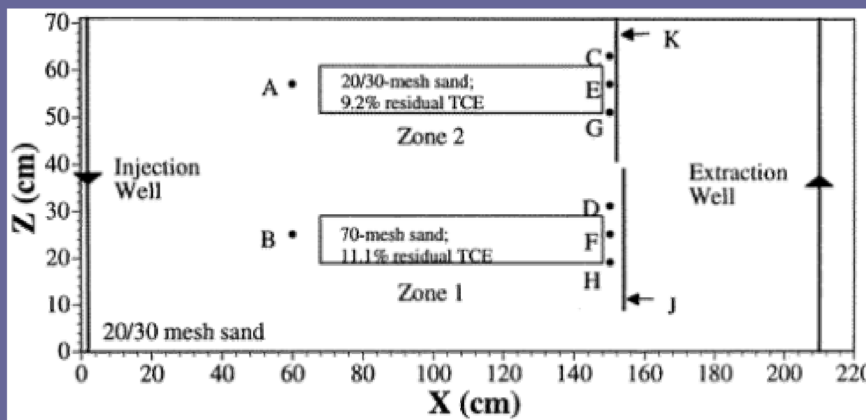
17

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

18

Flow-cell Schematic

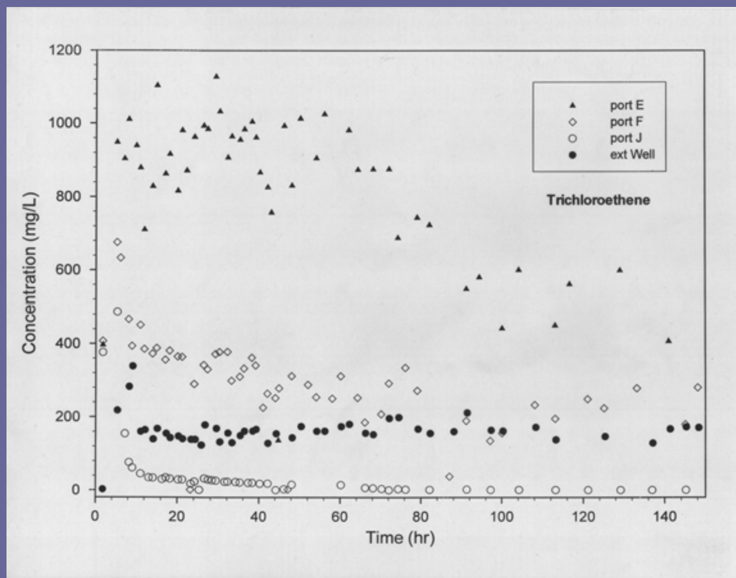


19

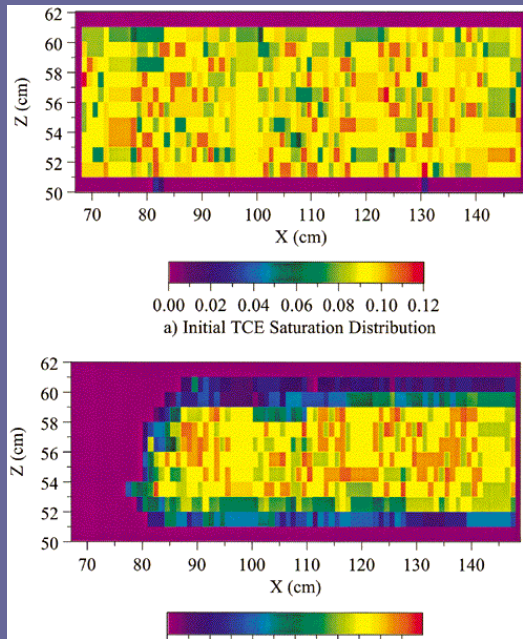
Flow Cell

20

TCE Concentrations

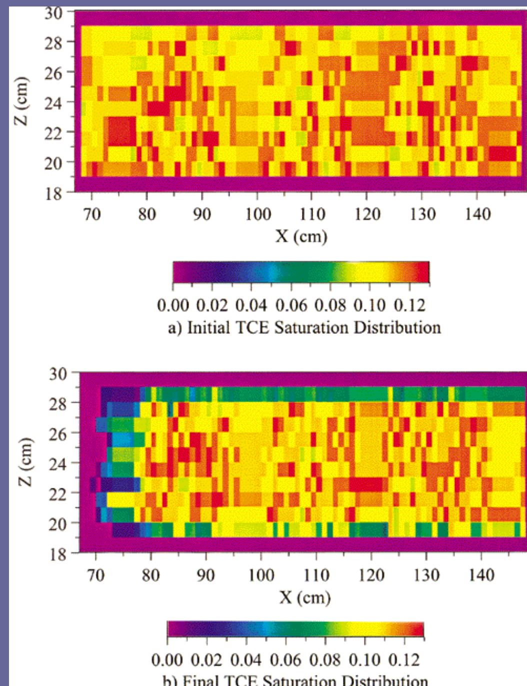


21



a) Initial TCE Saturation Distribution

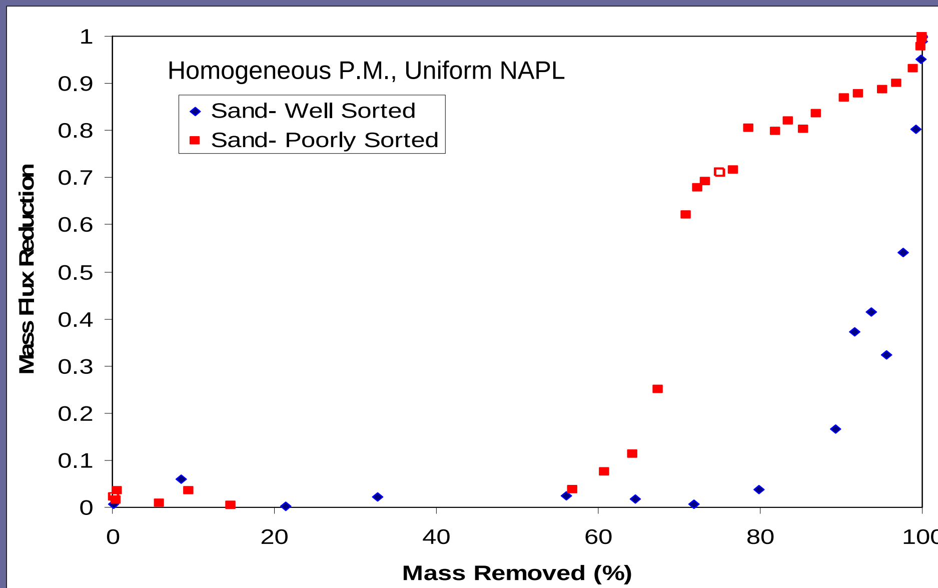
b) Final TCE Saturation Distribution



a) Initial TCE Saturation Distribution

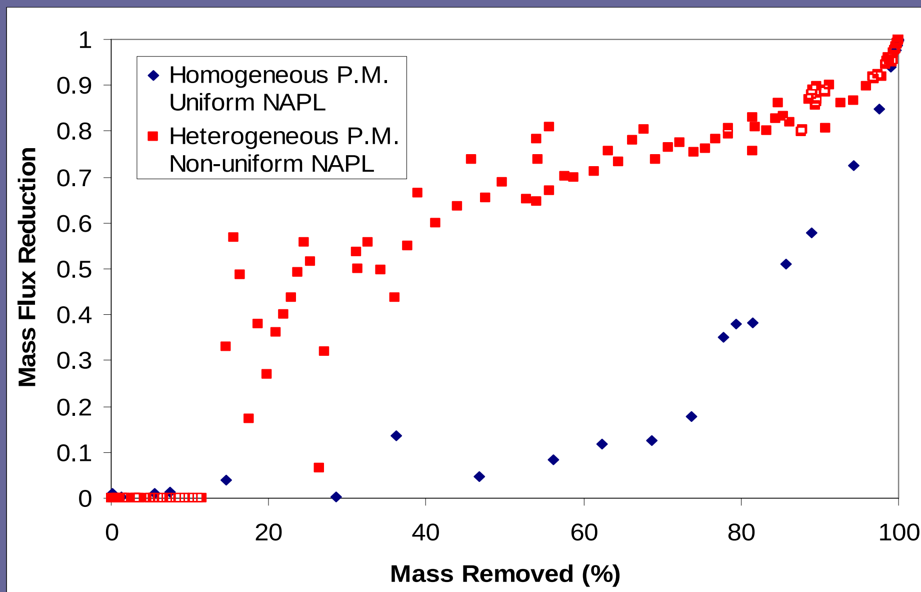
b) Final TCE Saturation Distribution

Mass Flux-Mass Removal



24

Mass Flux-Mass Removal



25

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

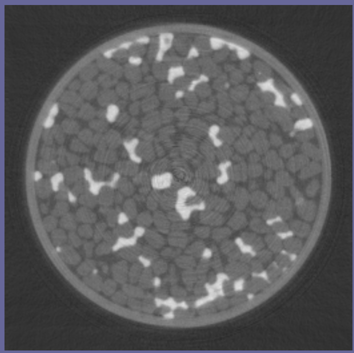
26

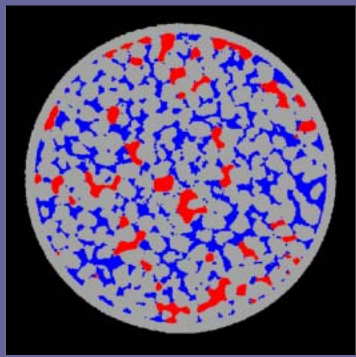
GeoSoilEnviroCARS

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

