Flux-Based Site Management
and Tools to Evaluate Contaminant Flux

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National Association of Remedial Project Managers
Annual Training Program

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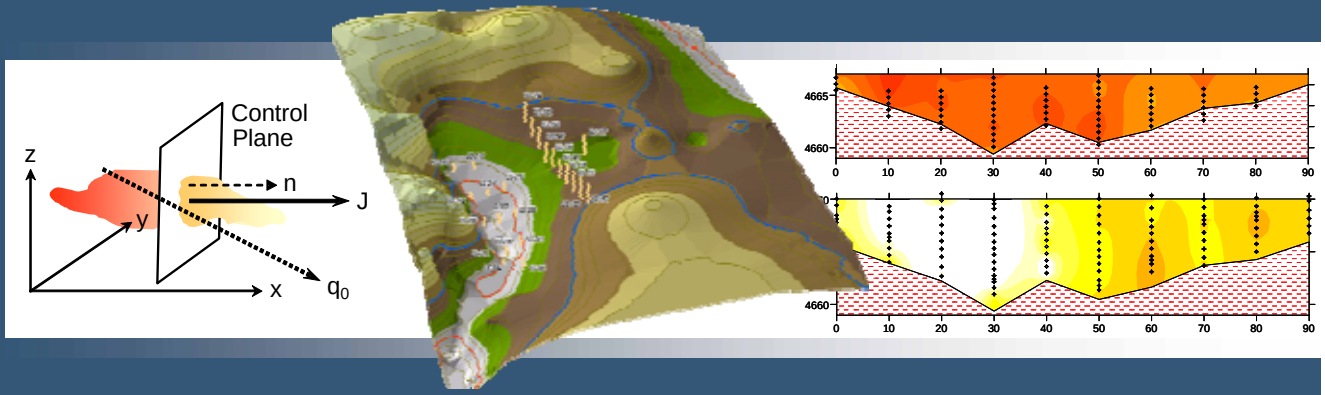

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Discussion Outline

I. Flux-Based Site Management Concepts

II. Summary of Recent Research

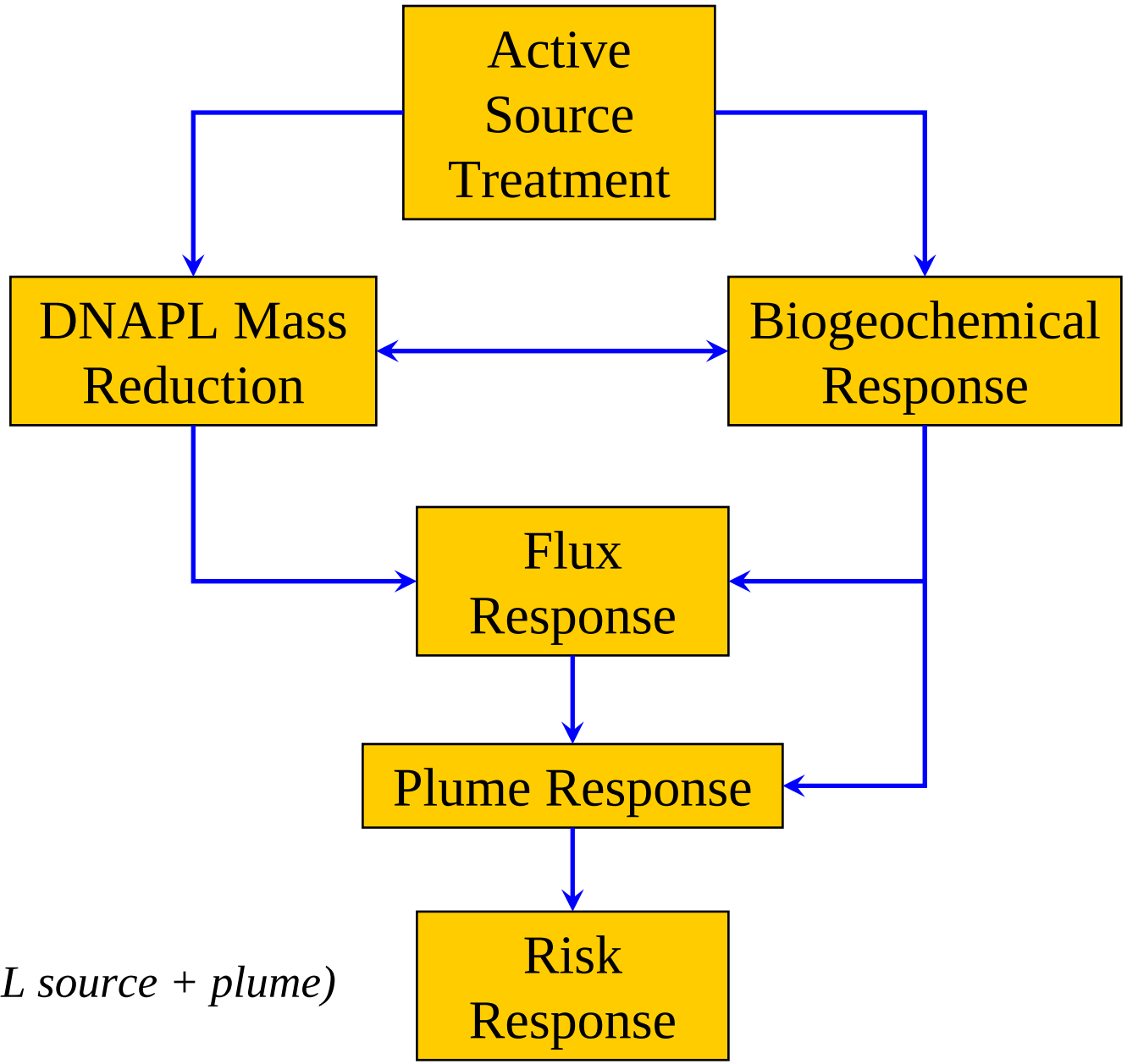
III. Brief Summary of Current Research

Acknowledgements

- Lynn Wood, U.S. EPA
- Michael D. Annable, University of Florida
- James W. Jawitz, University of Florida
- Kirk Hatfield, University of Florida
- Ron Falta, Clemson University
- P. Suresh Rao, Purdue University
- Carl Enfield, Enfield Environmental Research
- SERDP

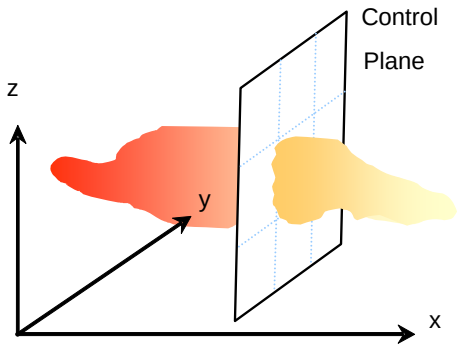
Benefits of Partial DNAPL Mass Removal?

Conceptual Research Model



Risk = f (DNAPL source + plume)

Flux-Based Concepts



Contaminant Mass Flux (J) – mass of contaminant moving across a unit area of a control plane per unit time ($ML^{-2}T^{-1}$)

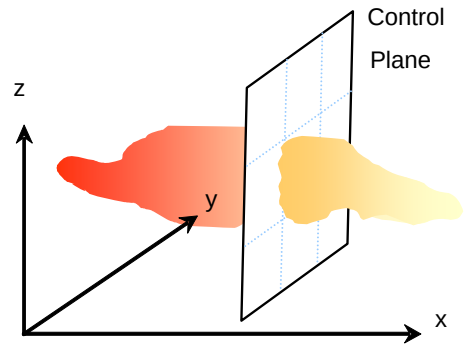
Contaminant Mass Discharge (M_D) – total mass moving across the control plane per unit time (MT^{-1}).

