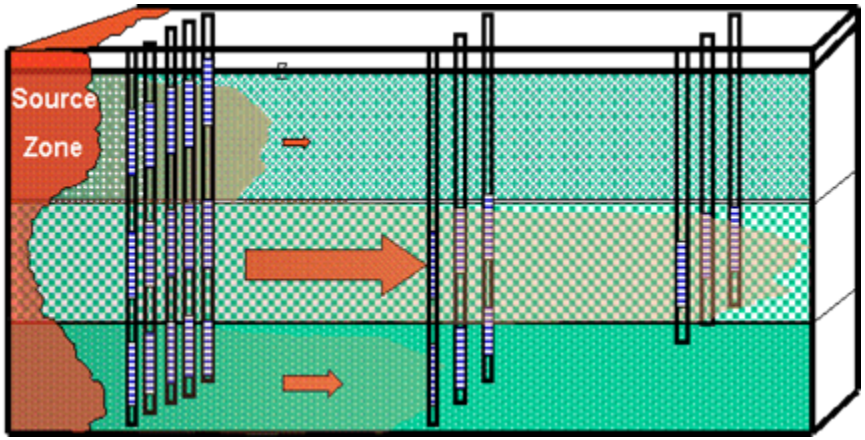
Mass Flux and Mass Discharge: Uses and Measurement



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ESTCP

MEASUREMENT AND USE OF MASS DISCHARGE AND MASS FLUX AT CONTAMINATED SITES

Start	End	Topic
8:30 AM	8:50 AM	Welcome & Introduction *(Dr. Hans Stroo)*
8:50 AM	9:40 AM	Flux-Based Site Management and Case Studies *(Dr. Michael Annable)*
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Use and Measurement of Mass Flux and Mass Discharge

An ITRC Technology Overview Document

Interstate Technology and Regulatory Council
(www.itrcweb.org)

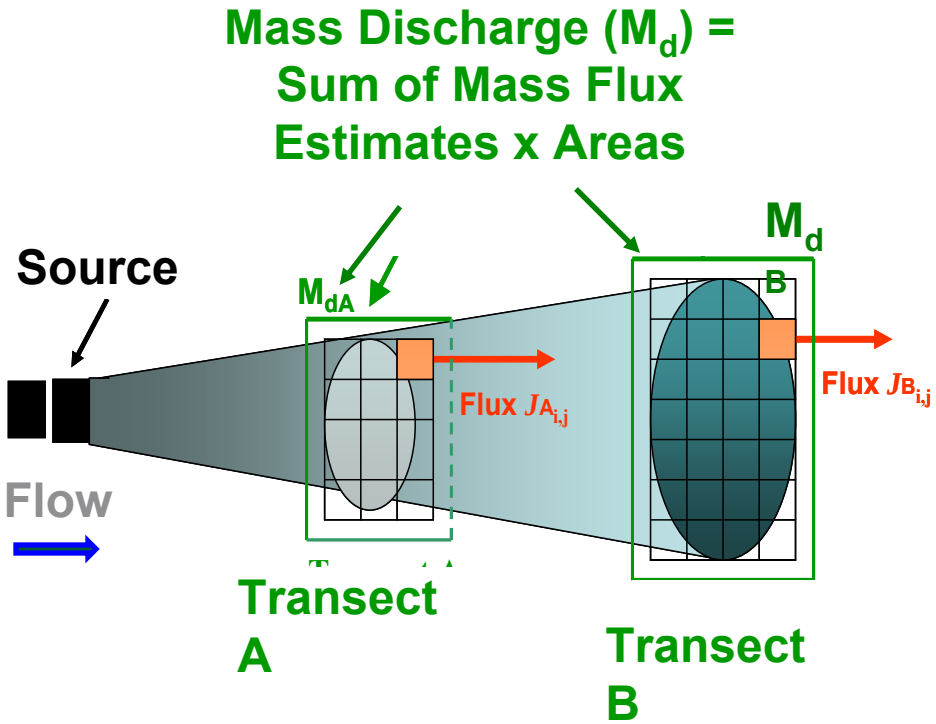
Definitions

Mass discharge

- The total mass of any solute conveyed by a plume at a given location.
- M_d is a scalar quantity, expressed as mass/time.

Mass flux

- The rate of solute mass moving across a specific defined area, usually a portion of the plume cross-section.
- MF is a vector quantity, w/ units of mass/time/area.



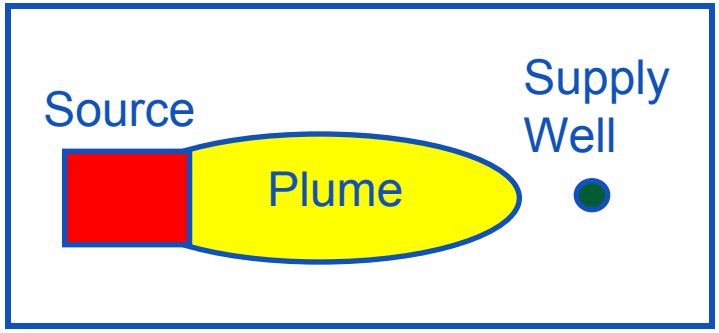
$J_{A_{ij}}$= Individual mass flux measurement at Transect A

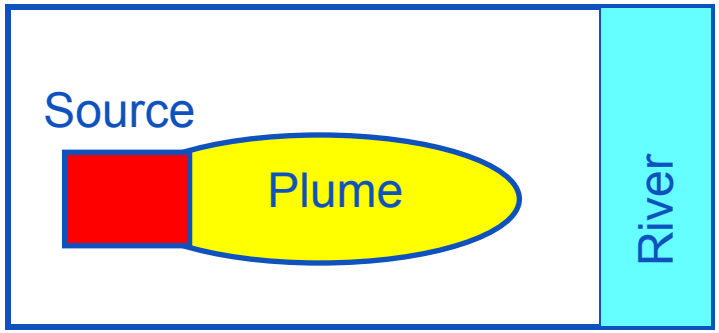
M_{dA}= Mass discharge at Transect A (Sum of all estimates of $J_{A_{ij}}$ x A)

Mass Flux and Mass Discharge: Why Care?

Better Understanding Yields Smarter Solutions!

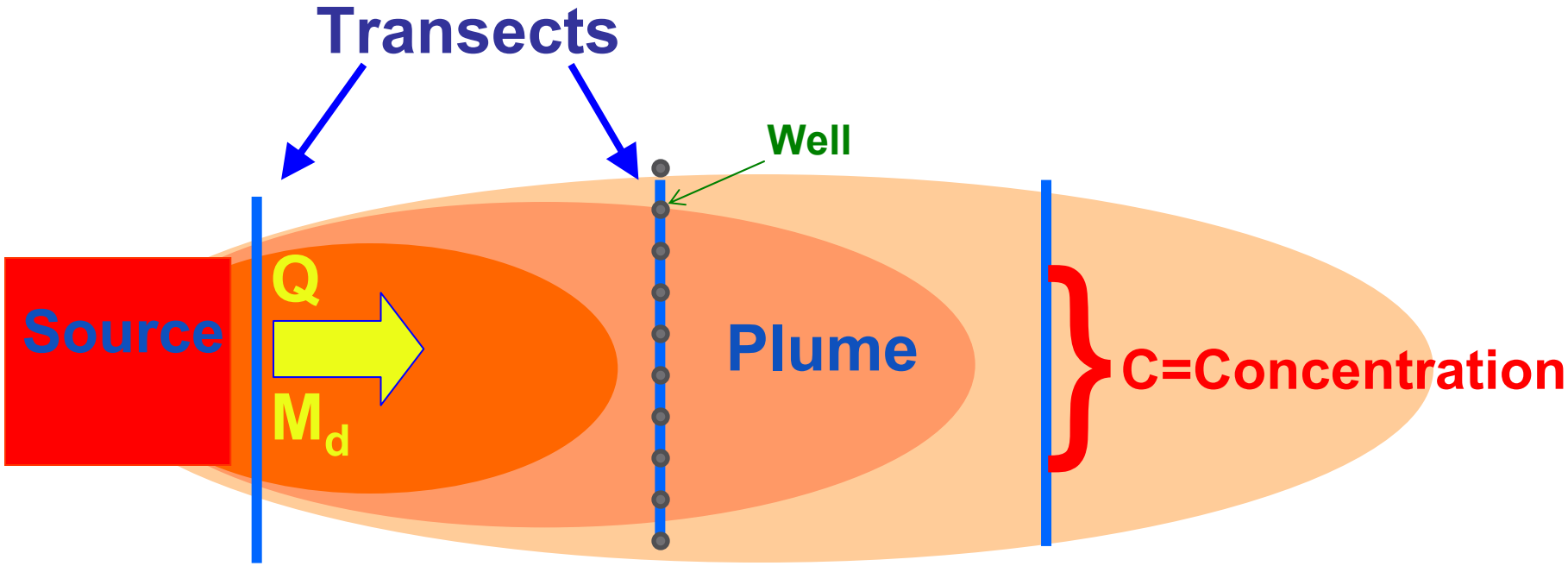
- To augment concentrations, not replace them
- Allows targeted remediation strategies
  - Most flux is in a small fraction of the volume
- Provides meaningful performance metrics
  - Links partial treatment to risk reduction
- Basis for existing groundwater models
  - Already used but often ignored
- Recent advances in techniques





Downgradient Risk Due to Mass Discharge NOT Concentration

Mass Discharge: Source or Plume Strength



Across any Transect, a Contaminant Plume Conveys:

Groundwater Discharge, **Q** (e.g., L/day)

Contaminant **Mass Discharge**, M_d (e.g., g/day or kg/year)