27

Synchrotron X-ray CT Images

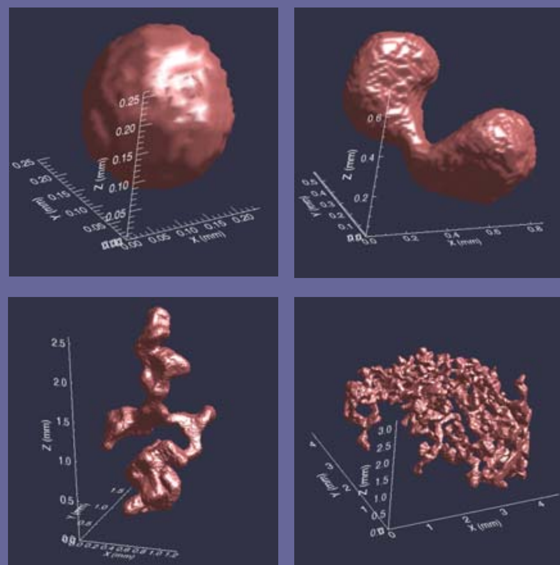




Solids = dark gray,
Water = black,
NAPL = white

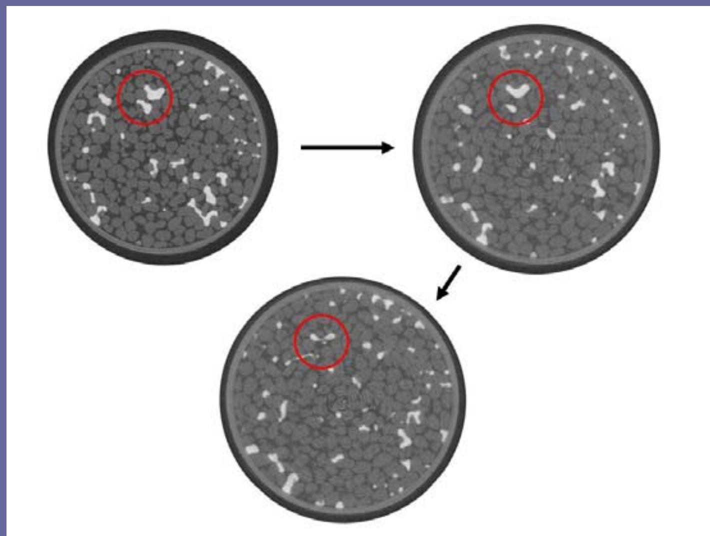
Solids = gray,
Water = blue,
NAPL = red

Examples of NAPL Ganglia



29

Time Series



30

Acknowledgements

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

31

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

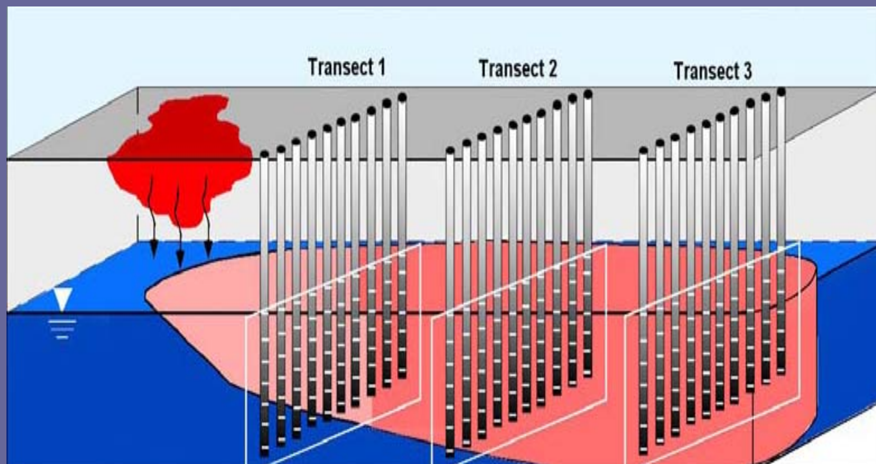
32

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)

Contaminant Flux Estimates by MLS Transects
(from Newell *et al*., 2003)



34

MLS Transect Method

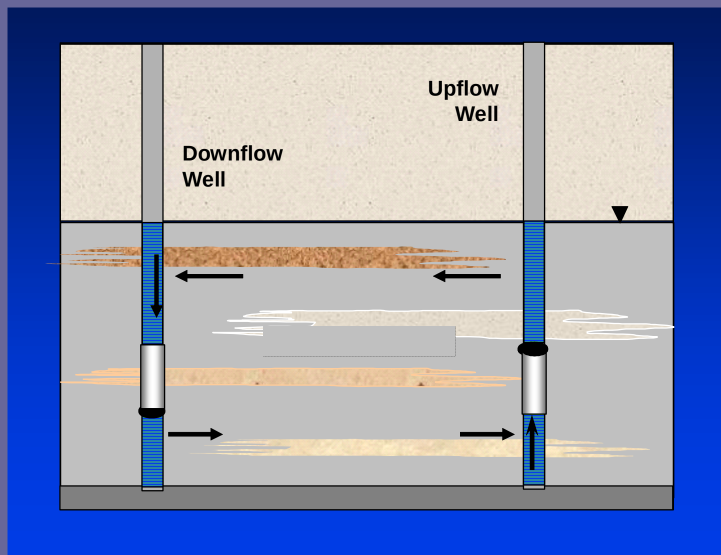
- Advantages:
  - Generates spatial information on concentration distributions
  - Methods exist to estimate uncertainty
  - Small waste volumes produced
  - Conventional