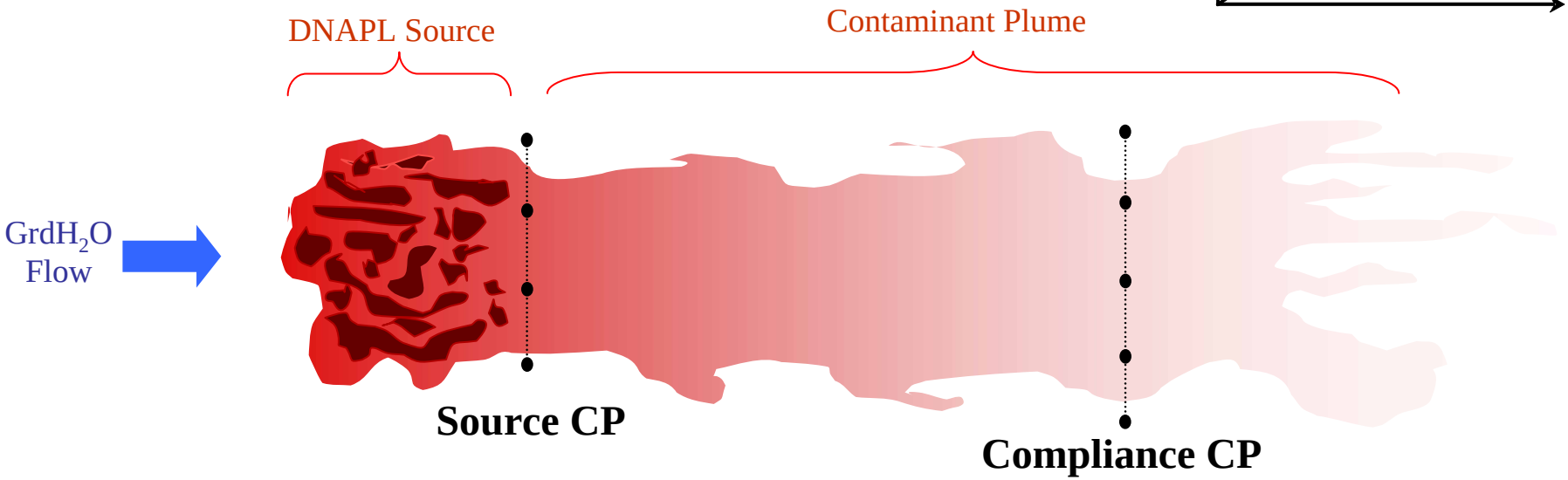
Groundwater Flux (q) – bulk groundwater velocity (LT^{-1}).

Control Plane – Transect of monitoring wells typically oriented perpendicular to the mean groundwater flow direction.

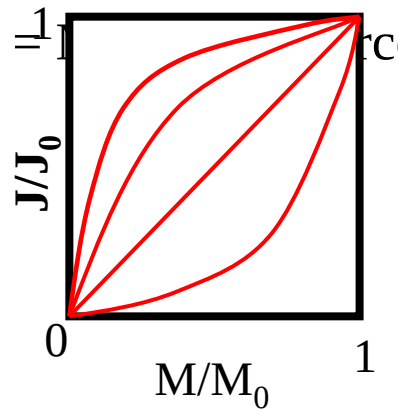
$$\mathbf{J} = \mathbf{C} * \mathbf{q} \longrightarrow \mathbf{K} * \boldsymbol{i}$$

Flux-Based Concepts





- Source Strength = 1 M rce CP
- Source Function

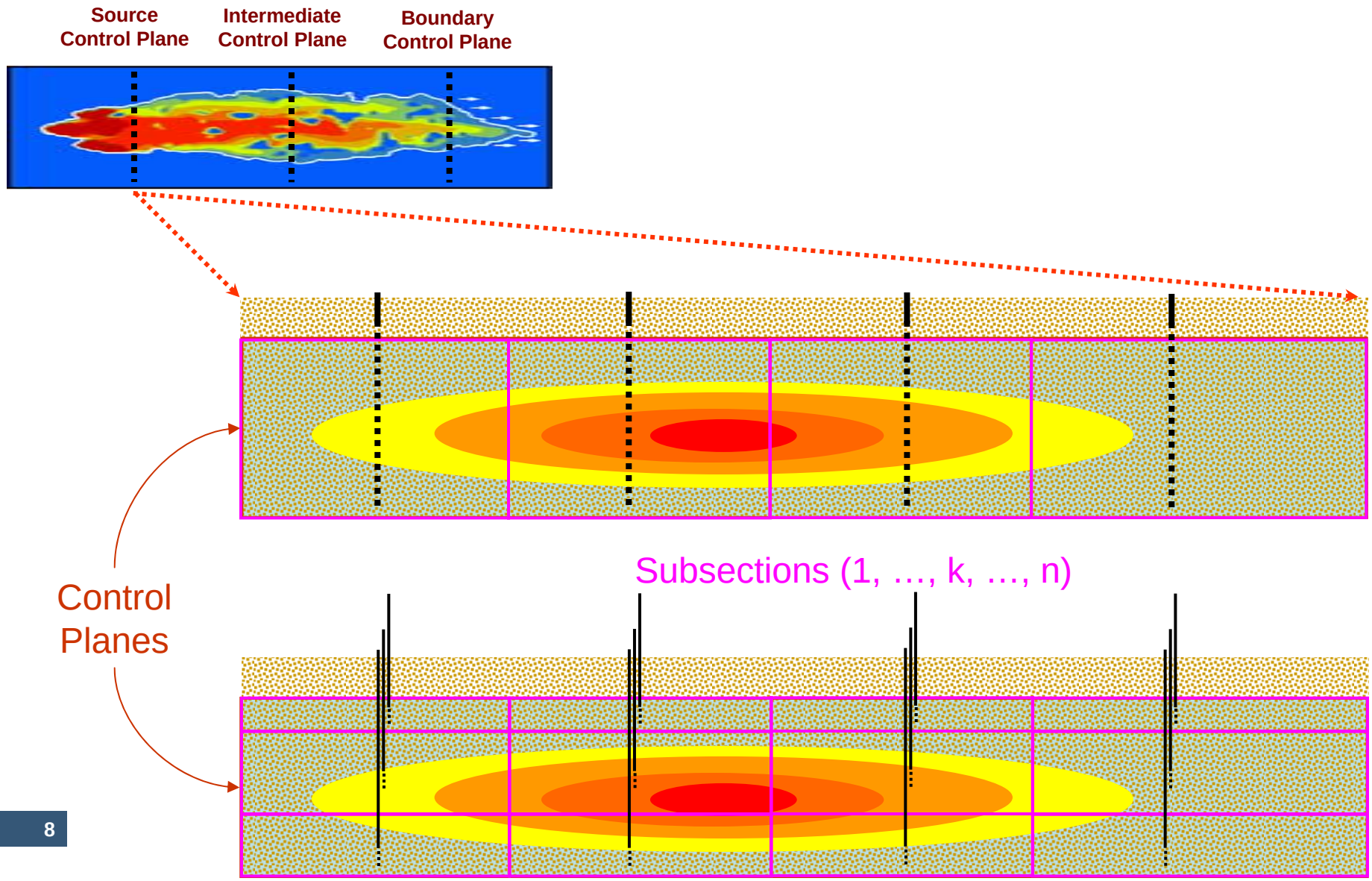


Flux-Based Site Management

Key Components	Application
•Source Strength •Plume Degradation •Source Function •Flux Distribution	•Prioritize site remediation •Monitor remedial performance •Predict plume response •Predict remedial benefits •Assess relative benefits (source vs plume) •Targeted treatment

Optimize Remedial Selection, Design, Implementation

Control Planes



Contaminant Flux & Mass Discharge at Control Planes

$$M_D = \sum_{k=1}^{n} J_k A_k$$

$$J_k = C_k q_k$$

$$q_k = Ki$$

$$A_k = \Delta x_k \Delta z_k$$

M_D = Mass Discharge [MT^{-1}]

J_k = Mass flux [ML^2T^{-1}]

q_k = Groundwater flux [LT^{-1}]

C_k = Concentration [ML^{-3}]

A_k = Area of element k [L^2]

K = Hydraulic Cond. [LT^{-1}]

i = Hydraulic gradient [-]