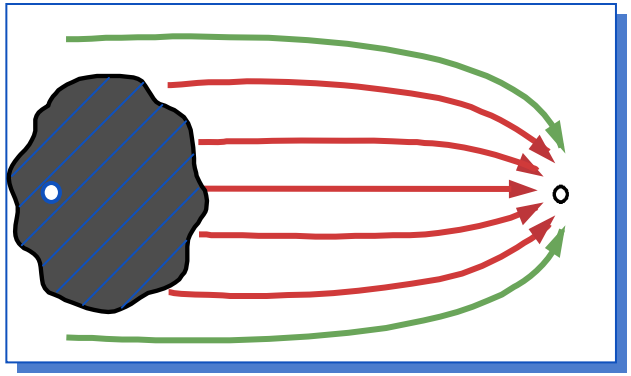
$$M_d = Q \times C \quad \text{(L/day x mg/L = mg/day)}$$

Figure 2-1

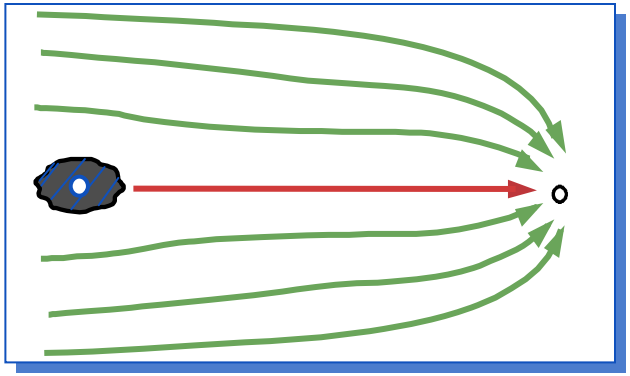
Mass Discharge and Concentration

- Concentration-based approach may not account for important site characteristics
  - Large vs. small releases
  - Pumping rate at the receptor well

Case A: Large Release
High Max. Conc. and High Md



Case B: Small Release
High Max. Conc. and Low Md



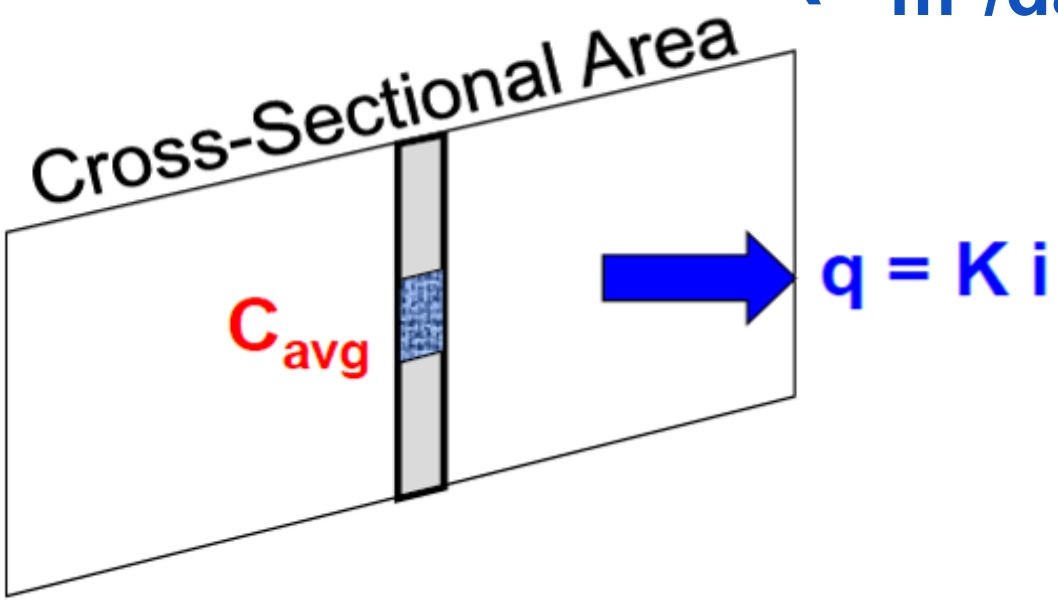
KEY POINT: **Evaluation of mass discharge (M_d) can increase understanding of site and be an important component of the site conceptual model**

What Is Mass Flux?

1. Specific Discharge, $q = K \times i$ $\left(\frac{L}{m^2/day}\right)$

2. Average concentration, C_{avg} (g/L)

3. Mass Flux, (J) = $q \times C$ $\left(\frac{g}{m^2/day}\right)$



Mass Flux Can Be Highly Variable

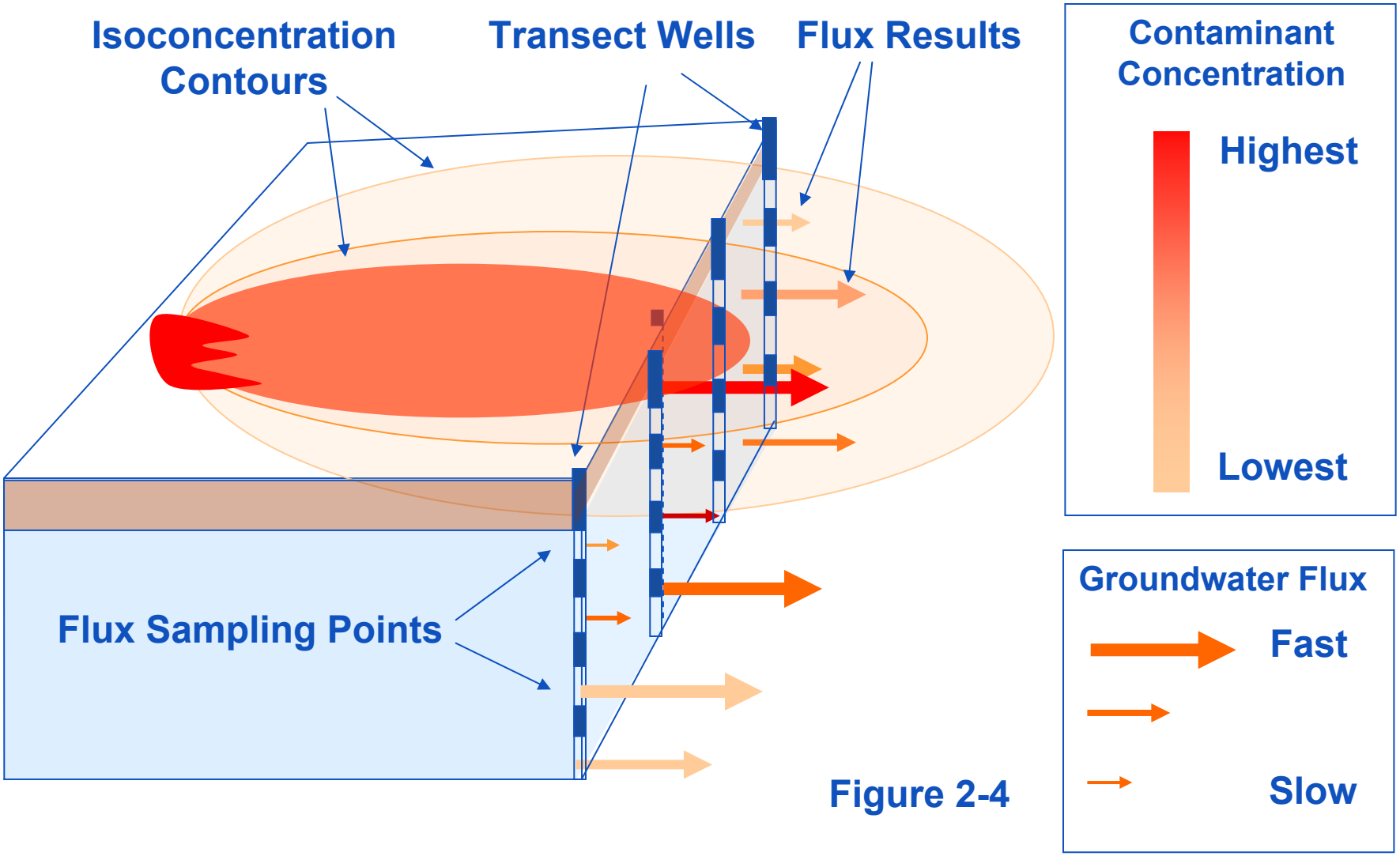
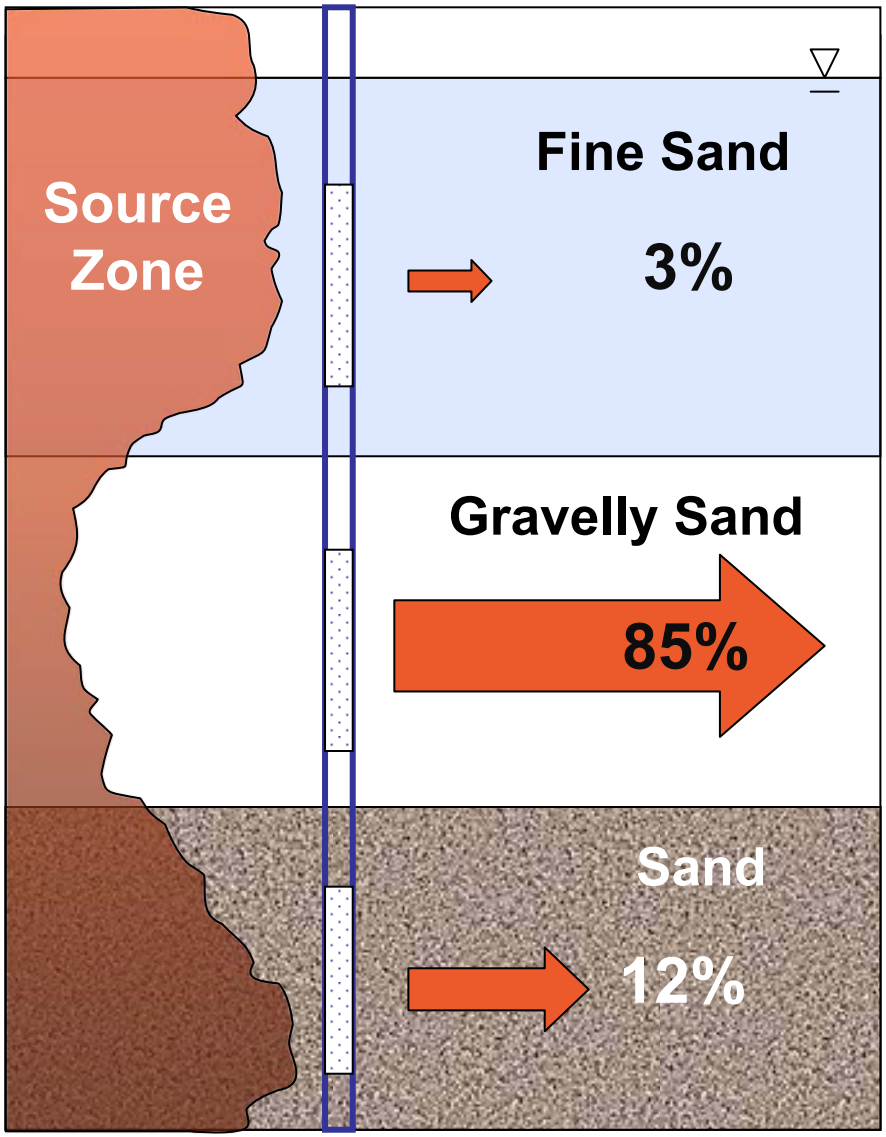