- 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

35

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

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

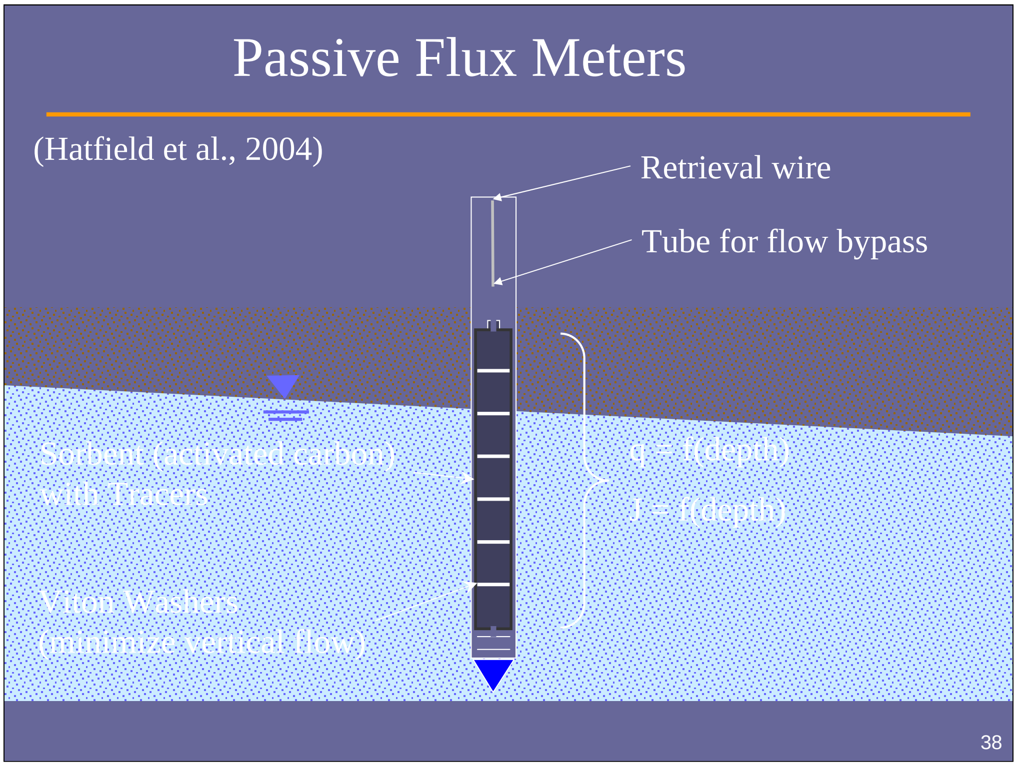


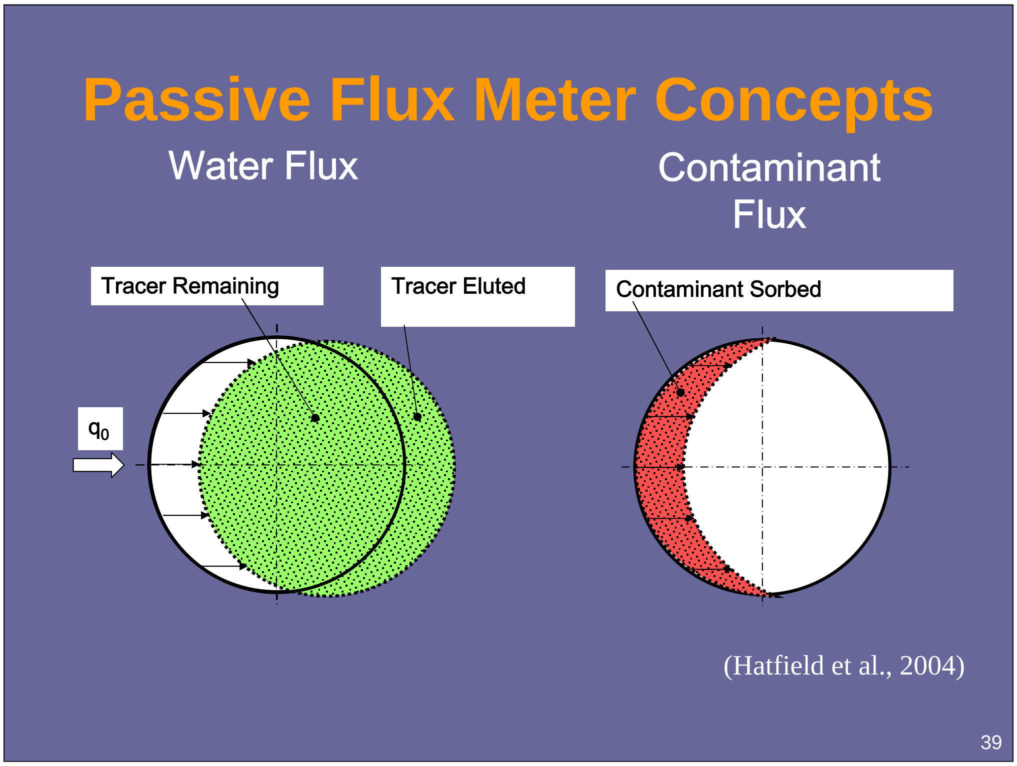
36

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

37


Passive Flux Meters
(Hatfield et al., 2004)
Retrieval wire
Tube for flow bypass
Sorbent (activated carbon)
with Tracers
Viton Washers
(minimize vertical flow)
q = f(depth)
J = f(depth)
38


Passive Flux Meter Concepts
Water Flux
Contaminant Flux
Tracer Remaining
Tracer Eluted
Contaminant Sorbed
q0
(Hatfield et al., 2004)
39

Passive Flux Meter Method

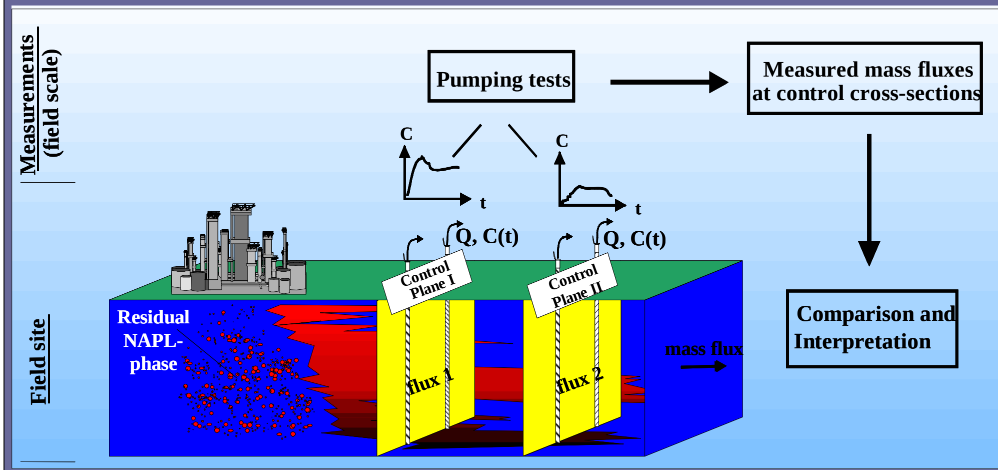
- Advantages:
  - Generates spatial information on cumulative water and contaminant mass flux
  - Methods exist to estimate uncertainty
  - Generates local estimates of horizontal aquifer conductivity
  - Small waste volumes are produced
  - Passive
  - Inexpensive