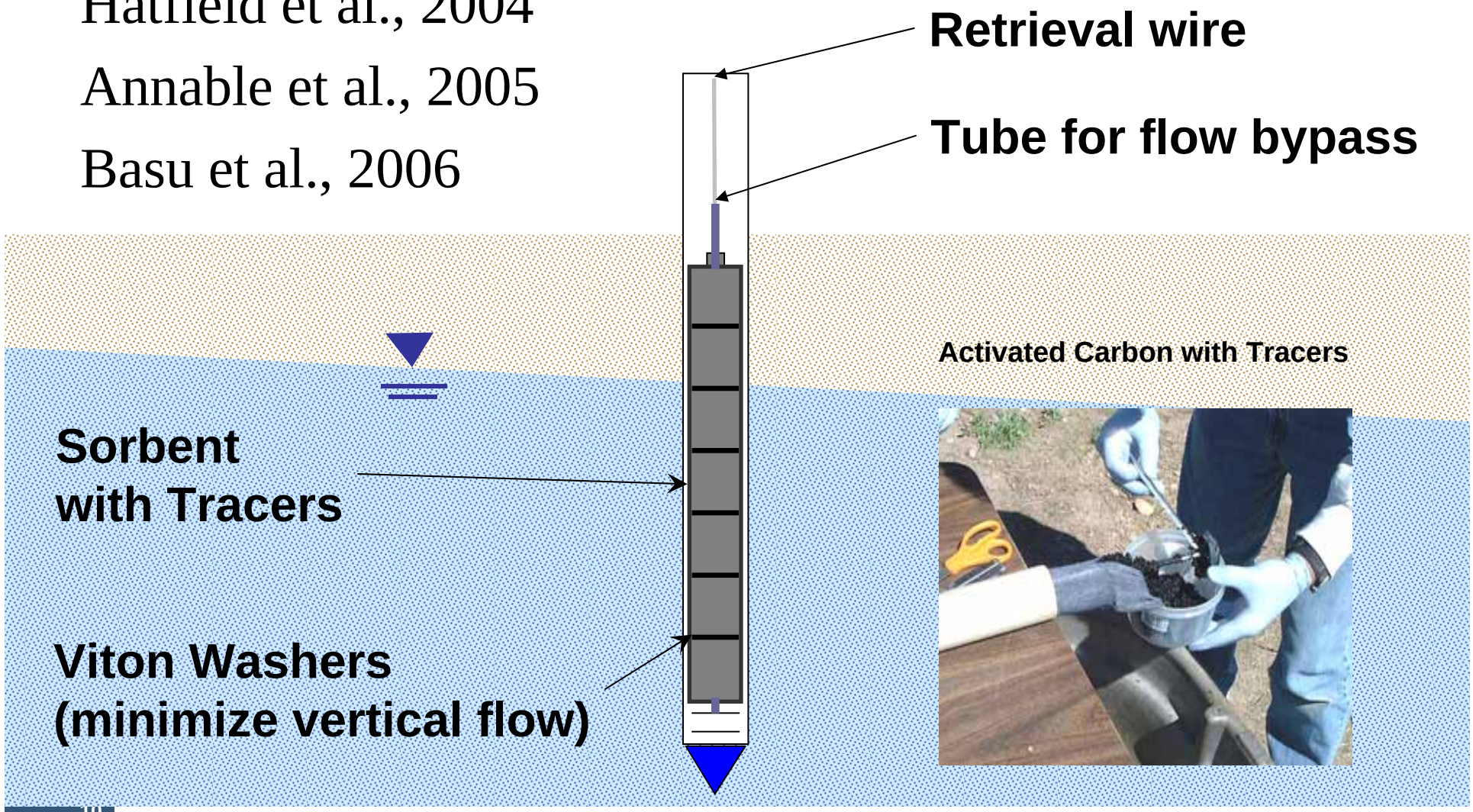
M_D, J, C, q, K, & i may be functions of both space and time

Passive Flux Meters (PFMs)

Hatfield et al., 2004

Annable et al., 2005

Basu et al., 2006



Pumping Methods

- Long-term pumping records (P&T Systems)
- Short-term pumping tests
  - Extraction Only
    - Sequential pumping, constant rate (Original IPT)
    - Concurrent pumping, constant rate
    - Concurrent pumping, variable rate
  - Injection/Extraction
    - Tandem circulation Well Tests
    - Forced Mass Discharge Test

Traditional Methods

$$J = C * q \rightarrow K * i$$

Concentration

- Screened Wells
- Multi-level Samplers
- Direct Push Sampling

Groundwater Flux

- Borehole dilution tests
- Heat-based velocity meter
- Colloidal-based velocity meter
- Tracer tests

Hydraulic Conductivity

- Permeameters
- Grain-size analysis
- Direct push technologies
- Pump tests
- Slug tests
- Borehole flow meter
- FLUTe™

Hydraulic Gradient

- Head measurements

Impact of Source Treatment on Flux?

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journal homepage: www.elsevier.com/locate/jconhyd

Changes in contaminant mass discharge from DNAPL source mass depletion: Evaluation at two field sites

Michael C. Brooks [a,*], A. Lynn Wood [a], Michael D. Annable [b], Kirk Hatfield [b], Jaehyun Cho [b], Charles Holbert [c], P. Suresh C. Rao [d], Carl G. Enfield [e,1], Kira Lynch [f], Richard E. Smith [g]

Hill AFB

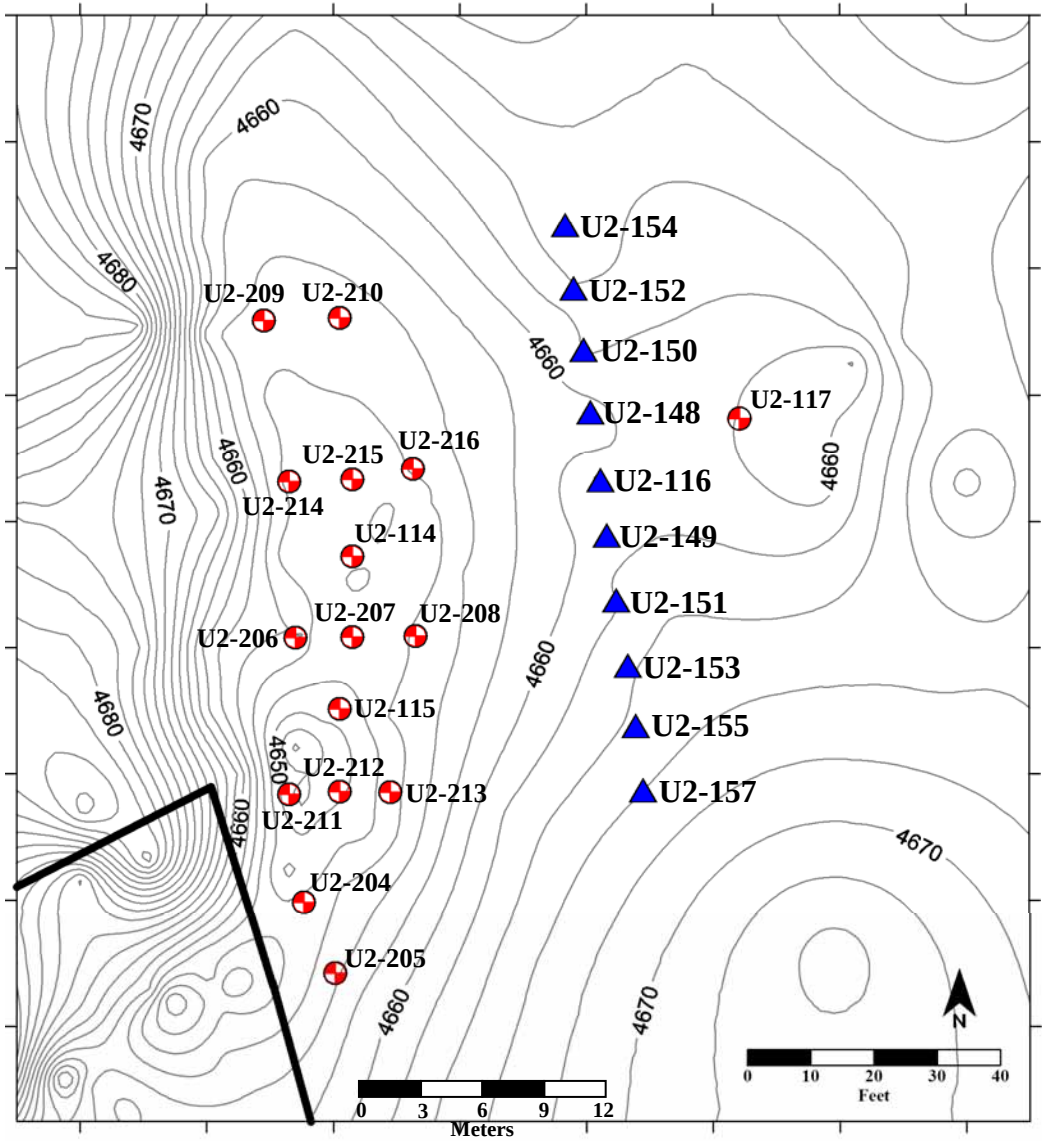
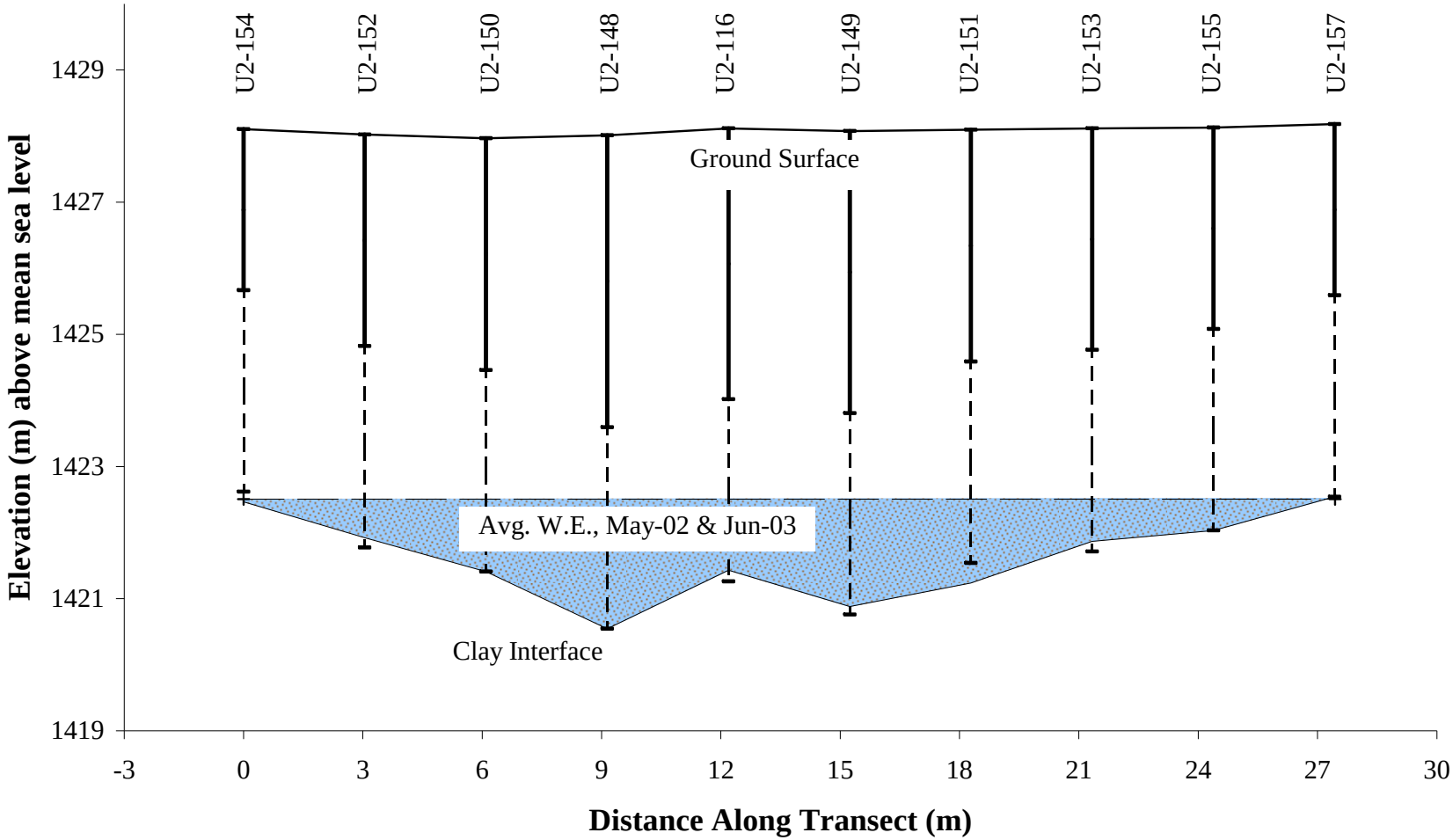