Figure 2-4

Mass Flux and Concentration Figure 2



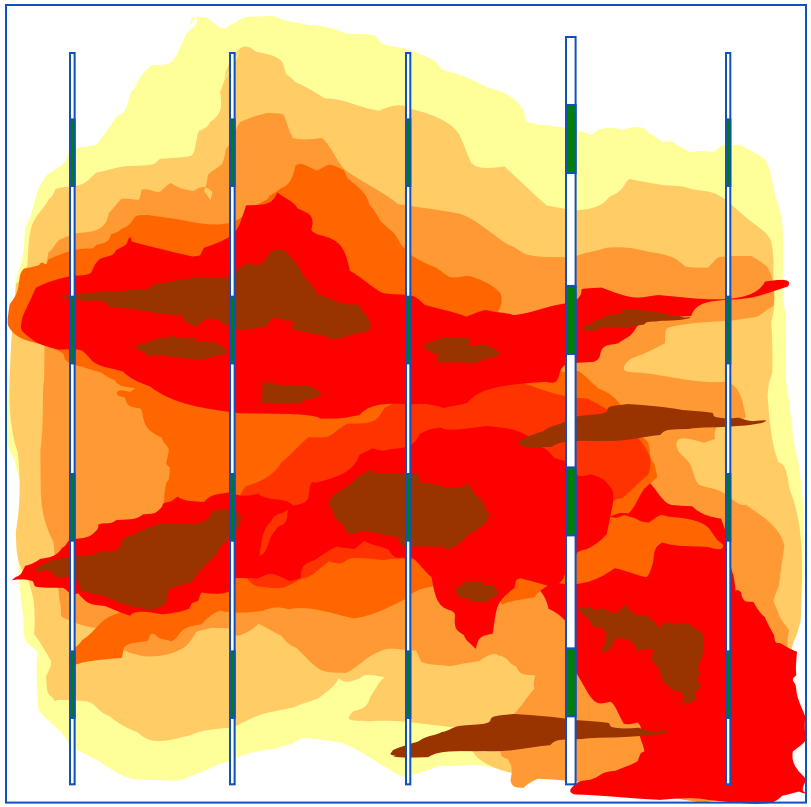
Mass Flux (*J*) = KiC

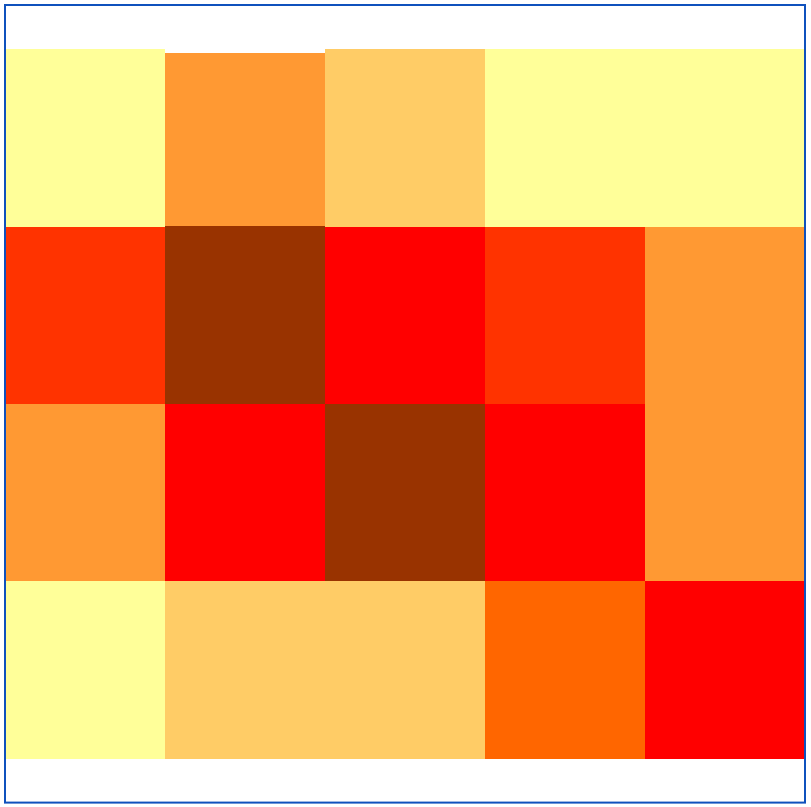
K = 1.0 m/day
i = 0.003 m/m
C = 10,000 μg/L
Mass Flux = 0.03 g/day/m^2

K = 33.3 m/day
i = 0.003 m/m
C = 10,000 μg/L
Mass Flux = 1 g/day/m^2

K = 5.0 m/day
i = 0.003 m/m
C = 10,000 μg/L
Mass Flux = 0.15 g/day/m^2

Interpolation



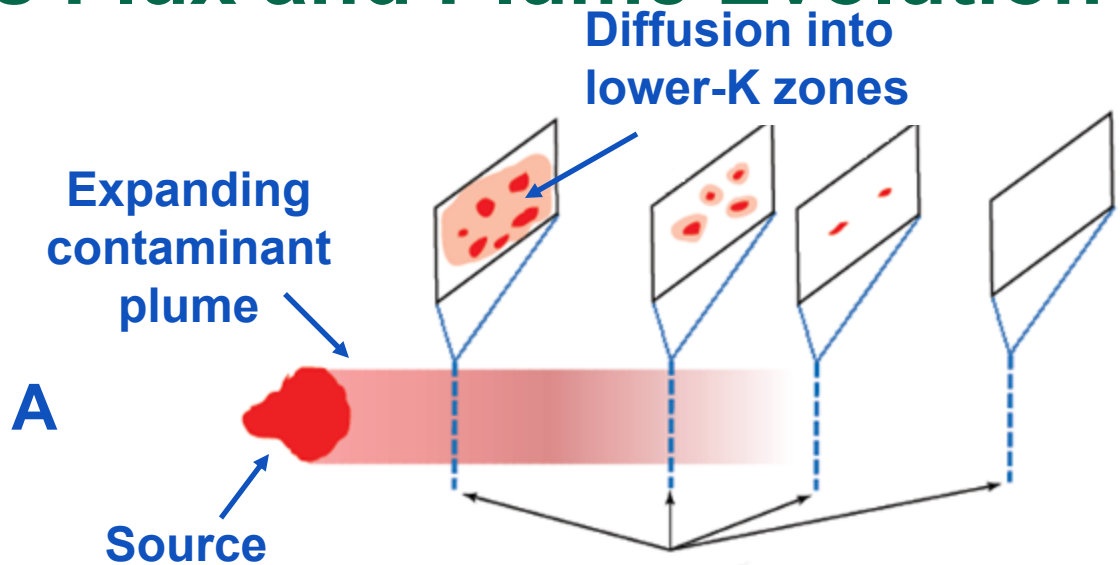


- Scale matters – what needs to be measured
- How to interpolate between highly variable data
- Most transects sample < 1% of the groundwater