- 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

40

Integral Pumping Test

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



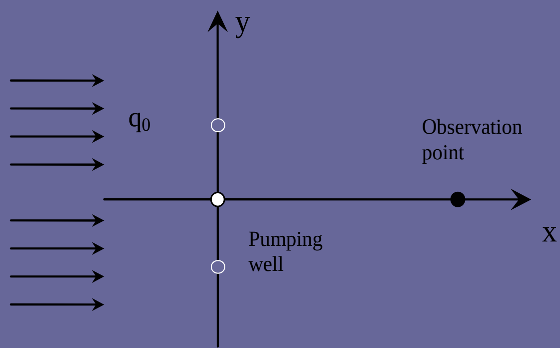
41

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

42

Modified Integral Pumping Test



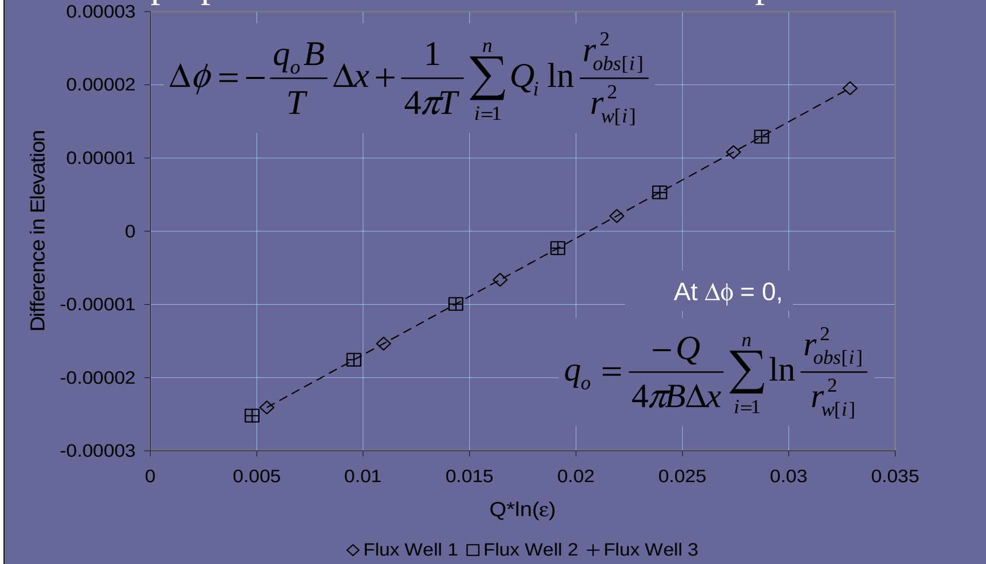
$$J = q_0 c$$

Interpreted from concentration –time series

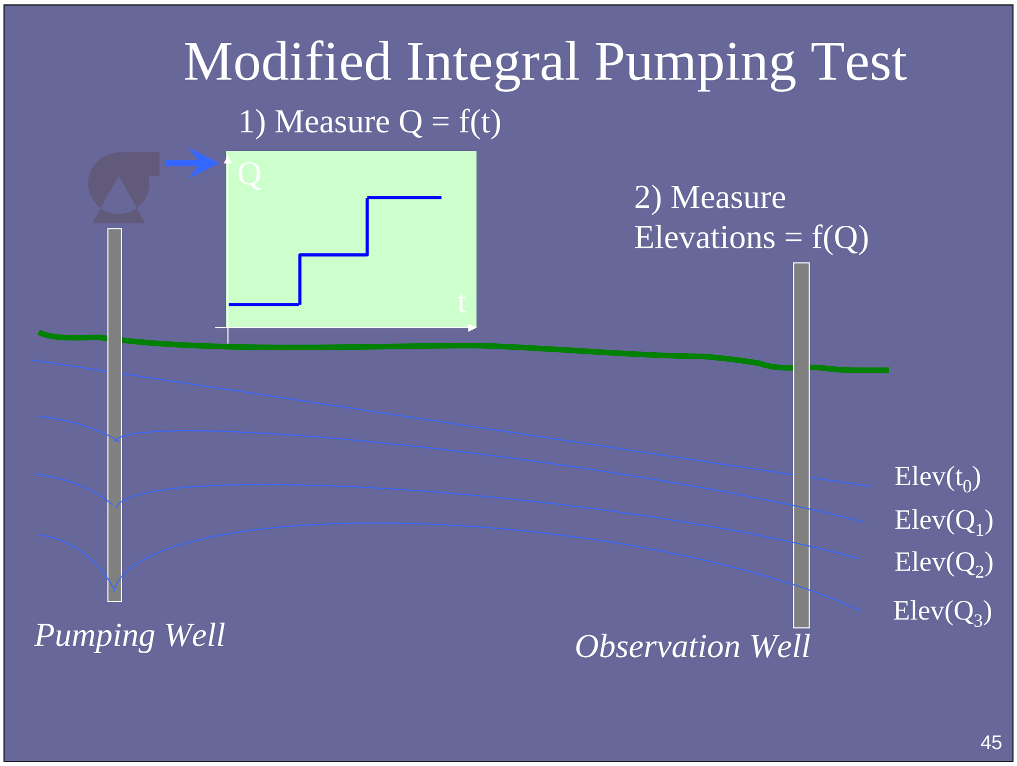
Estimate q_0 directly from IPT results

Modified Integral Pumping Test

Superposition of Uniform flow and multiple Sink terms



44

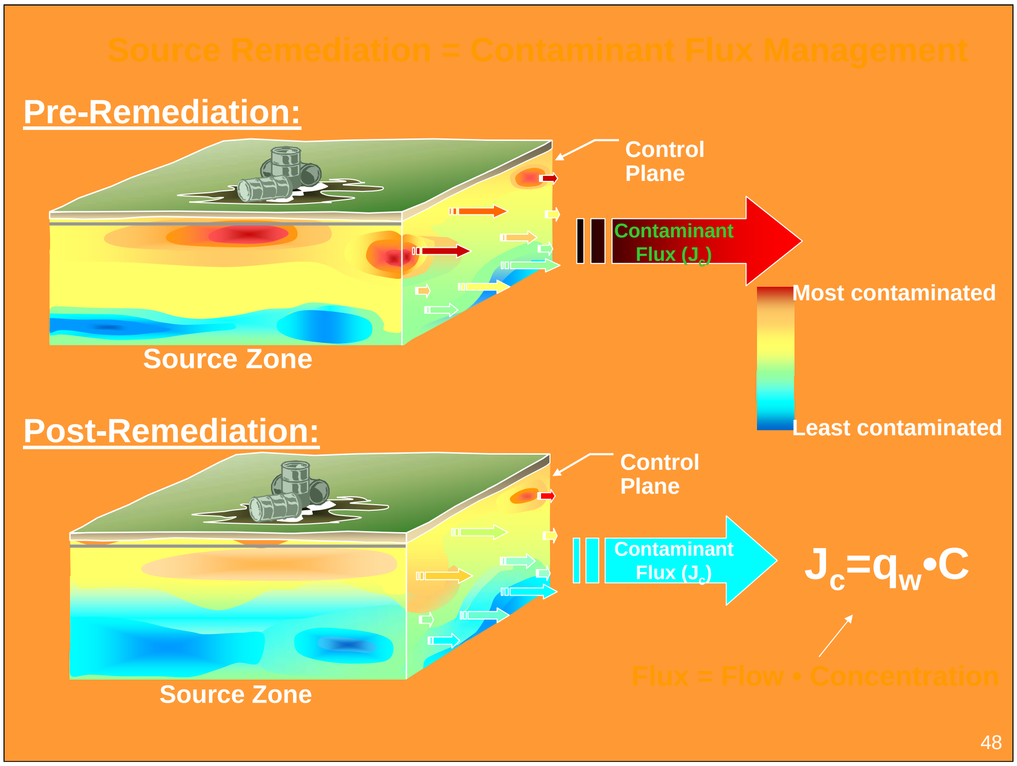

Modified Integral Pumping Test
1) Measure Q = f(t)
Q
t
2) Measure
Elevations = f(Q)
Elev(t0)
Elev(Q1)
Elev(Q2)
Elev(Q3)
Pumping Well
Observation Well
45

Modified Integral Pumping Method

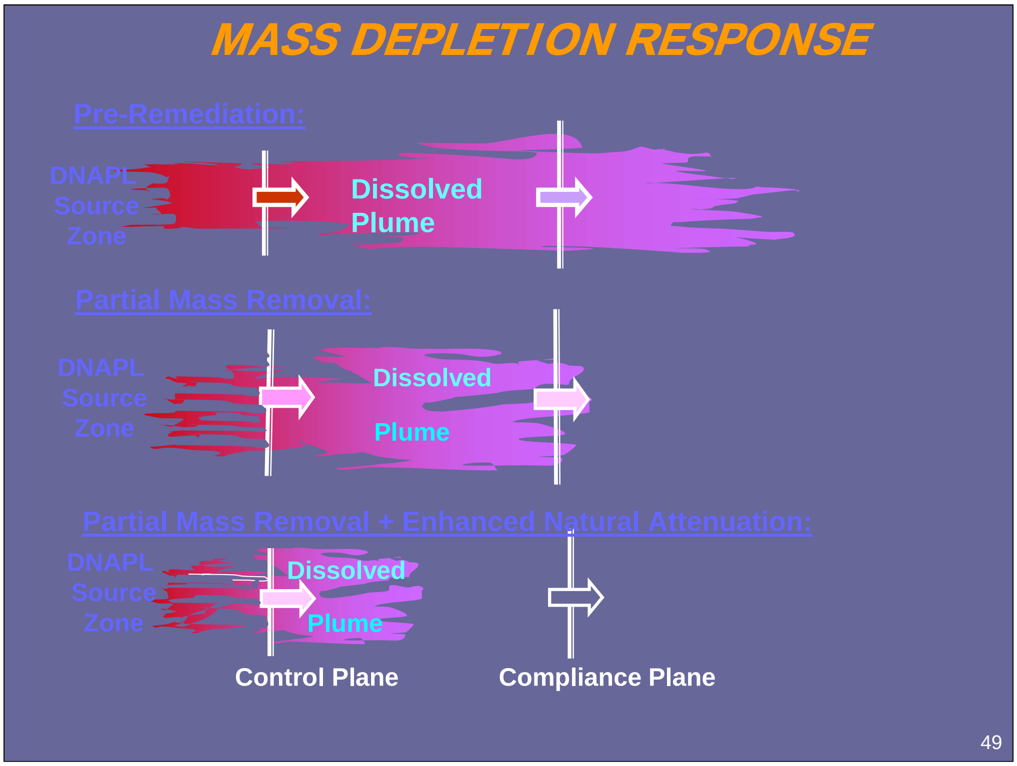
- Advantages:
  - Generates contaminant mass flow estimates
  - Interrogates large volumes of aquifer
  - Can be used in deep aquifers
  - Estimates water flux
- Disadvantages:
  - Costly (wastewater disposal)
  - Requires lengthy time execution
  - Assumes aquifer is homogeneous
  - Does not provide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

Assessing DNAPL Source Remediation Performance

47



Source Remediation = Contaminant Flux Management
Pre-Remediation:
Control Plane
Contaminant Flux (Jc)
Most contaminated
Source Zone
Least contaminated
Post-Remediation:
Control Plane
Contaminant Flux (Jc)
$J_c = q_w \cdot C$
Flux = Flow • Concentration
Source Zone
48



MASS DEPLETION RESPONSE
Pre-Remediation:
DNAPL Source Zone
Dissolved Plume
Partial Mass Removal:
DNAPL Source Zone
Dissolved
Plume
Partial Mass Removal + Enhanced Natural Attenuation:
DNAPL Source Zone
Dissolved
Plume
Control Plane
Compliance Plane
49