Figure 1. Plan view of the Panel 5 area at Hill AFB. The thick black line in the lower left corner represents the containment wall installed around OU2. The triangular symbols represent wells used for mass flux measurements. The grey contour lines represent the surface of the clay unit (contours in feet) underlying the surficial aquifer.

Brooks et al., JCH, 102(2008), 140-153

Hill AFB



q = ~3 cm/day; Area = 25 m^2

Brooks et al., JCH, 102(2008), 140-153

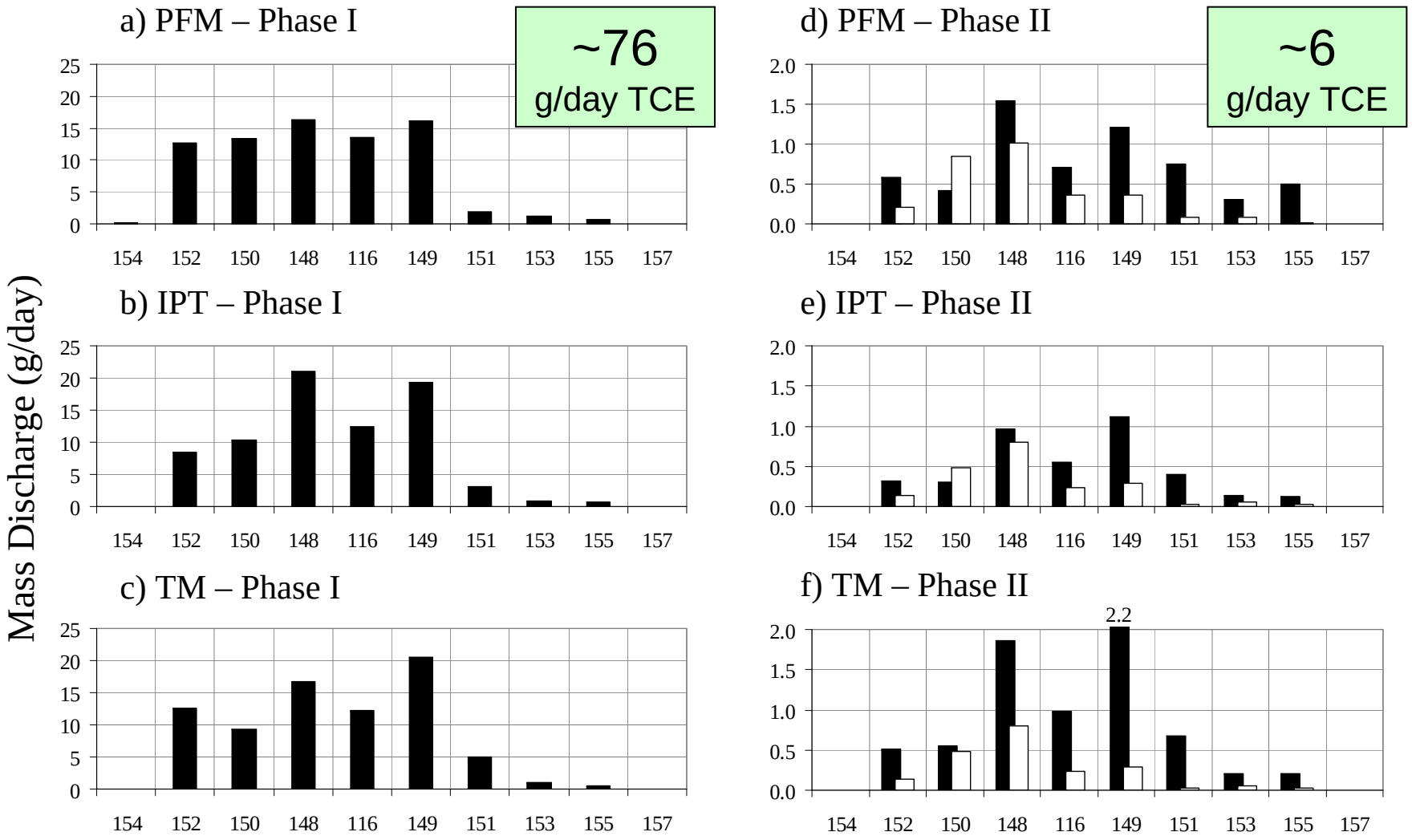


Figure 6. Average mass discharge (g/day) for each well at Hill AFB, as measured in Phase I (May-02) by a) PFM, b) IPT, and c) TM methods; and as measured in Phase II (Jun-03) by d) PFM, e) IPT, and f) TM. TCE is shown in black and *cis*-DCE in shown in white. Note the change in scale on the y-axis to accommodate the reduced discharge during Phase II (Jun-03) measurements.