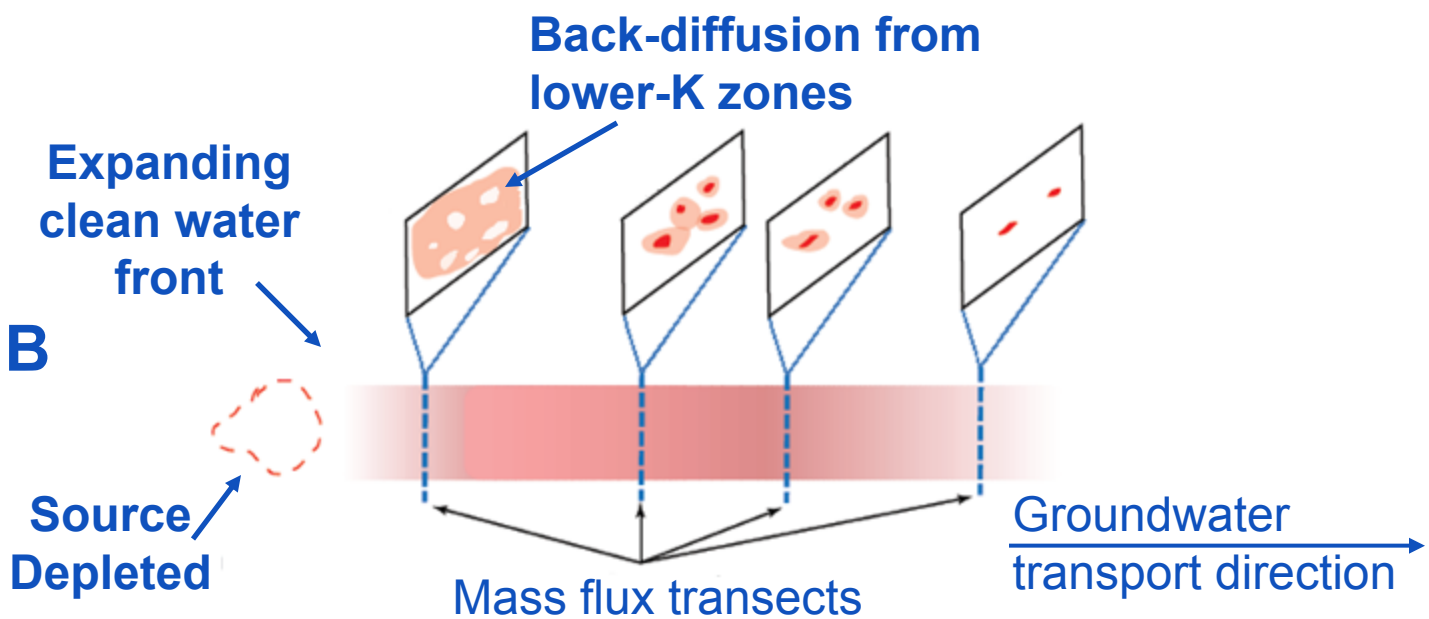
Mass Flux and Plume Evolution

Figure 2-6

Early Phases – Plume Expanding



Later Phases – Source Depleted



Uncertainty and its Management

- Uncertainty inevitable, but manageable
  - Similar uncertainty with concentration data
  - Usually a more difficult compliance goals
- Spatial heterogeneity and sample volumes
  - May need >> 1% (Li and Abriola, 2006)
- Source / Plume Boundary?
  - Hard to find and hard to define
- Solutions
  - Work Smart – Consider source architecture, plume evolution, hydrogeology, etc
  - Consider iterative investigation
  - Vertical variability is usually >> Lateral

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Flux-Based Site Management and Case Studies

Michael D. Annable

UNIVERSITY OF FLORIDA

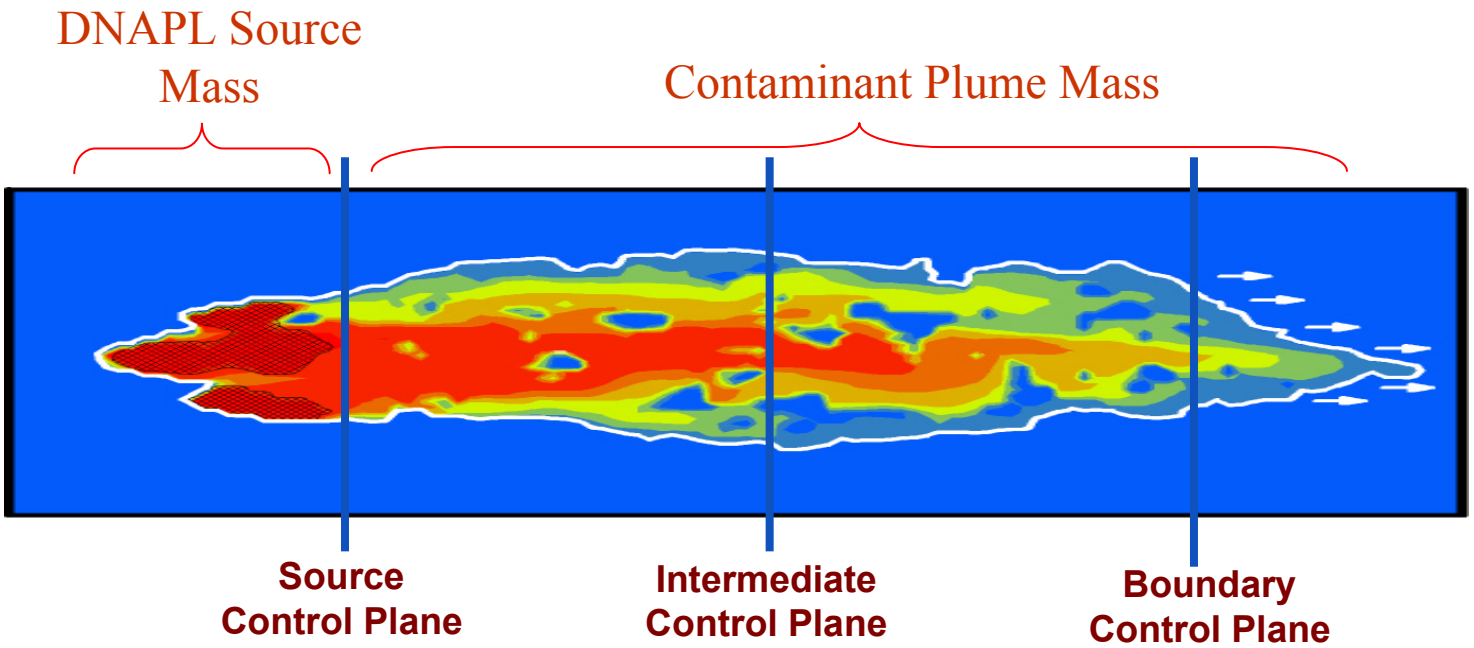
Presentation Outline

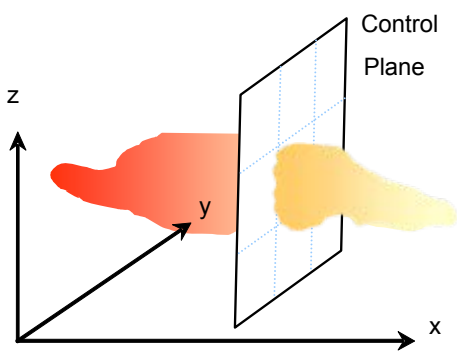
- Brief Review Site mass balance and mass flux concepts
- Source Strength Function Models
- Utility of Mass Balance and Mass Flux
- Field Site Case Studies
- Thoughts / Questions / Discussion

The following is based on the work of many individuals!

- Suresh Rao Purdue University
- Nandita Basu University of Iowa
- Kirk Hatfield & James Jawitz University of Florida
- Lynn Wood & Michael Brooks, US EPA-Ada
- Ronald Falta, Clemson University
- Greg Davis, Colin Johnston & Brad Patterson, CSIRO-Perth
- Ravi Naidu, Megh Mallavarupu & Subhas Nandy CRC-CARE & University of South Australia

Flux-Based Concepts





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

$$J_k = C_k q_k$$

$$q_k = Ki$$

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

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

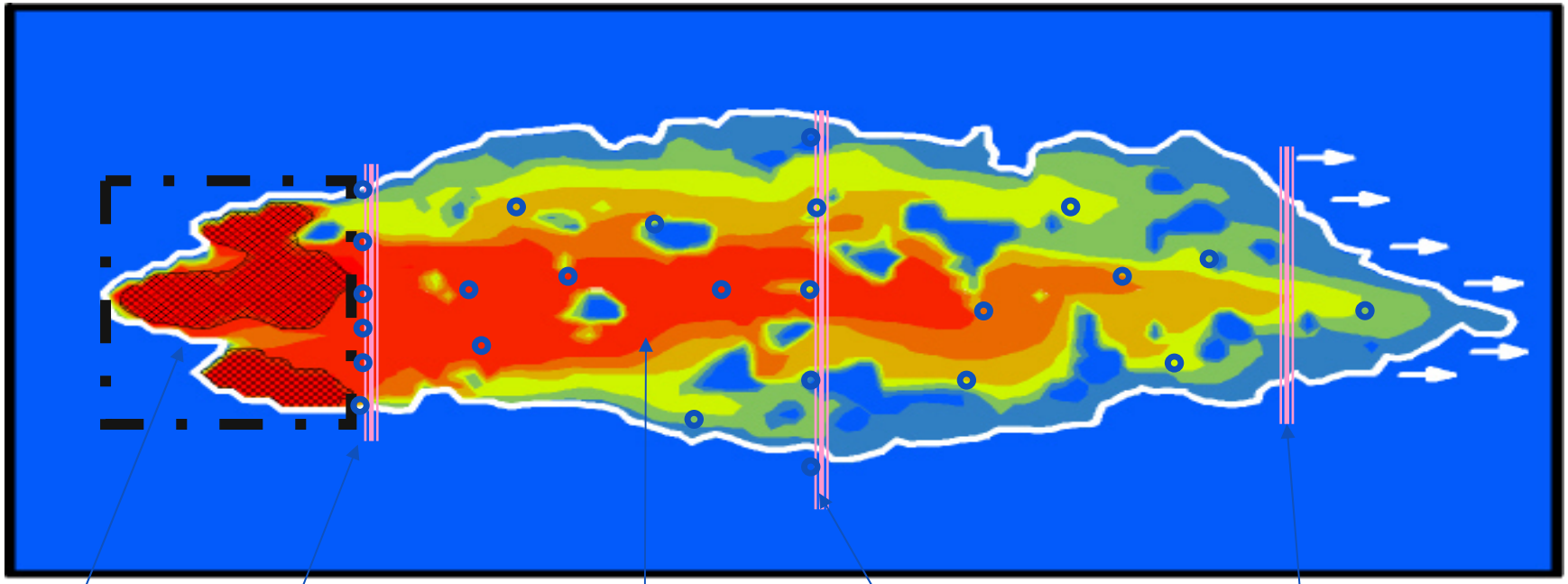
J = Mass flux [ML^2T^{-1}]

C = Concentration [ML^{-3}]

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

Site Monitoring:

Enhancing Archived Site Data



Source Mass
M_0 and M_{now}

Source Control Plane
$M_D(t)$

Plume Mass (Parent + Products)
$M_p(t)$ & $\lambda(t)$

Plume Control Plane

Pump & Treat Wells or Interception Trench or Stream etc.
$E(t)$

Contaminant Fluxes & Mass Discharge at Control Planes

$$M_D = \Sigma J_i A_i$$

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

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

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

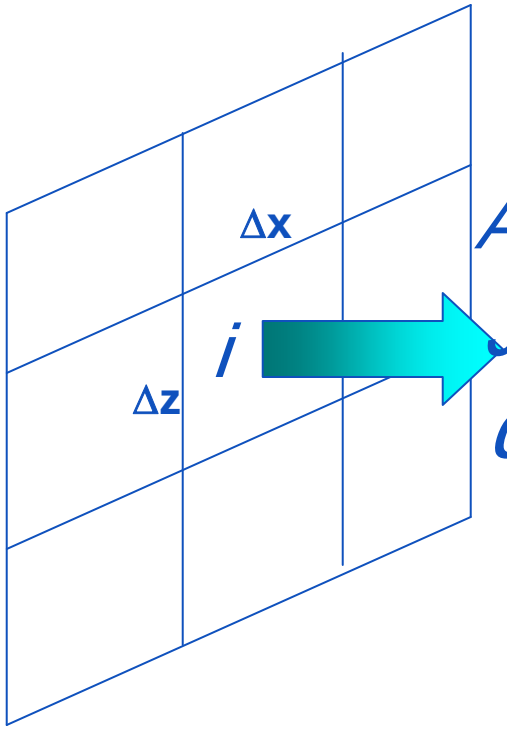
A_i = Area of element i (L^2)

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

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

j = Hydraulic gradient (-)

Control Plane (CP)



$A_i = \Delta x \, \Delta z$

$J_i = q_i C_i$

$q_i = -K_s j$

Enhanced data is generally collected at a higher spatial resolution

Control plane area should be just large enough to completely inscribe the dissolved plume width

Source Strength Function

The mass discharge change over time is defined as the "Source Strength Function" $M_D(t)$

Site Age

The site age can be considered as the fraction of the initial mass that has been removed from the source zone (R_m).

R_m = 0.2 indicates that only 20% of the mass has been removed.
R_m = 0.9 is an old site with 90% having been removed.

The **Source Strength Function** at DNAPL contaminated sites is a function of the architecture of the DNAPL source area and the complexity of the water flow field.

Source Strength Function Models

Power Law Model (Rao et al., 2001; Falta et al., 2005)

Exponential Decay (Exponent 1.0 in Power Law Model) (Newell et al., 2006)

Equilibrium Streamtube Model (Jawtiz et al., 2005)

Mass Transfer Model (Parker and Park, 2005)

Simplified Source Depletion Models

$C_f(T)$ = f (HS, DS)
$C_f(T)$ = Flux-avg. Concentration at Source Control Plane
HS = Hydrodynamic Structure
DS = DNAPL Structure

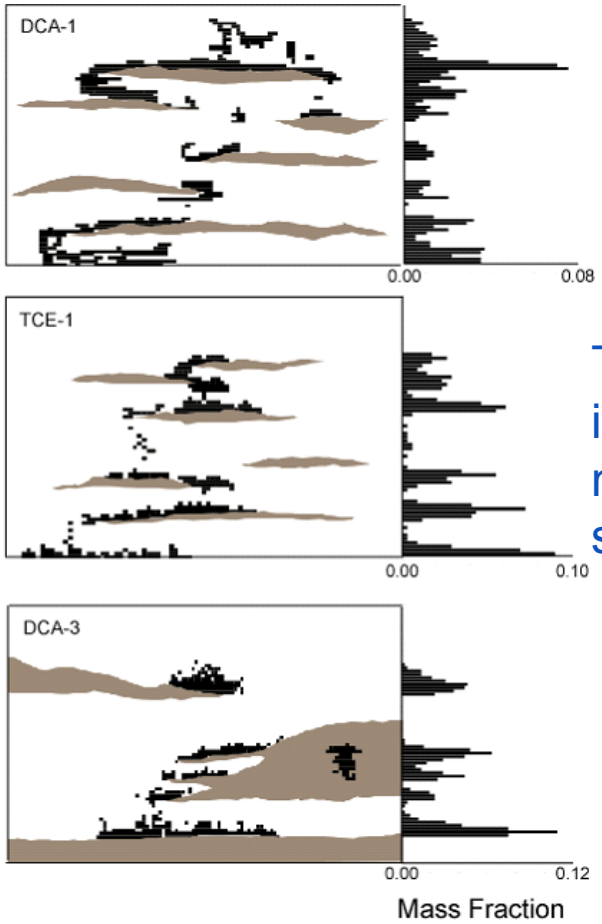
Streamtube Model (Jawitz et al. 2005)	$\frac{C_f(T)}{f_c C_s} = \frac{1}{2} - \frac{1}{2}\mathrm{erf}\left[\frac{\ln T - \mu_{\ln\tau}}{\sigma_{\ln\tau}\sqrt{2}}\right]$	μ_{lnT}= Mean of Hydrodynamic Field and DNAPL Architecture σ_{lnT}= Variability of Hydrodynamic Field and DNAPL Architecture
Power Law Model (Zhu and Sykes 2005)	$\frac{C_f(T)}{f_c C_s} = \left[\frac{M(T)}{M_o}\right]^{\beta}$	M_0 – Initial Mass of NAPL β - Variability Index
Damkohler Model (Parker and Park 2005)	$\frac{C_f(T)}{C_s} = 1 - \exp\left[-\left(\frac{\kappa_o L}{\bar{K}_s}\right)\left(\frac{M(T)}{M_o}\right)^{\beta_2}\right]$	M_0 = Initial Mass of NAPL, κ_0 β_2 = Mass Depletion Exponent

Basu et al., 2006, JCH

How can we estimate source strength function $M_D(t)$?

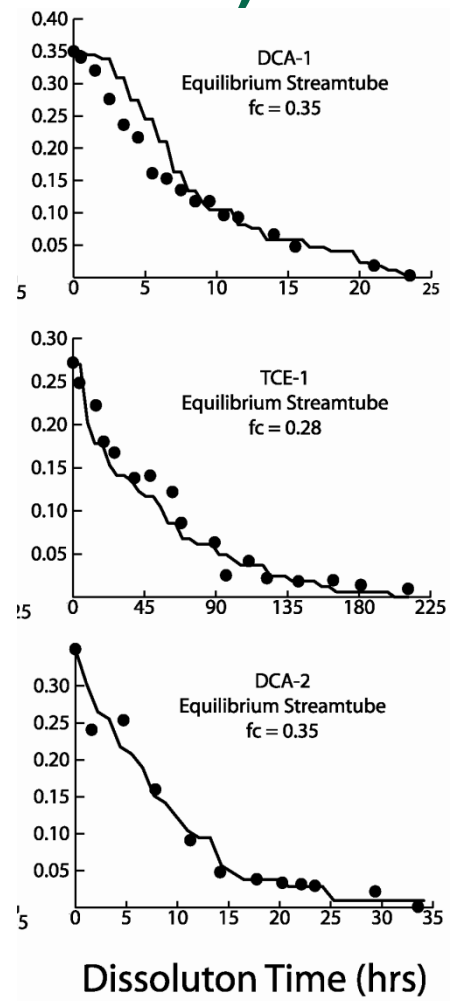
- Measure flux over time (we don't have time)
- Site historical data (transect method $M_D(t)$)
- Characterize the source zone architecture
- Incorporate plume mass balance

In laboratory experiments we can predict mass discharge using trajectory-integrated NAPL content (in the lab all information is known)