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

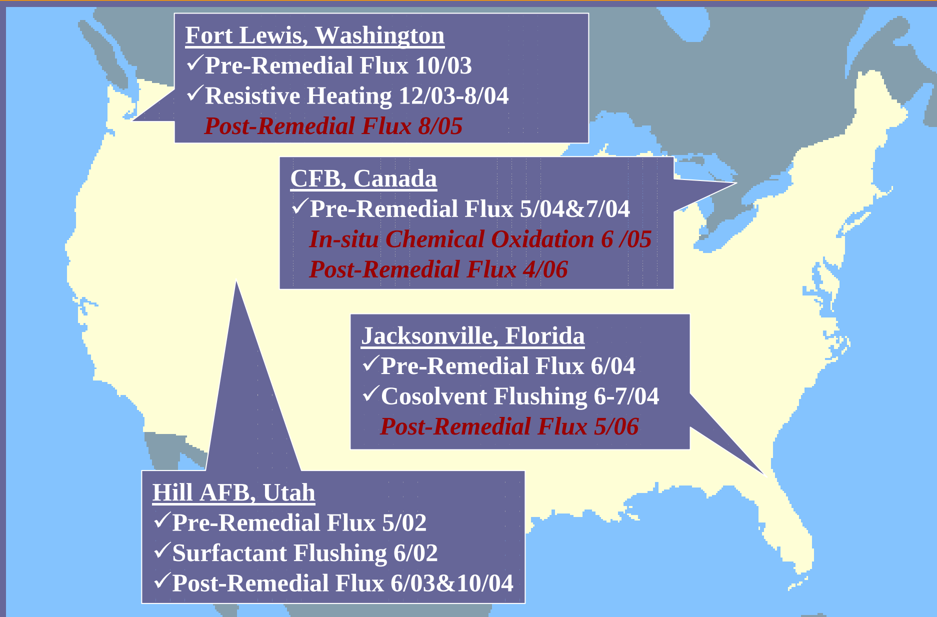
Mathematical Modeling

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

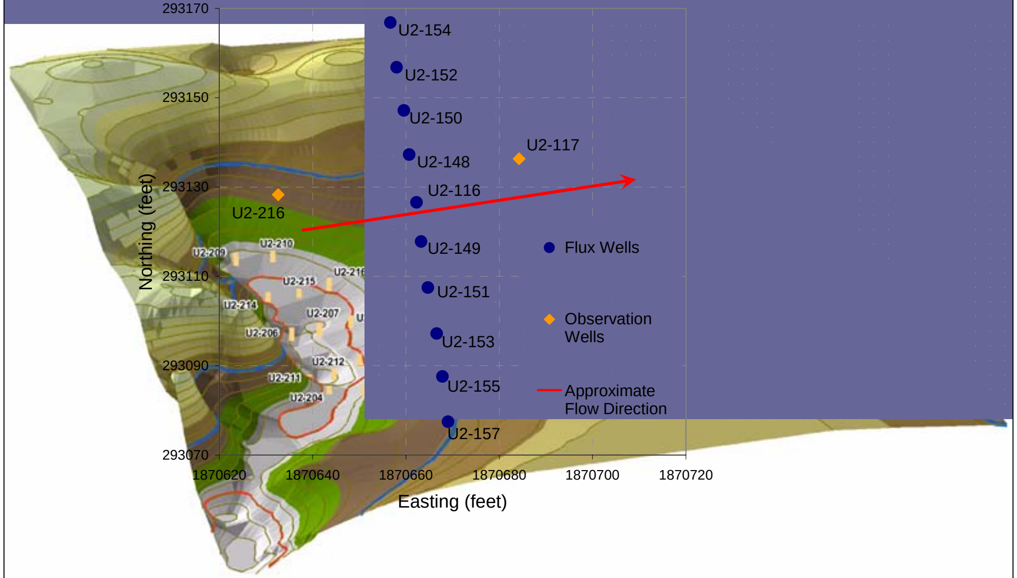
51

DNAPL Field Sites

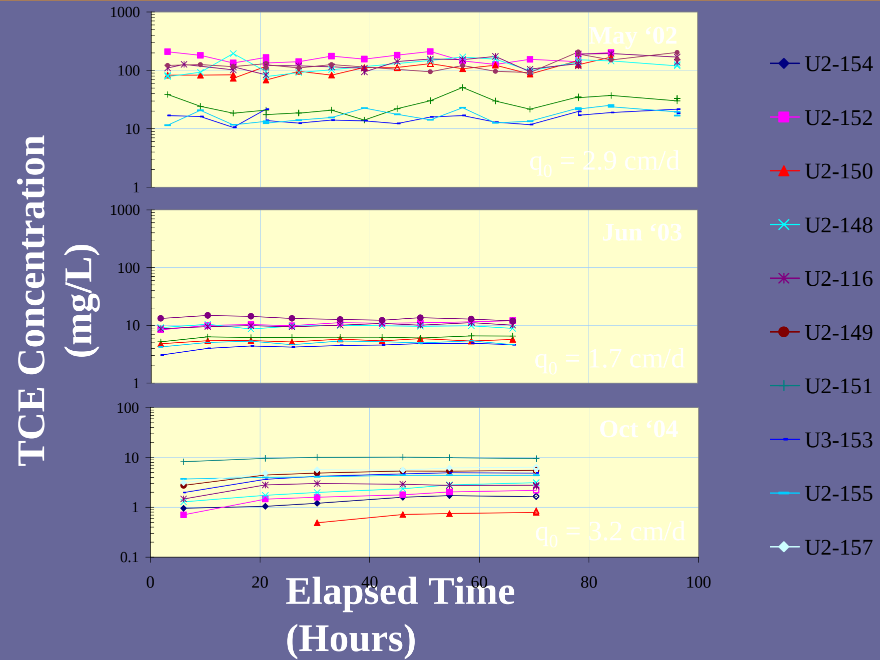


52

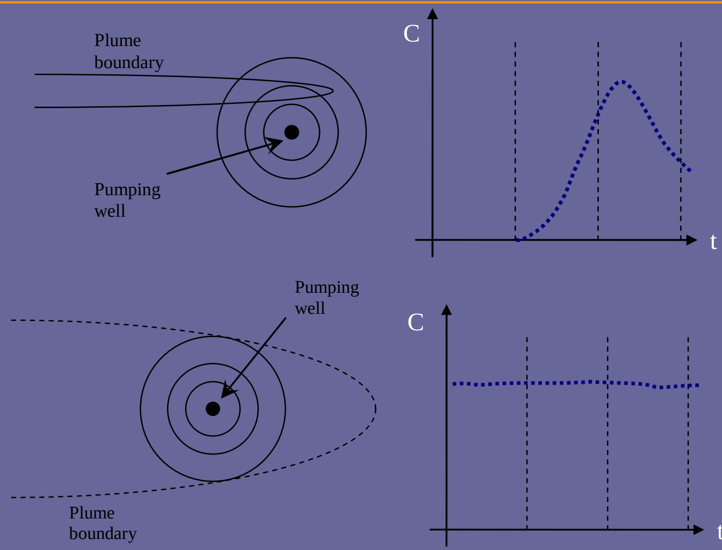
Hill AFB OU2 Layton, Utah



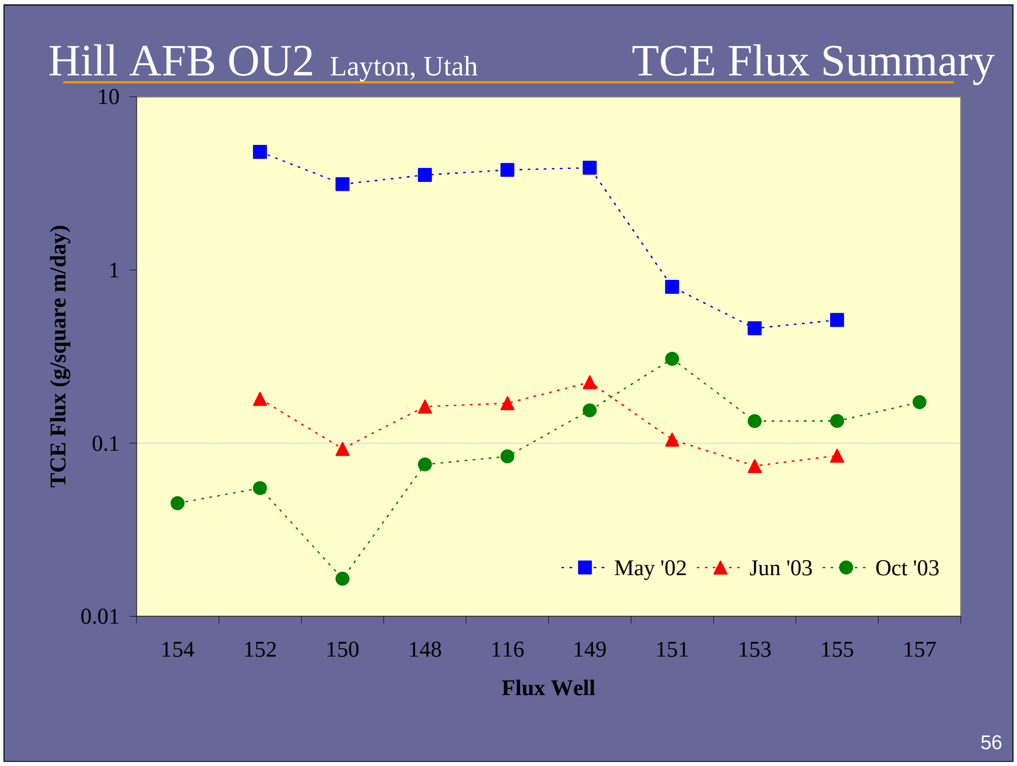
TCE Concentration Time Series

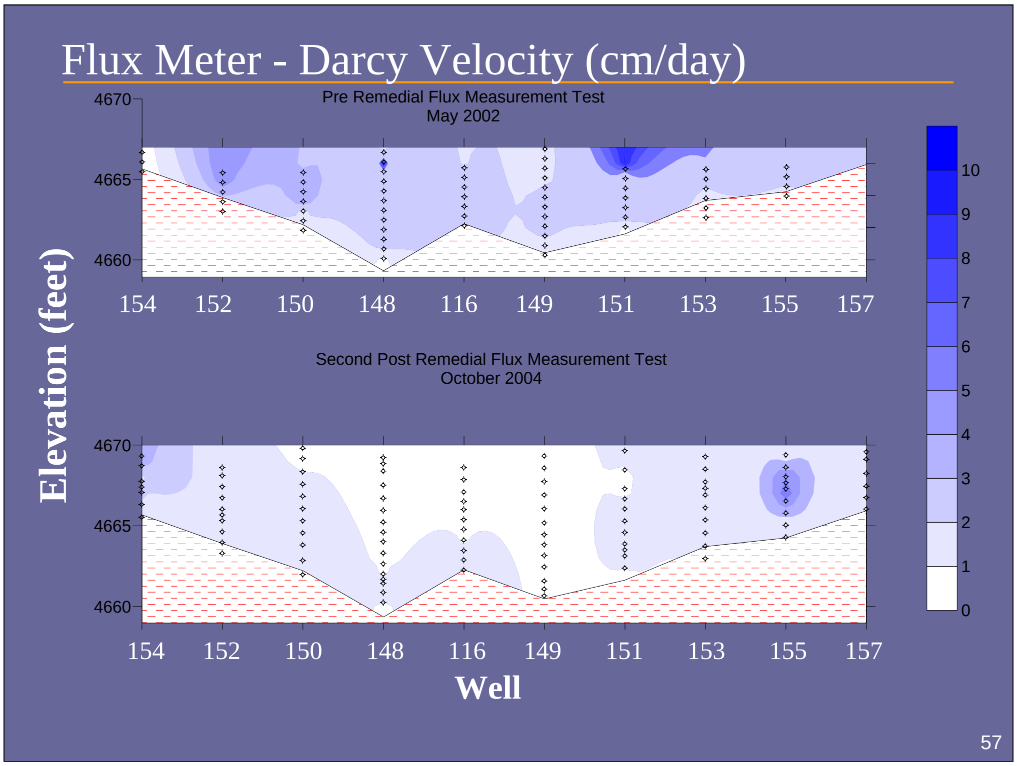


Interpretation of CT series

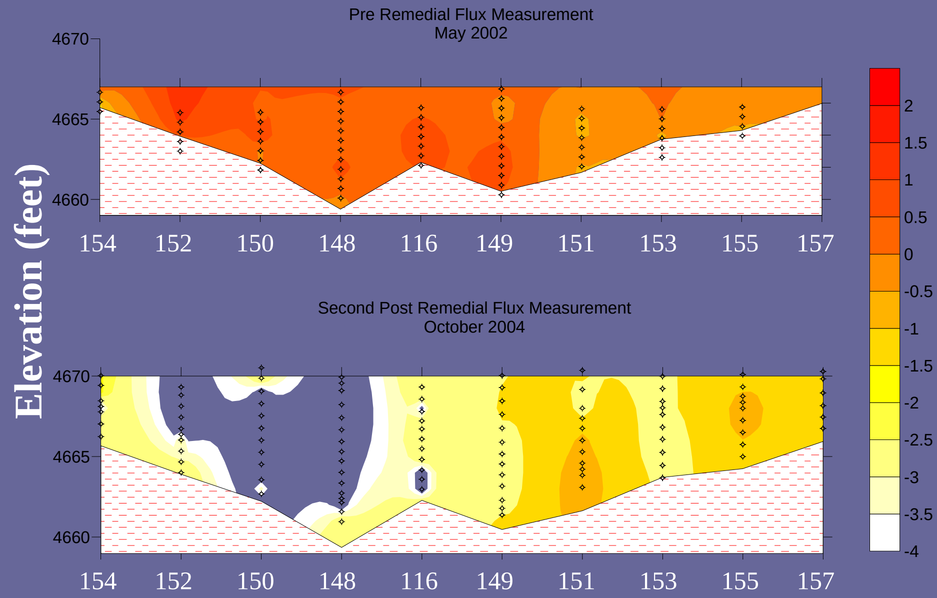