Brooks et al., JCH, 102(2008), 140-153

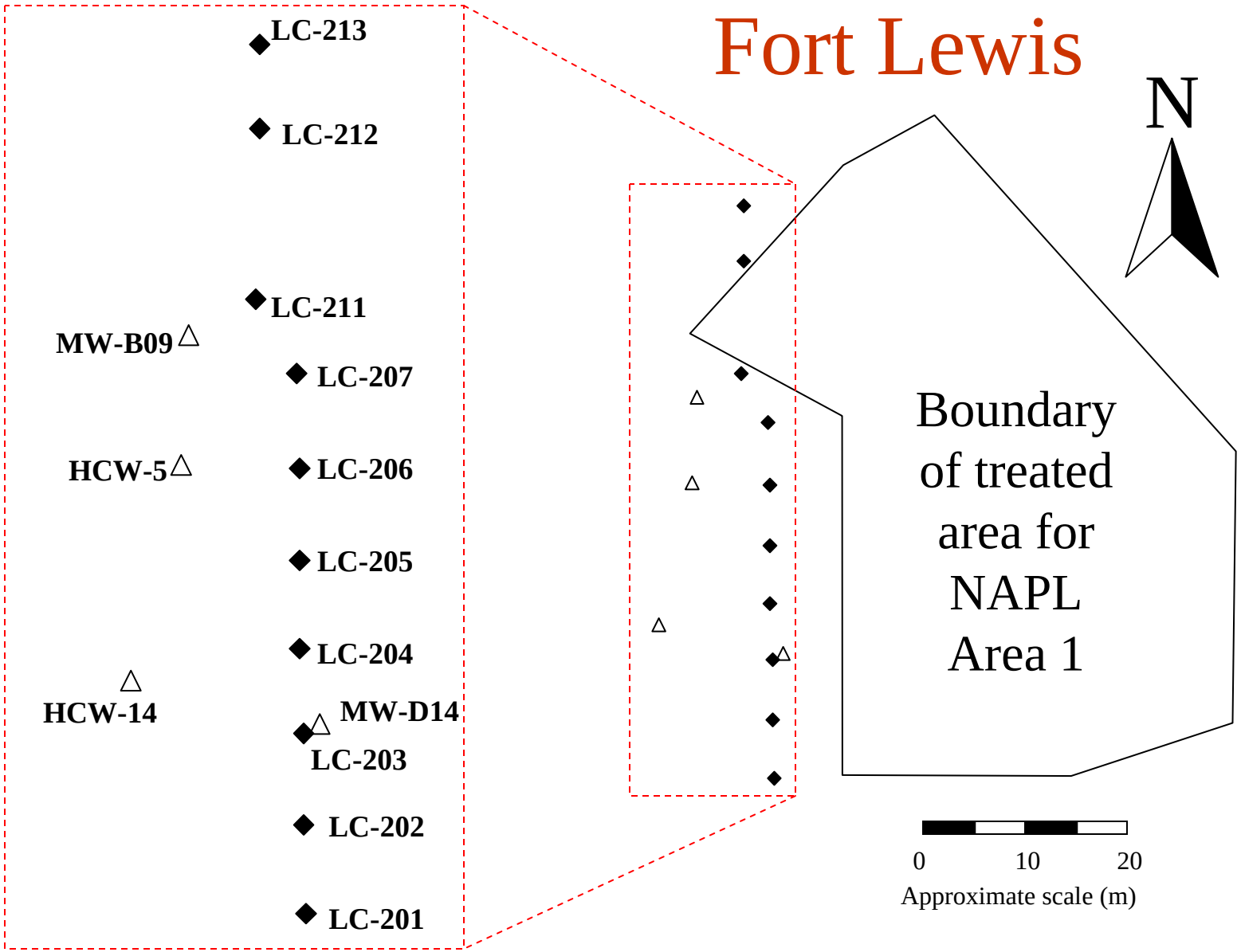
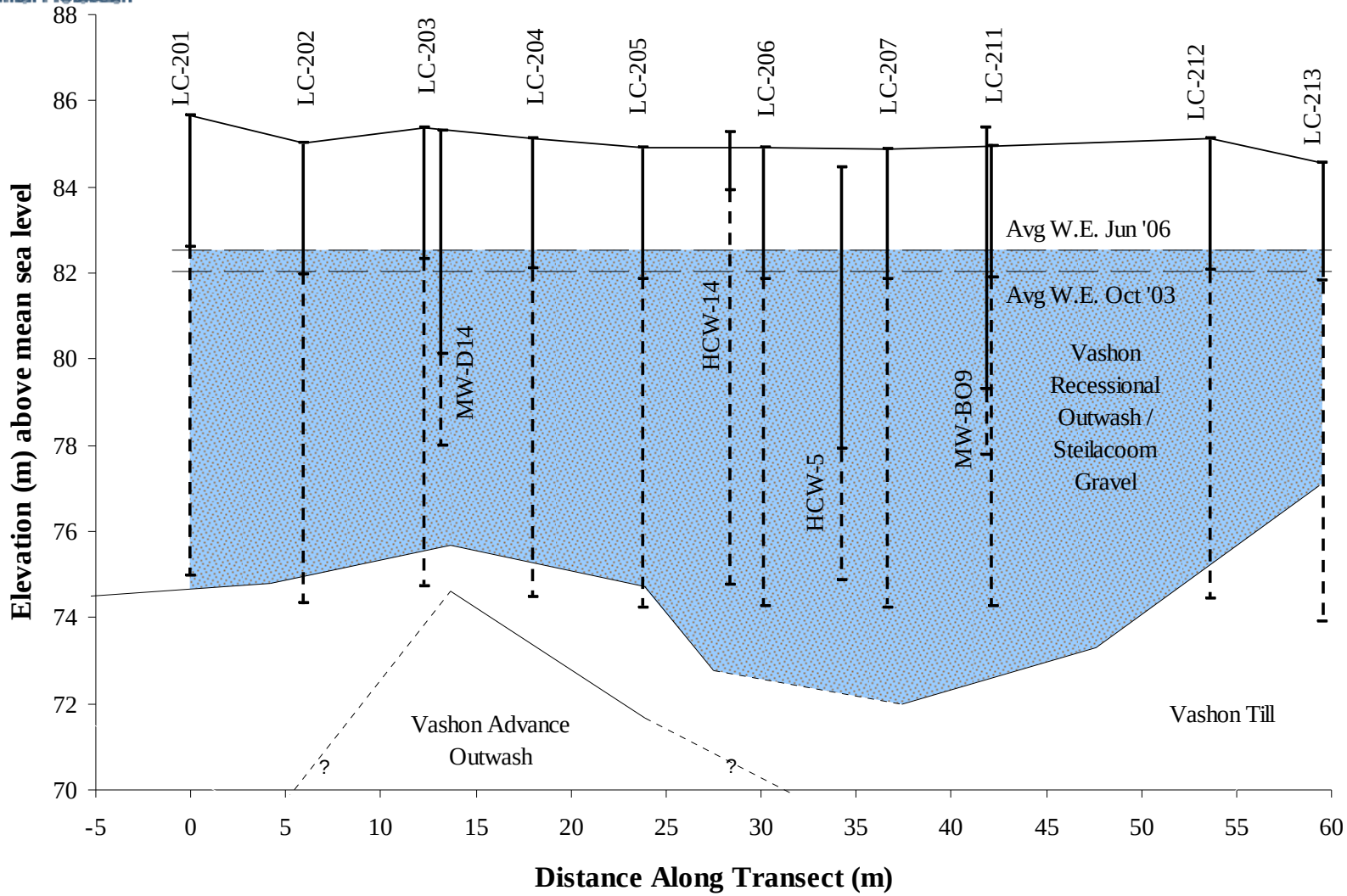


Figure 3. Plan view of the NA1 source area at the East Gate Disposal Yard site at Fort Lewis, and the downgradient flux well transect. The diamonds represent flux wells and the triangles represent hydraulic monitoring points.