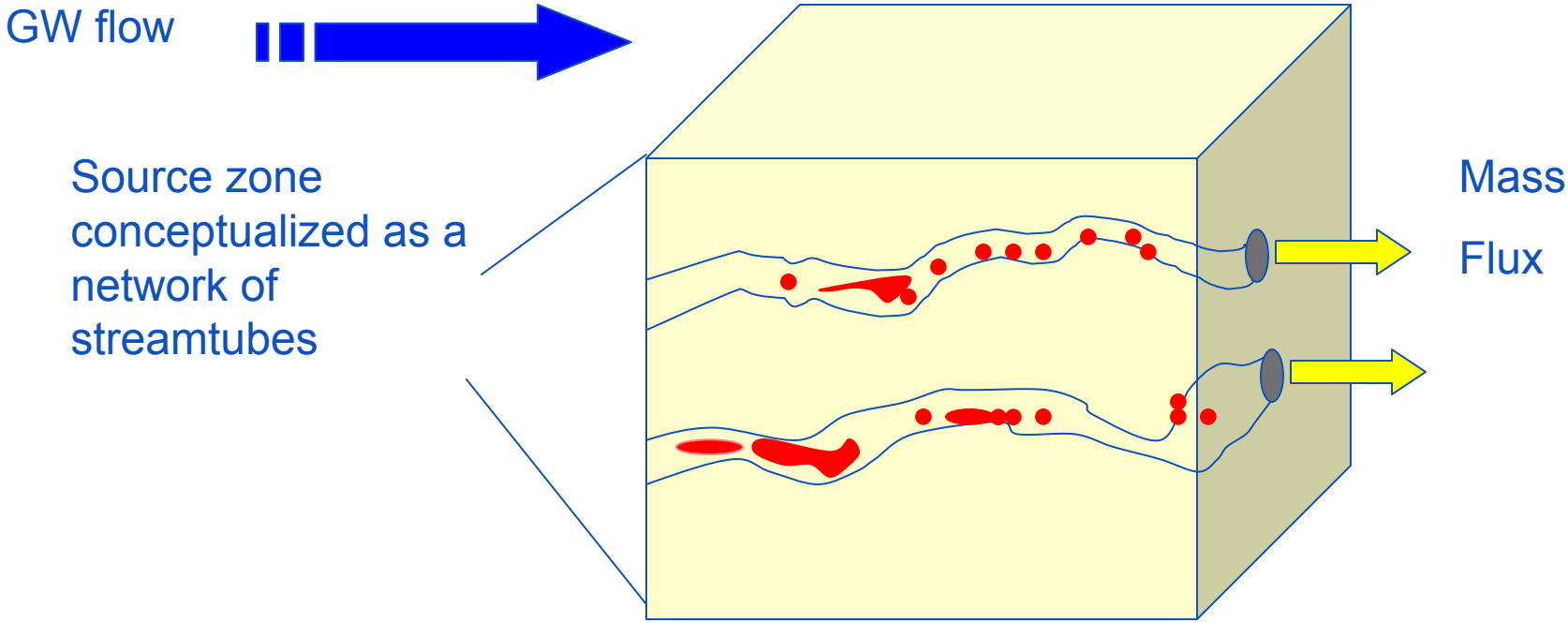
Trajectory-integrated measurements

Predicted dissolution compared to measured data



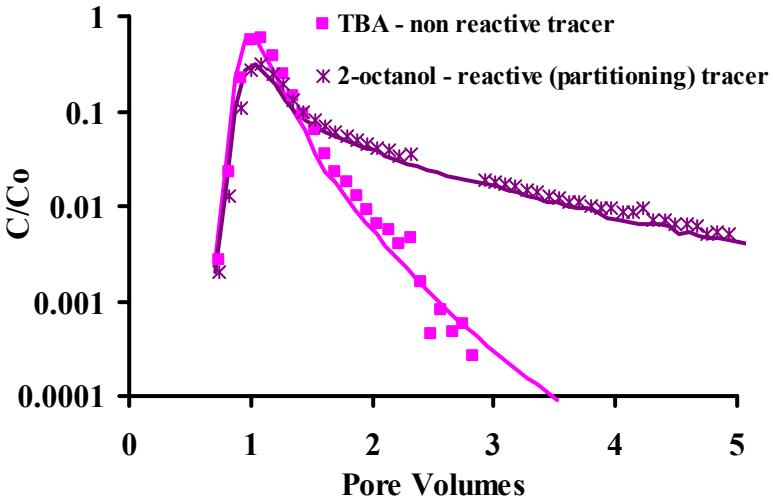
Fure et al., 2006. *JCH*.

Lagrangian definition of source zone architecture



Each streamtube characterized by velocity (travel time) and NAPL saturation

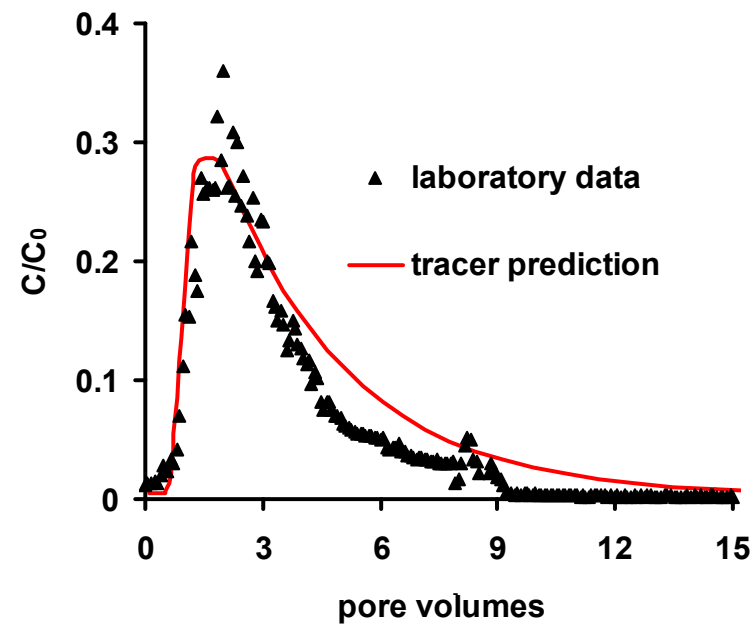
Mass discharge can be predicted using trajectory-integrated NAPL content based on partitioning tracers



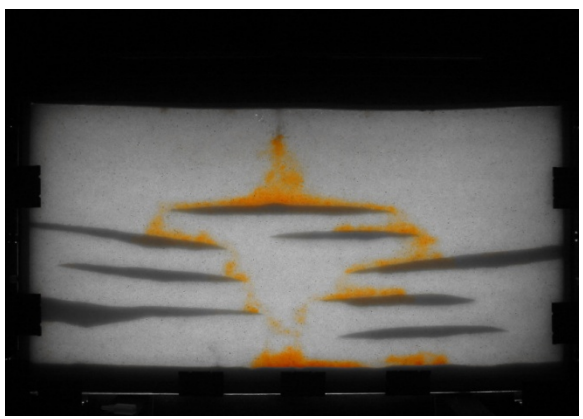
μ_{lnT}= 0.265 Mean of the tracer travel time distribution

σ_{lnT} = 1.084 Standard deviation of the tracer travel time distribution

Also characterize the trajectory average NAPL content with μ_{lnS} and σ_{lnS}



33 cm

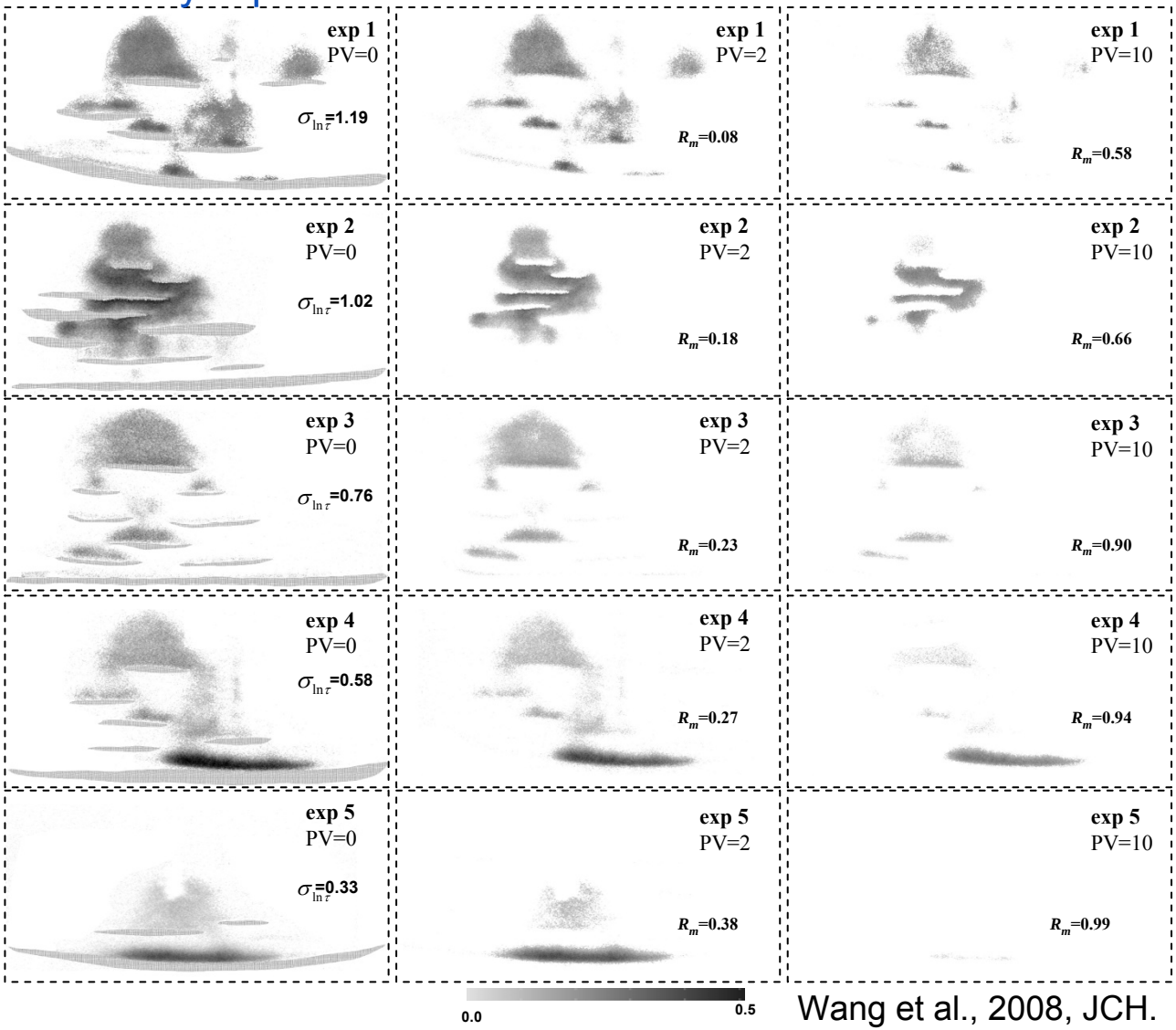


61 cm

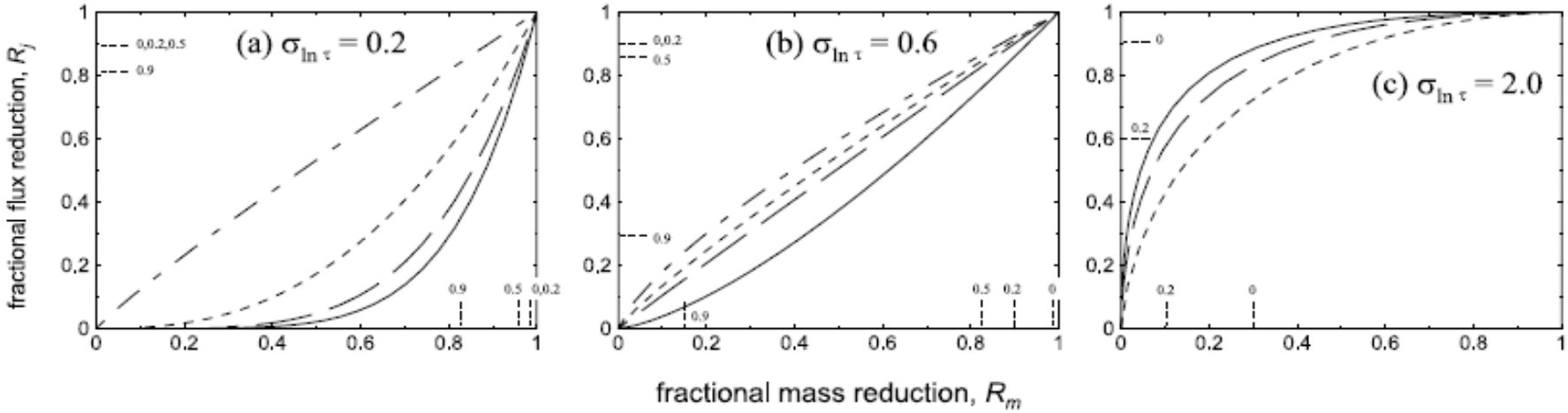
Porous media heterogeneity in discrete layers