Adapted from Bockelmann et al. (2003)


Hill AFB OU2 Layton, Utah
TCE Flux Summary
TCE Flux (g/square m/day)
10
1
0.1
0.01
154
152
150
148
116
149
151
153
155
157
Flux Well
May '02
Jun '03
Oct '03
56


Flux Meter - Darcy Velocity (cm/day)
Pre Remedial Flux Measurement Test
May 2002
Second Post Remedial Flux Measurement Test
October 2004
Elevation (feet)
4670
4665
4660
154
152
150
148
116
149
151
153
155
157
Well
10
9
8
7
6
5
4
3
2
1
0
57

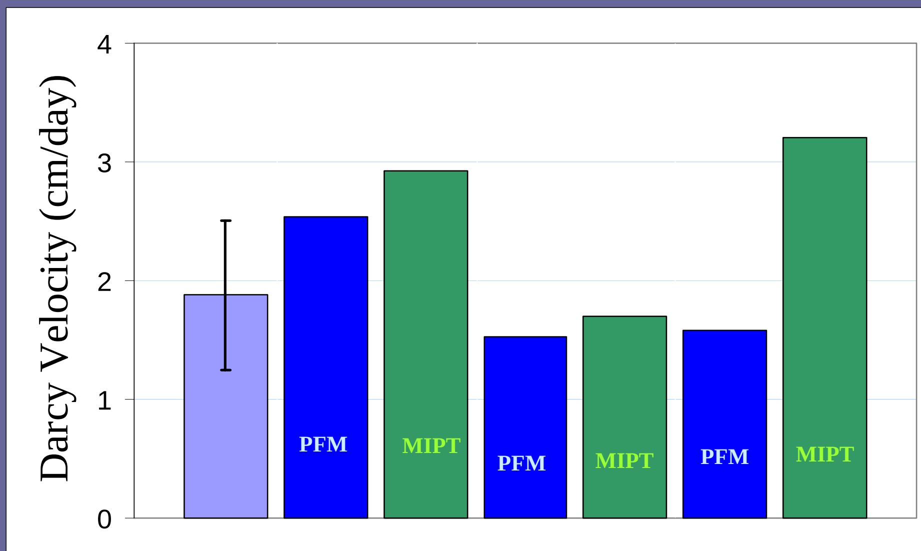
Flux Meter – Log TCE Flux (gram/square meter/day)