Brooks et al., JCH, 102(2008), 140-153

Fort Lewis



q = ~25 cm/day; Area = 418 m^2

Brooks et al., JCH, 102(2008), 140-153

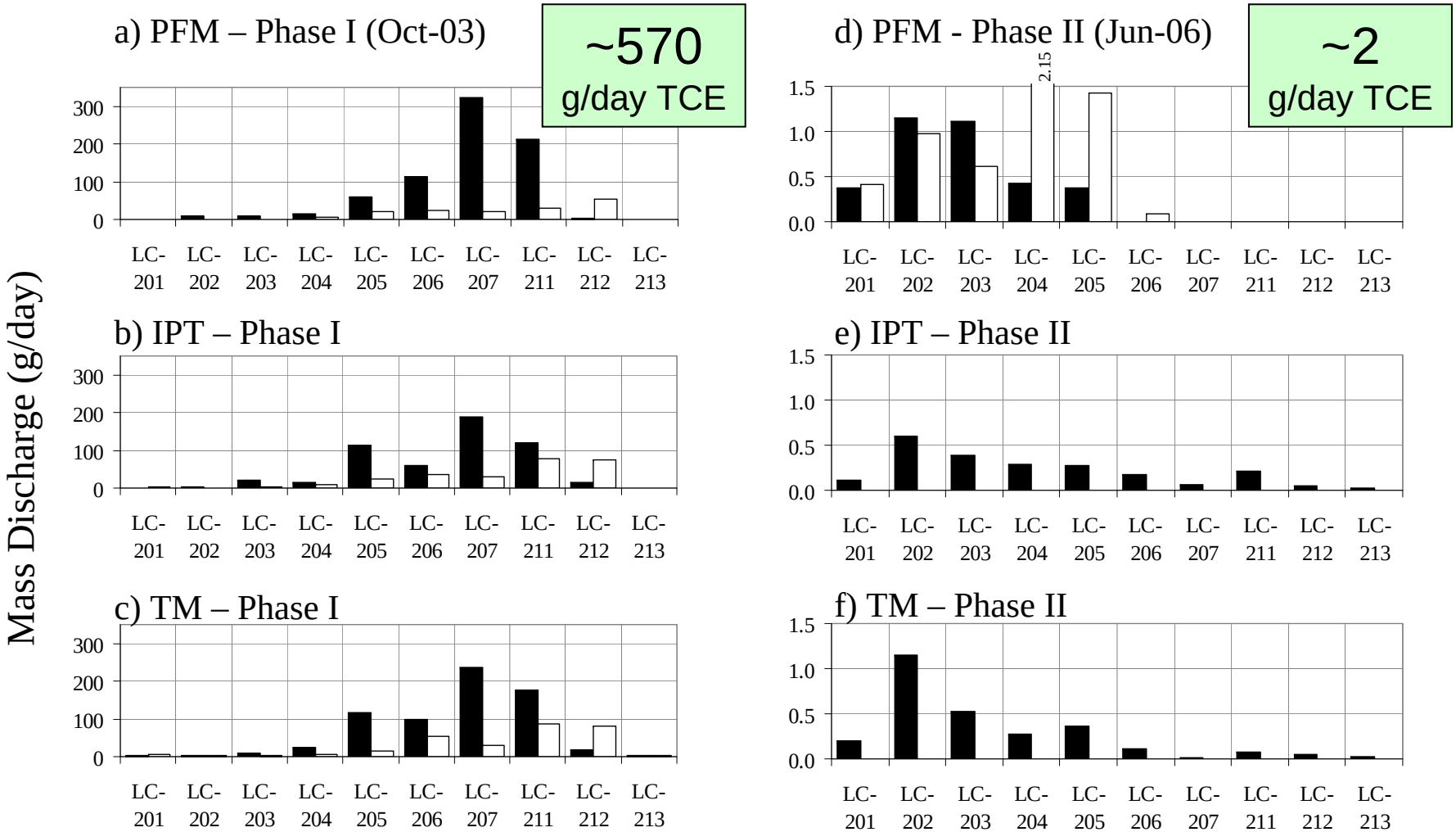


Figure 7. Average mass discharge (g/day) for each well at NA1 Fort Lewis, as measured by a) PFMs, b) IPT, and c) TM for Phase I tests (Oct-03); and as measured by d) PFMs, e) IPT, and f) TM for Phase II tests (Jun-06). TCE is shown in black, and *cis*-DCE in shown in white. Note the change in scale on the y-axis to accommodate reduced discharge during Phase II (Jun-06) tests.

Brooks et al., JCH, 102(2008), 140-153

Key Points

- Flux measurements at both sites indicate that TCE source mass depletion (>60%) through aggressive treatment resulted in substantial (>90%) reduction in TCE mass discharge at the SZ control plane.

- Data from both sites suggest that a significant fraction of the mass discharge occurs over a small portion of the SZ control plane, consistent with other field observations (Guilbeault et al., 2005; Basu et al., 2007).

- Flux-based site management should be used as a collaborative process with other traditional characterization and remedial assessment approaches.

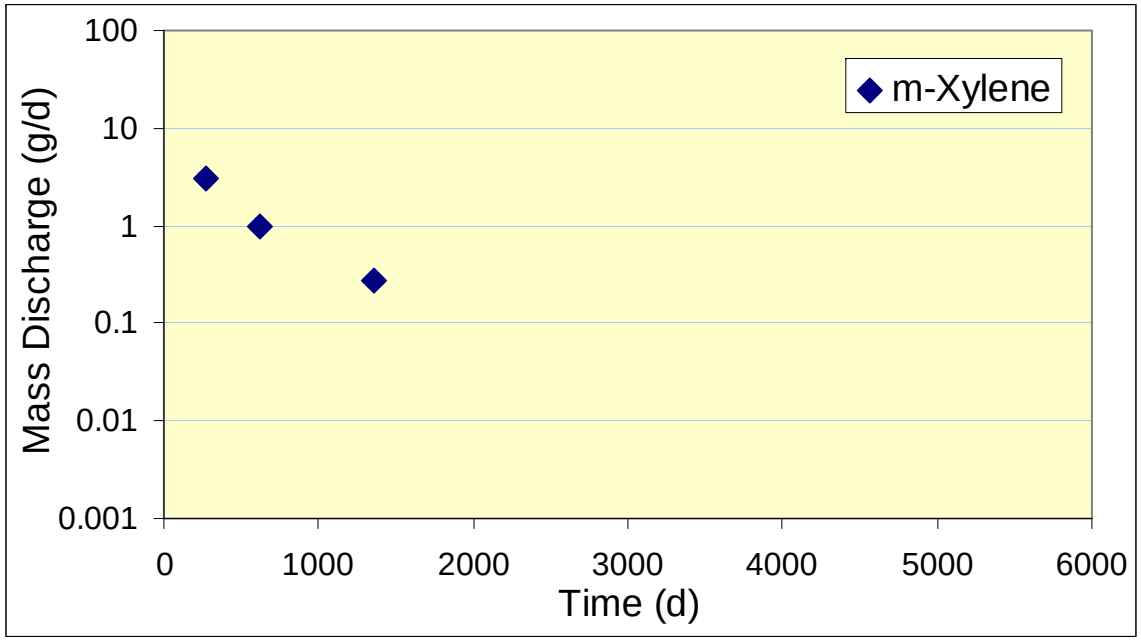
Current Work

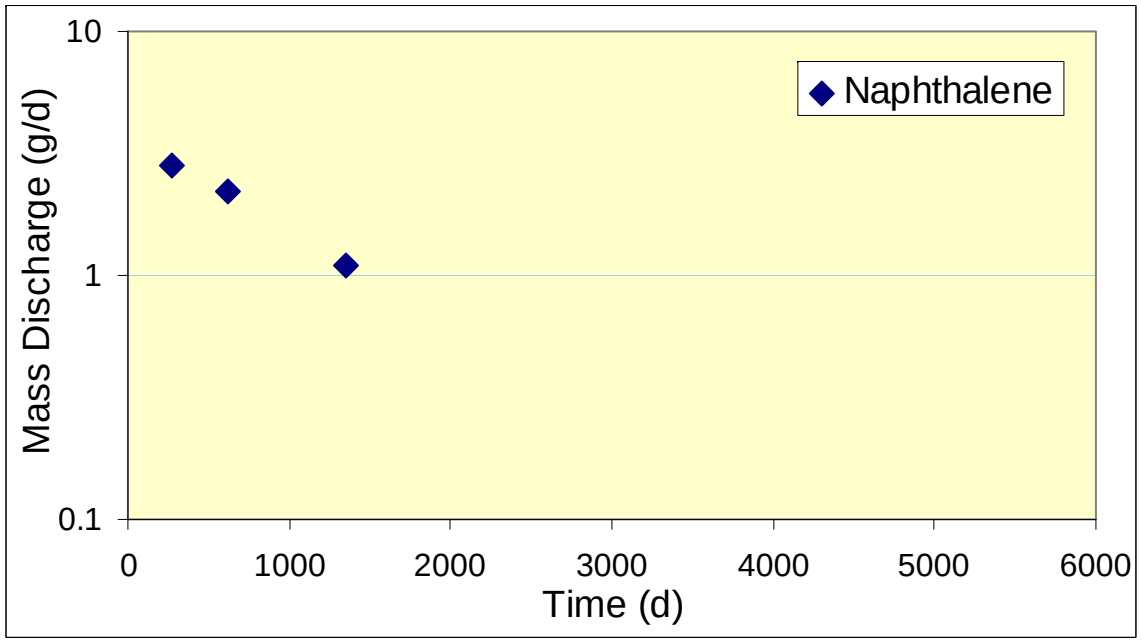
Predicting DNAPL Source Zone and Plume Response Using Site-Measured Characteristics

Example Application Based on a Published Site

- Borden Coal Tar Emplacement Experiment (King and Barker, 1999; King et al., 1999).
- 14 years of monitoring data.
- Mass Balance/Mass flux Analysis (Fraser et al., 2008).