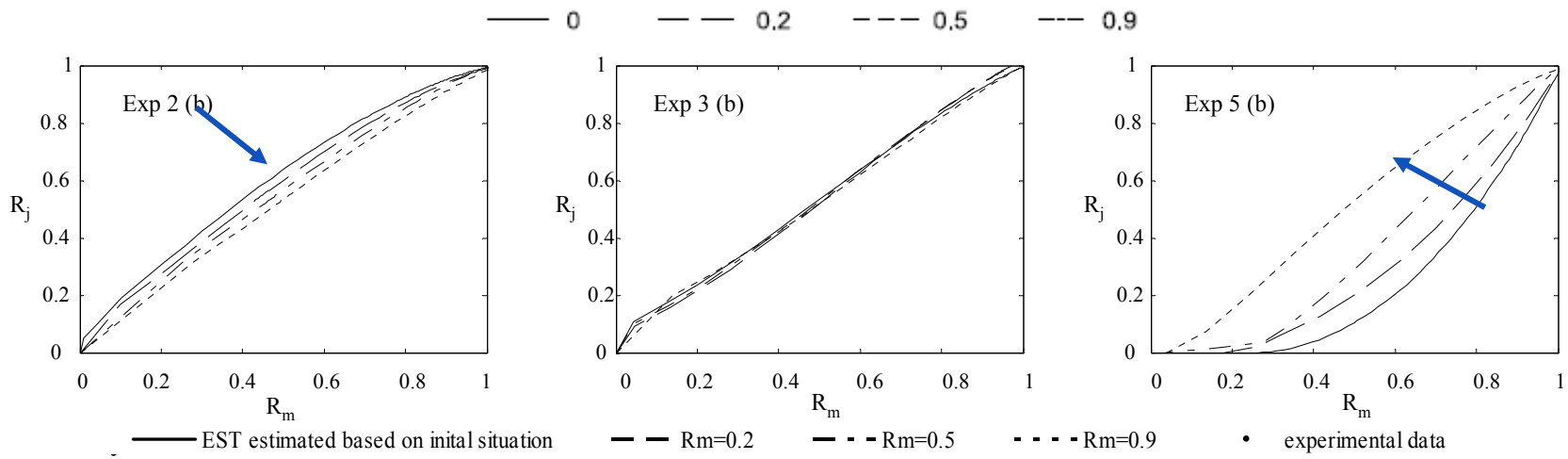
Chen et al., ES&T in review.

A wide range of DNAPL architectures were evaluated in laboratory aquifer models



Wang et al., 2008, JCH.
Chen and Jawitz, 2009. ES&T (in review).

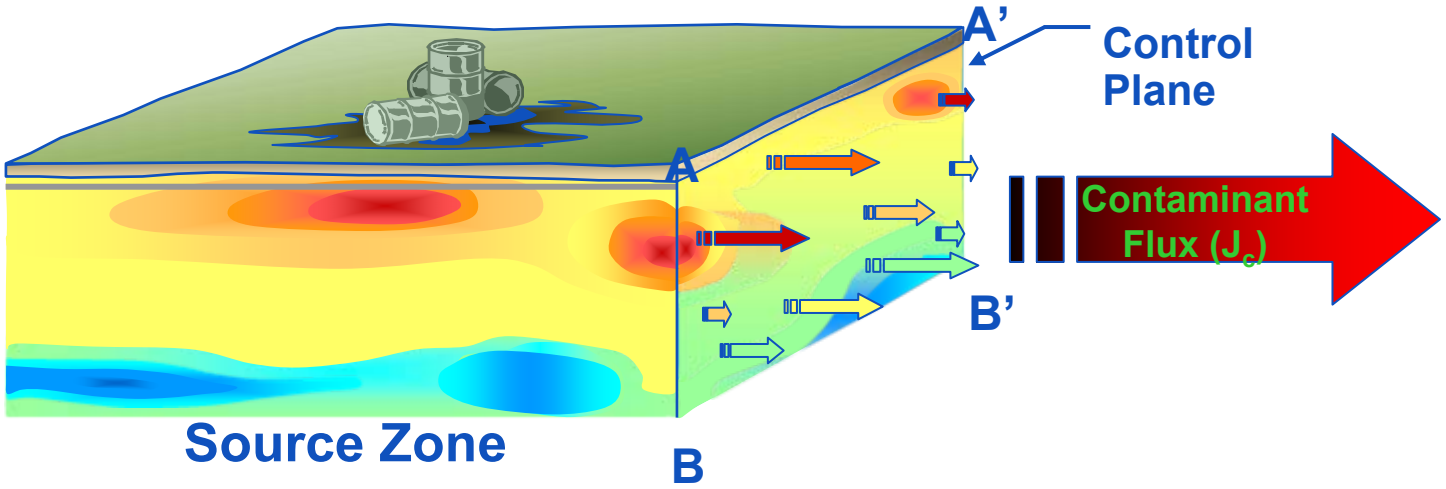




Chen and Jawitz, 2009. ES&T (in review).

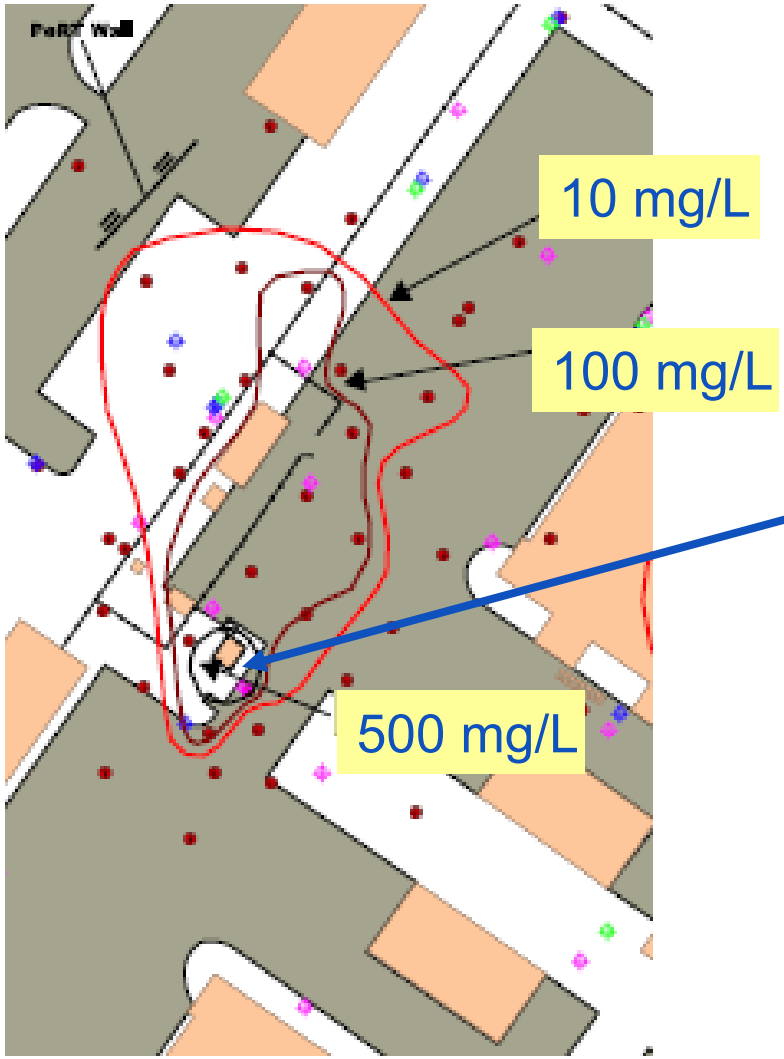
Results indicate that all sites approach an exponential decay model