58

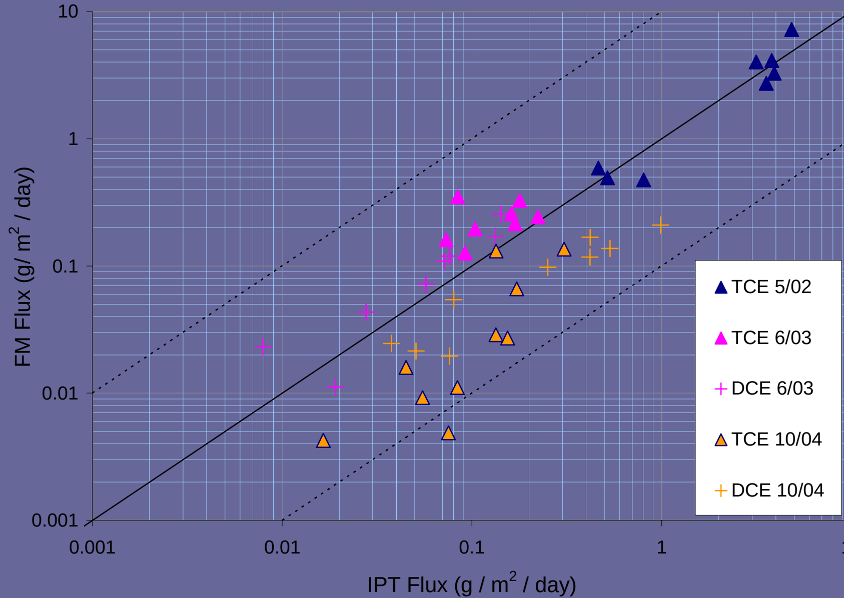
Hill AFB OU2 Layton, Utah

Darcy Velocity Comparison



59

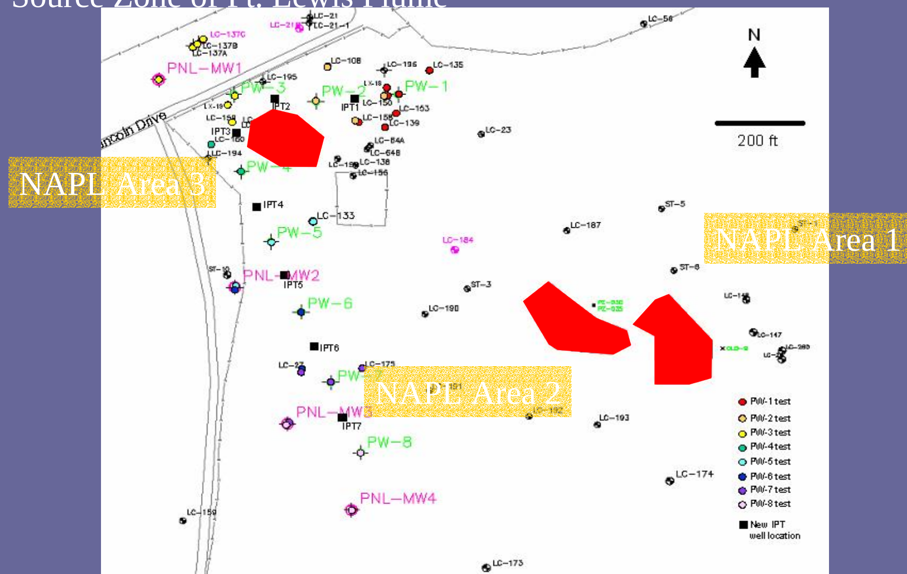
Well-Averaged Flux Summary



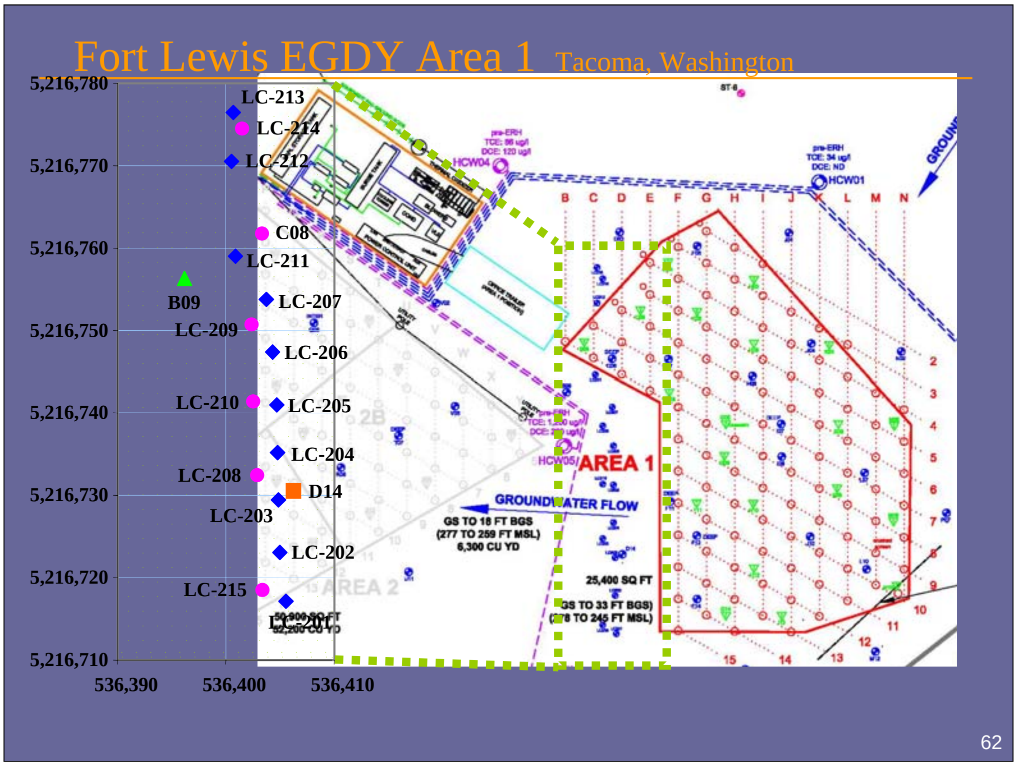
60

Fort Lewis EGDY Area 1 Tacoma, Washington

Source Zone of Ft. Lewis Plume

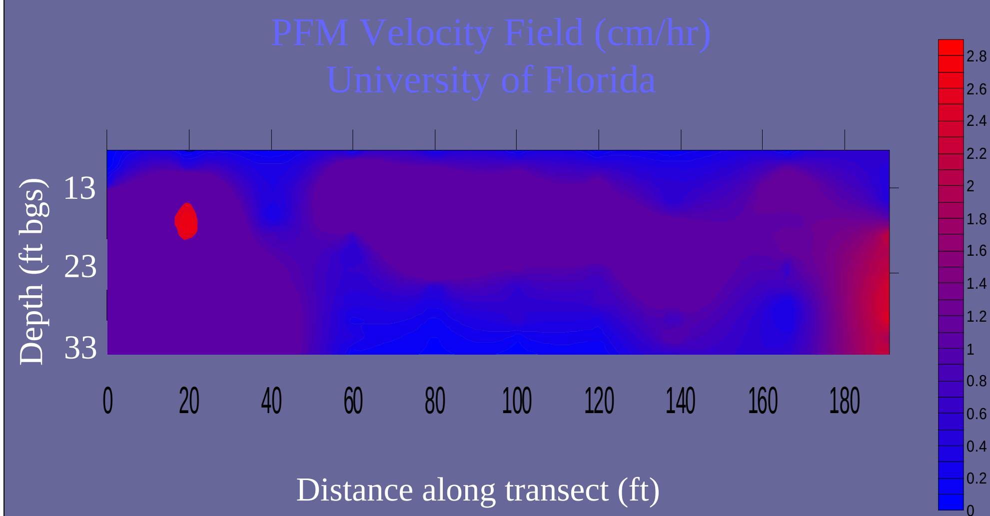


61

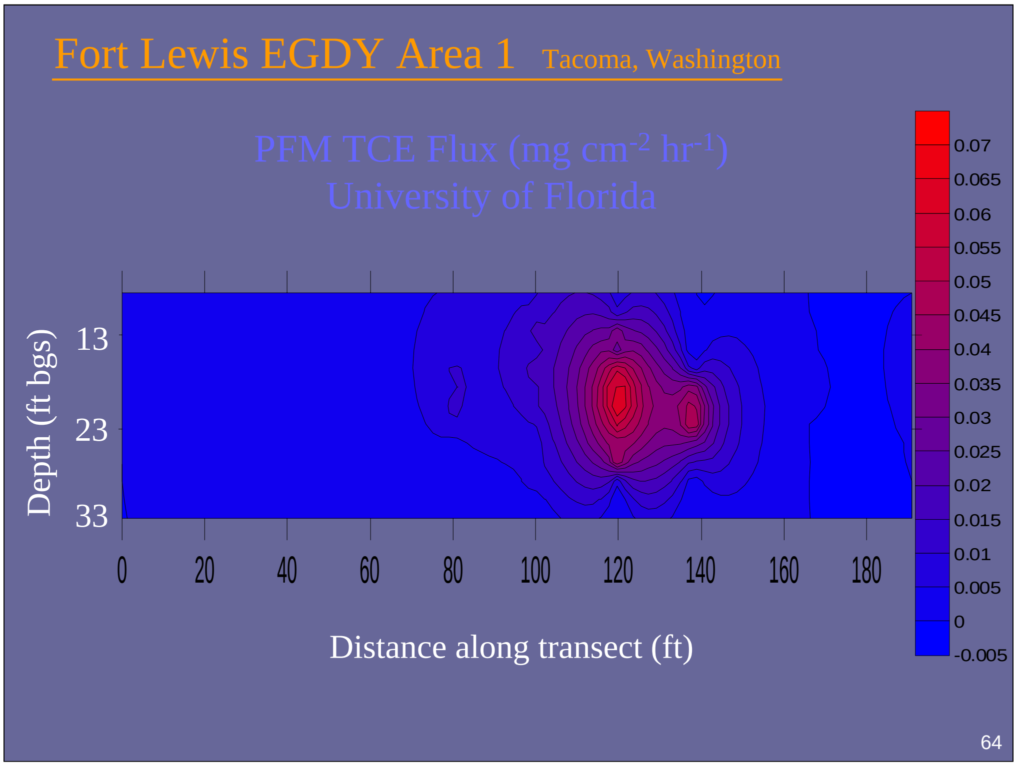


Fort Lewis EGDY Area 1 Tacoma, Washington
5,216,780
5,216,770
5,216,760
5,216,750
5,216,740
5,216,730
5,216,720
5,216,710
536,390
536,400
536,410
LC-213
LC-214
LC-212
C08
LC-211
B09
LC-207
LC-209
LC-206
LC-210
LC-205
LC-204
LC-208
D14
LC-203
LC-202
LC-215
LC-201
HCW04
HCW01
HCW05
AREA 1
AREA 2
GROUNDWATER FLOW
GS TO 18 FT BGS
(277 TO 259 FT MSL)
6,300 CU YD
25,400 SQ FT
GS TO 33 FT BGS)
(278 TO 245 FT MSL)
62