(1) Estimate SZ M_D from Historic Data

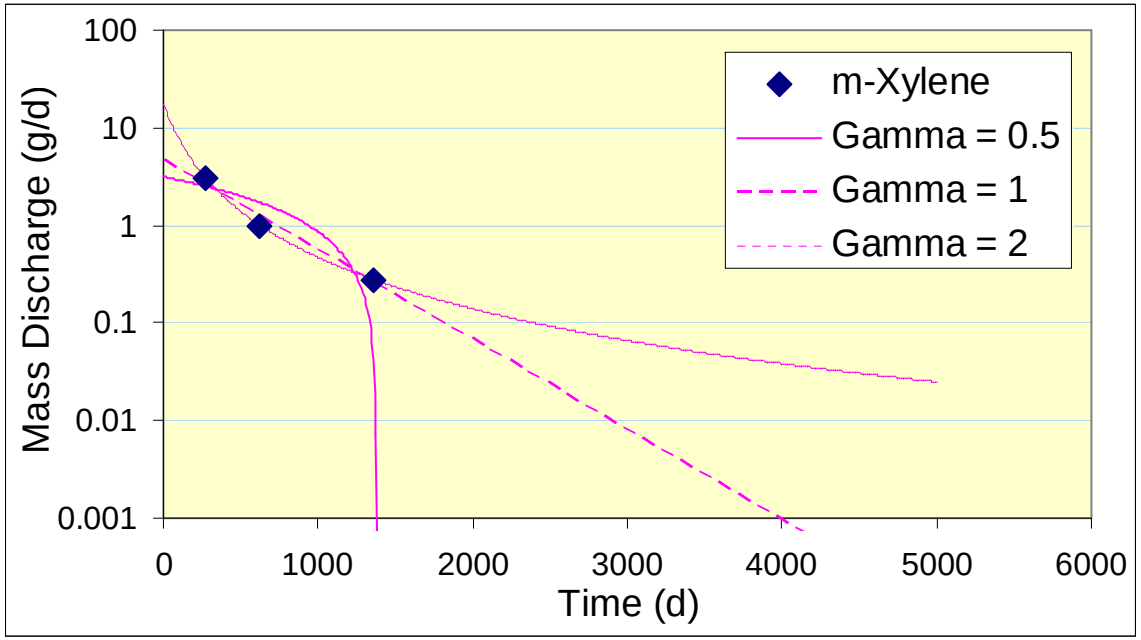


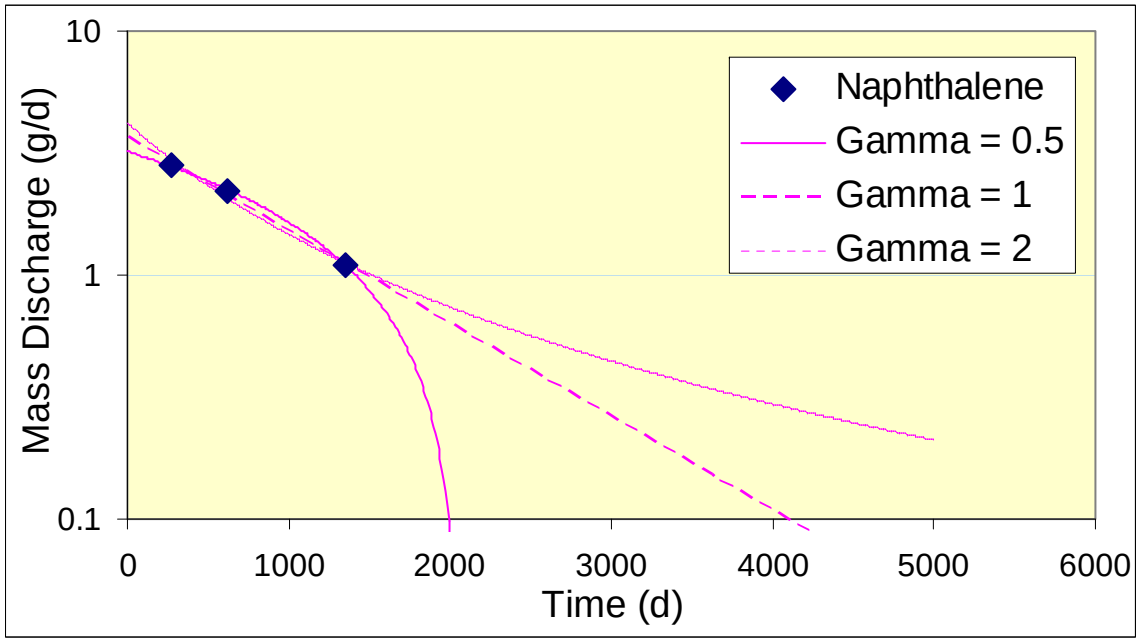


Data from Fraser et al., JCH, 100(2008), 101-115

(1) Estimate SZ M_D from Historic Data

(2) Fit Power-Law Model (Falta et al., 2005)



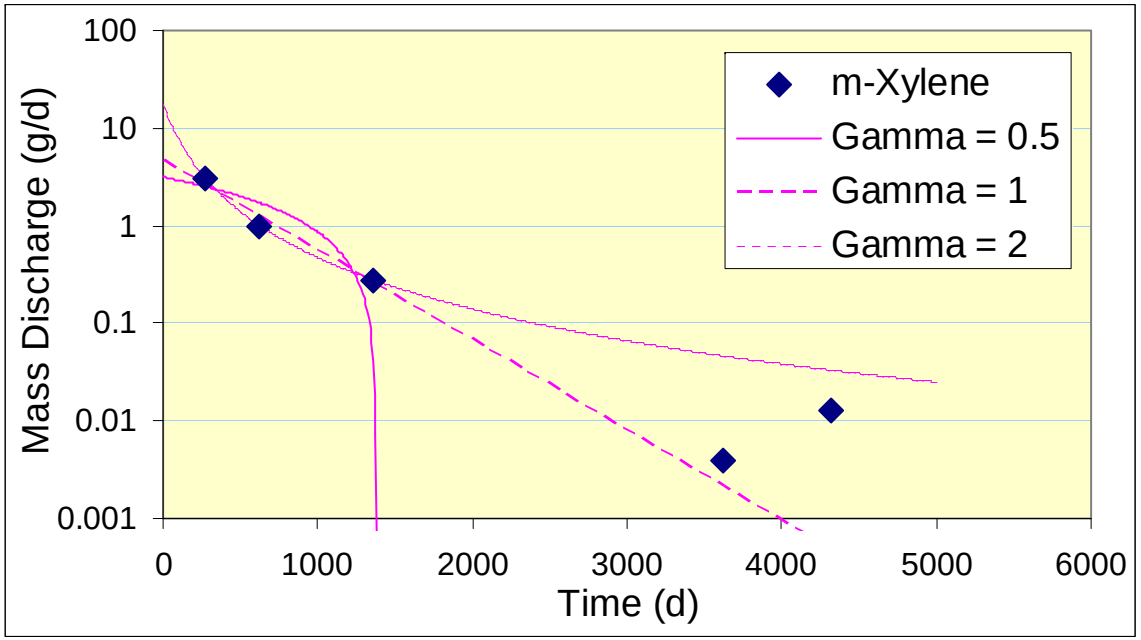


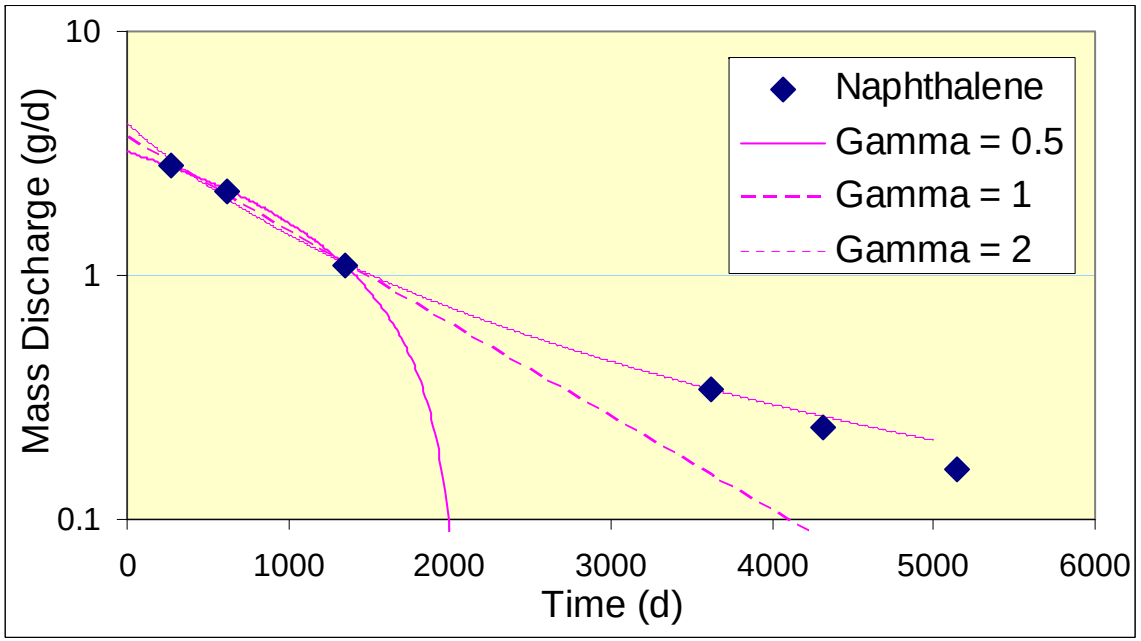
Data from Fraser et al., JCH, 100(2008), 101-115