Fort Lewis EGDY Area 1 Tacoma, Washington

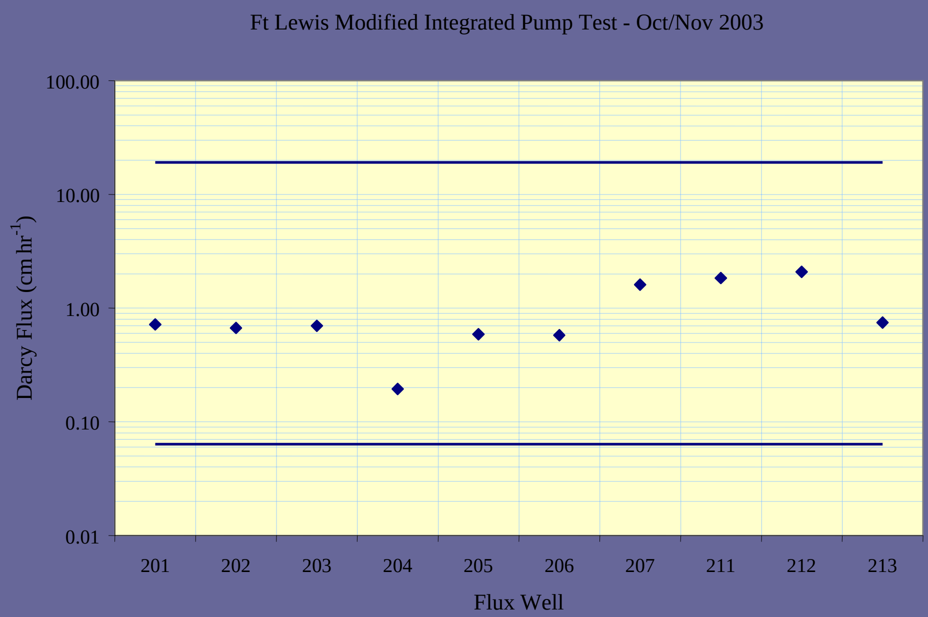


63



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

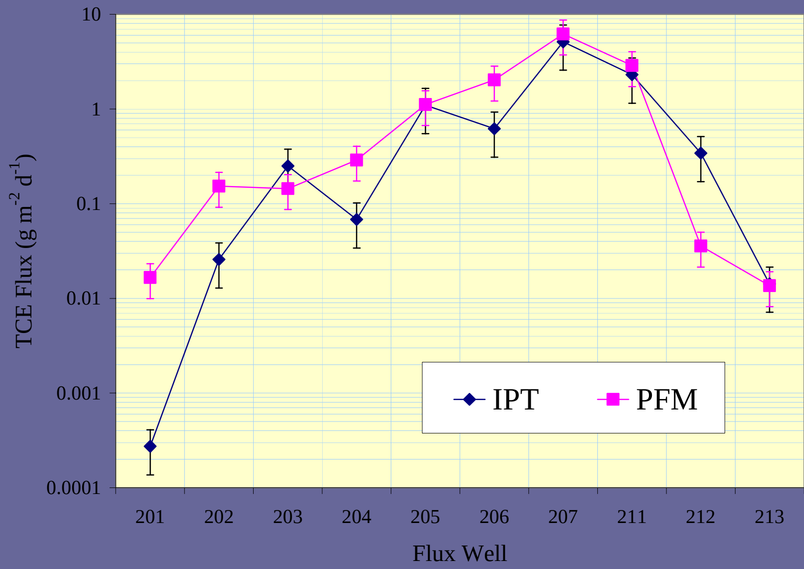
Fort Lewis EGDY Area 1 Tacoma, Washington



65

Fort Lewis EGDY Area 1 Tacoma, Washington

Average Pre-Remedial Flux, Oct/Nov 2003



66

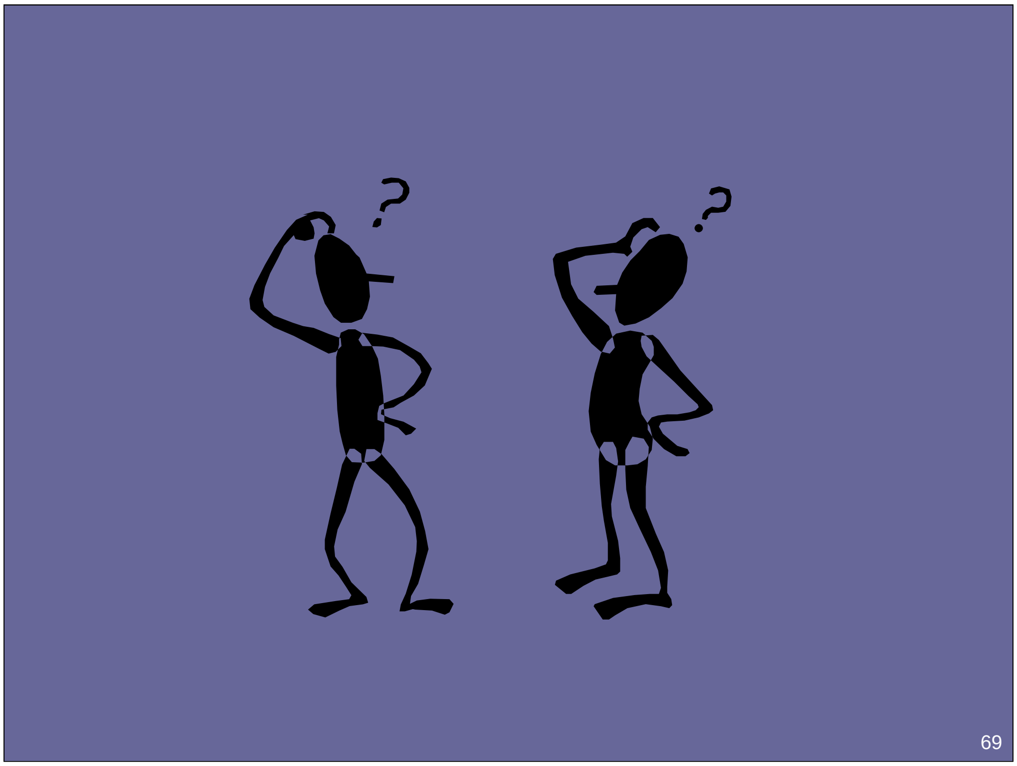
Summary

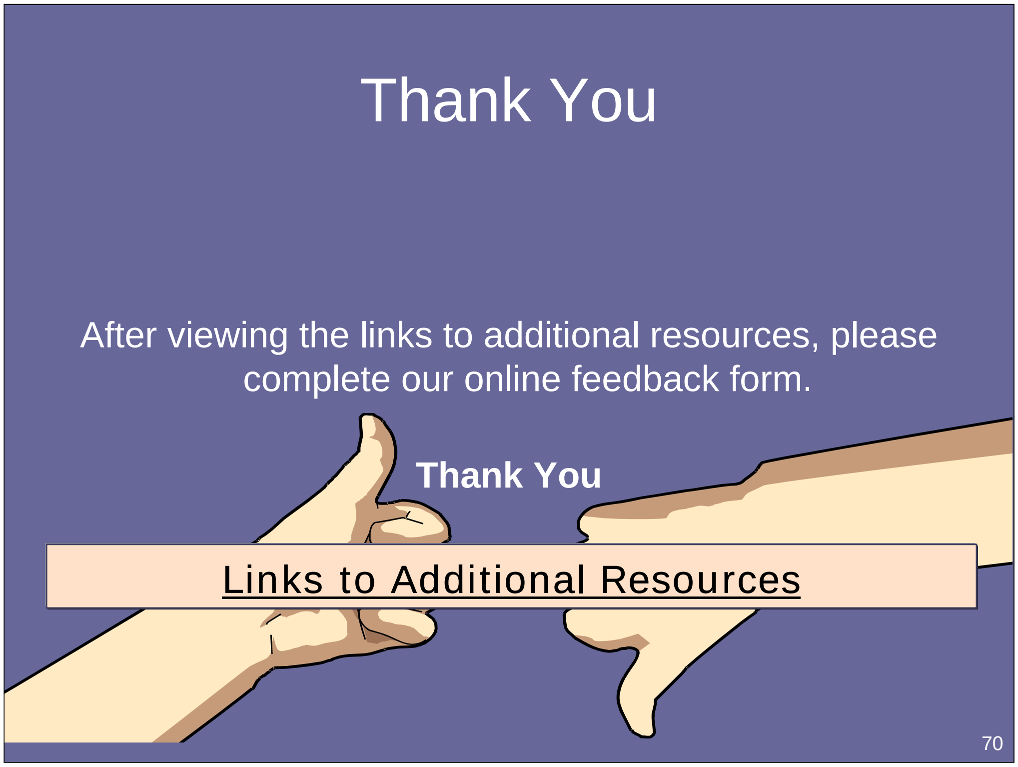
- Modified IPT method is being used to measure pre- and post-remedial flux
- Approximately an order of magnitude decrease in flux at Hill AFB
- Flux estimates based on flux meter and IPT methods to date are comparable

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)


69


Thank You
After viewing the links to additional resources, please complete our online feedback form.
Thank You
Links to Additional Resources
70