(1) Estimate SZ M_D from Historic Data

(2) Fit Power-Law Model (Falta et al., 2005)

(3) Compare Predictions with Observations





Data from Fraser et al., JCH, 100(2008), 101-115

Source Mass Prediction

Compound	Reported Initial Mass (g)*	Predicted Initial Mass (g)		
		$\Gamma = 0.5$	$\Gamma = 1.0$	$\Gamma = 2.0$
m-Xylene	2,850	2,170	2,204	3,441
Naphthalene	7,110	3,298	4,176	6,076

Predictions based on:

(1) Approximately four years of M_D data at the Source Control Plane.

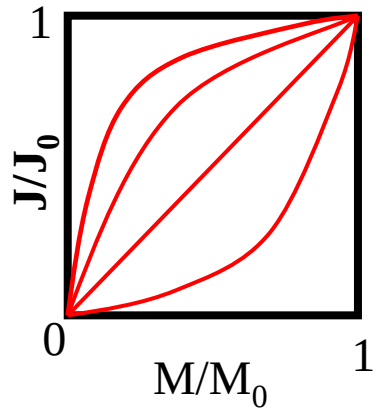
(2) Knowledge of the when the release occurred.

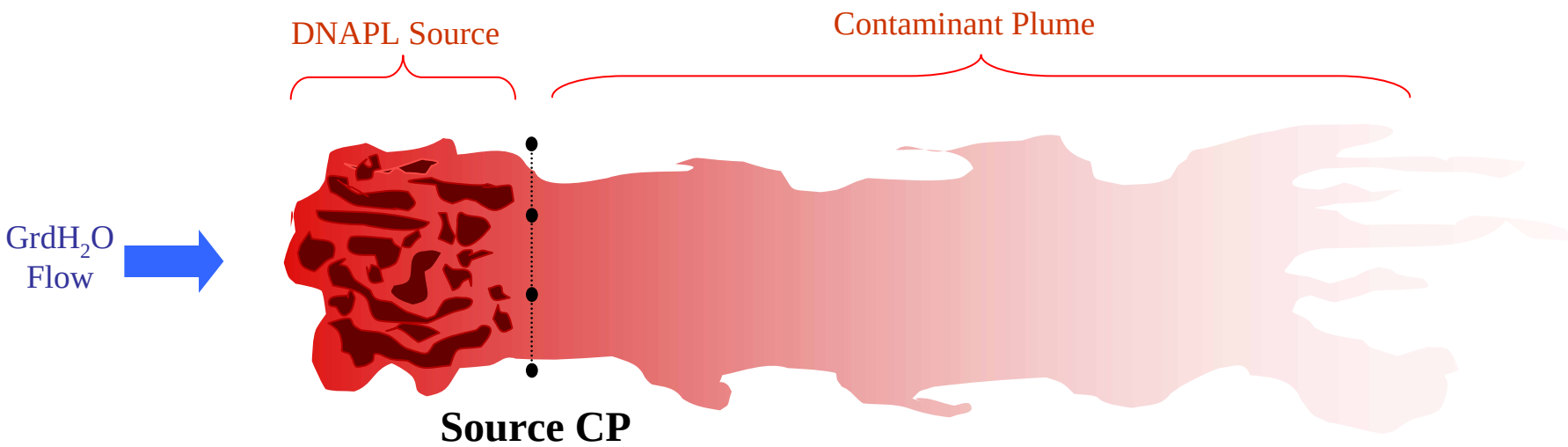
(3) Power Law Model with assumed values of Γ.

**Fraser et al., JCH, 100(2008), 101-115*

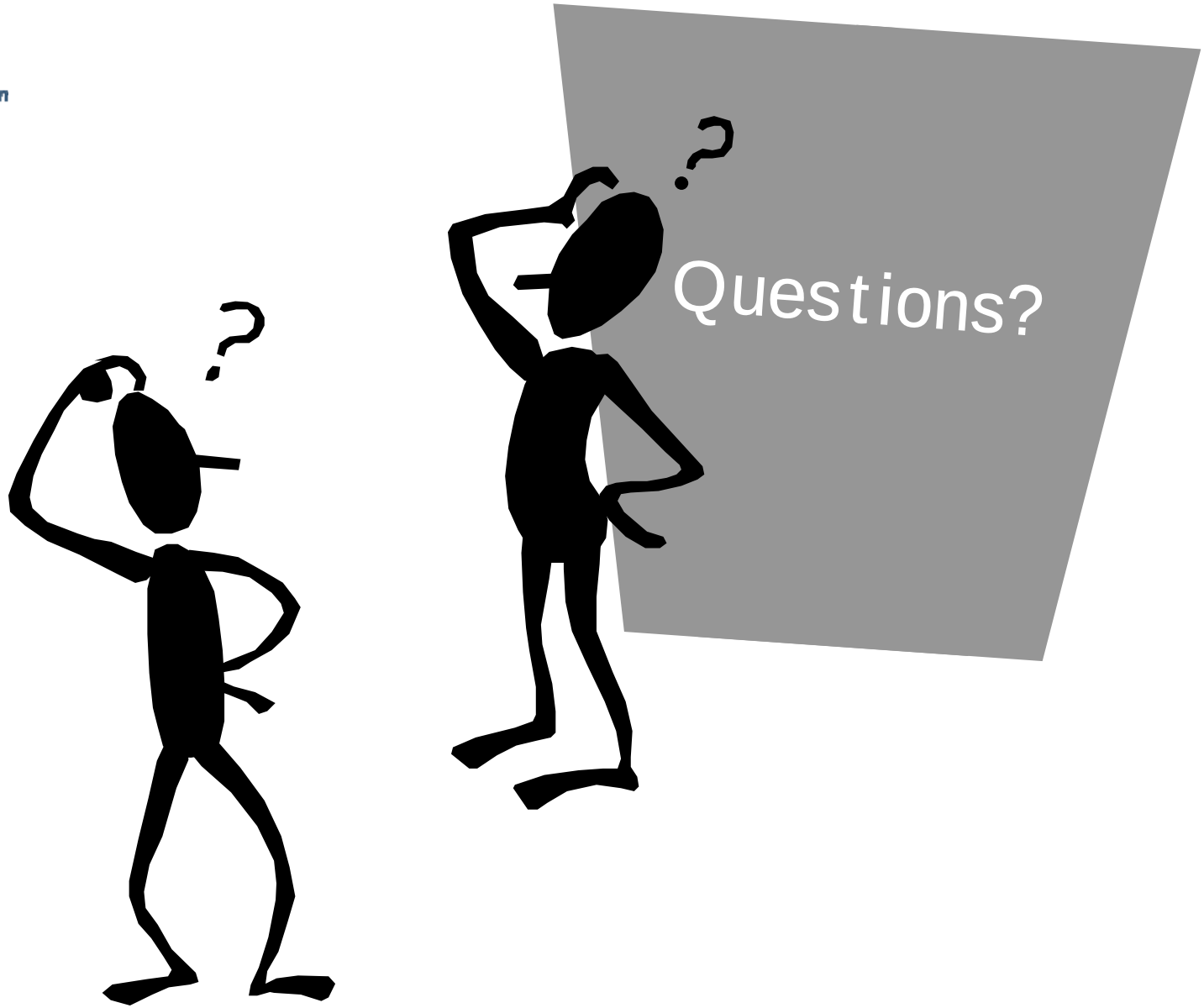
Flux-Based Concepts

➢Source Function





Next Steps

- Predict plume behavior (with and without source zone remediation)
- Qualifiers related to this example: Small field-scale research site, very high sampling density, emplaced DNAPL.
- Complete similar analysis at other sites, with more typical historical data sets.
- Augment predictions at selected sites with limited field measurements

United States Environmental Protection Agency