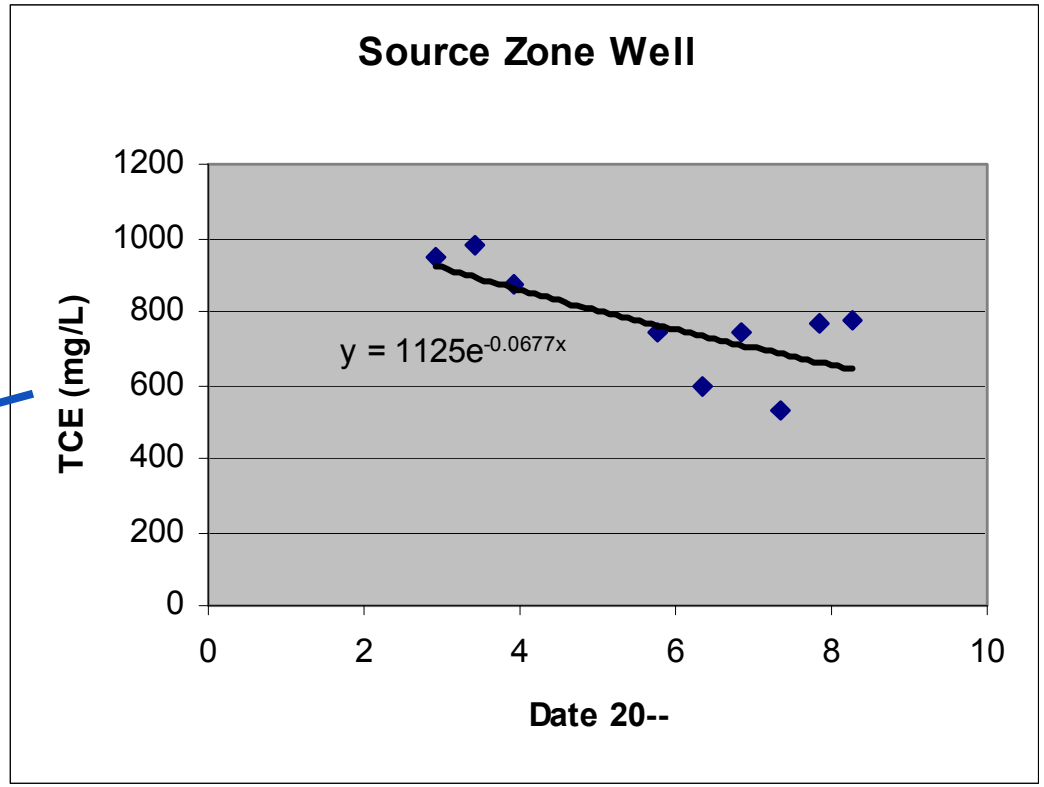
Challenge is lack of data
(due to cost and focus on contaminant delineation)



Look at Hangar K site Cape Canaveral for basic historic site data evaluation

Hangar K Source Strength Function Data





Shows slow decline in source zone TCE concentration (requires wells in or near the source zone)

If we assume simplest source strength function model - exponential decay

The solution for the exponential decay model can be written:

$$C = C_0 \exp\left(-\frac{J_0}{M_{A,0}} t \right)$$

For the Hangear K site using an estimated Darcy flux of 7 m/yr we can solve for the upgradient mass $M_{A,0}$ = 90 Kg/m^2. The approximate size of the source zone can be estimated to provide a source zone of about **2400 Kg**.

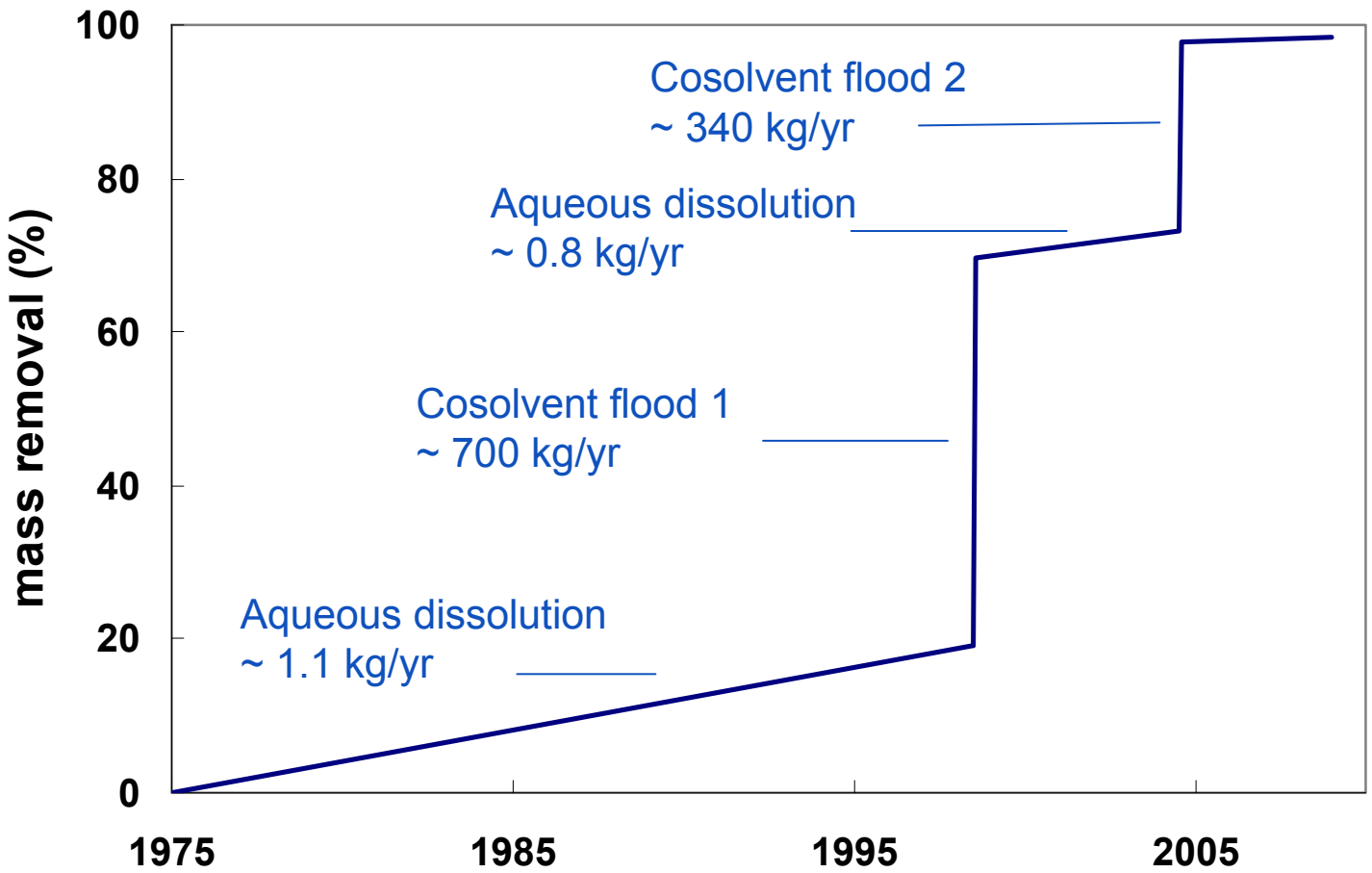
Note that the average NAPL saturations, S_N, in the source zone can be also calculated based on an assumed porosity of 0.33

$$S_N = \frac{V_N}{V_V} = 0.04$$

The Basic Mass Balance Provides an Estimate of Site Age

- Plume Mass based on direct push sampling event was about 1500 Kg
- Thus site age is about 0.38 (38% of mass has been discharged from the source zone)
- Mass Balance can also be used to improve the estimated source strength function (not a simple exponential function)

Flux and Mass Balance Calculation can be used to Produce a Site Mass Removal History (Age) Sages Drycleaner Site Florida



Source Depletion

$$C_s(t) = \frac{C_0}{M_0^{\Gamma}} \left\{ \frac{(\Gamma - 1) V_d A C_0}{M_0^{\Gamma}} t + M_0^{1-\Gamma} \right\}^{\frac{\Gamma}{1-\Gamma}}$$

Falta et al. 2005a

where,

$C_s(t)$ and C_0 =

flux-avg. conc. at source CP at time = t; and t=0

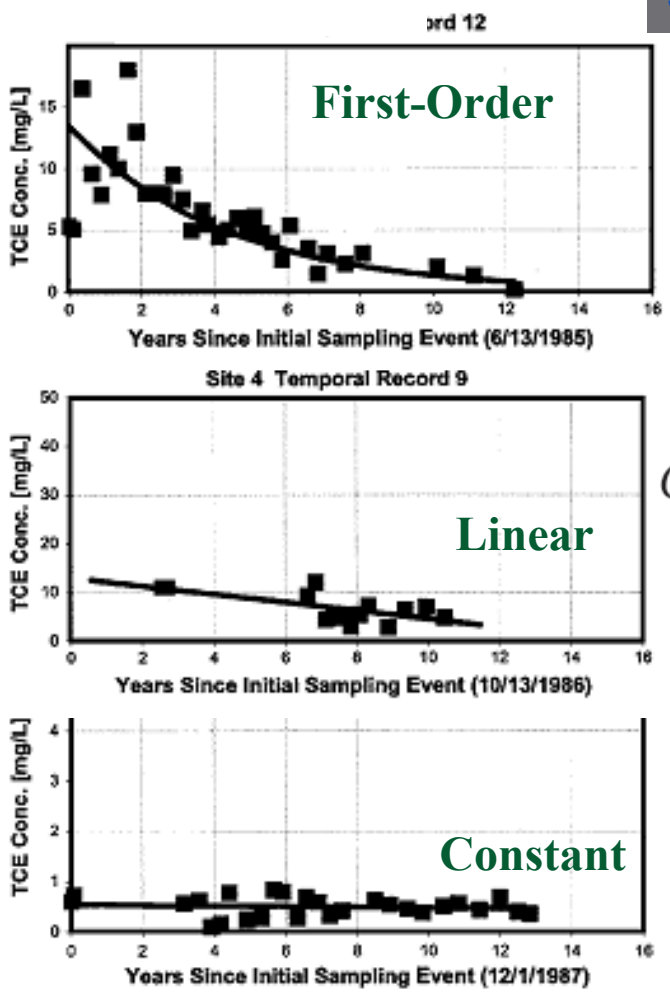
M_0 = initial source mass

V_d = Darcy flux

A = Source CP Area

Γ = empirical constant

Newell et al., 2006, *Jour. Env. Eng.*
Suarez et al., 2004, *Remediation.*



Simple Cases

Γ=1

$$C_s(t) = C_0 e^{-\frac{V_d A C_0}{M_0} t}$$

Γ = 0.5

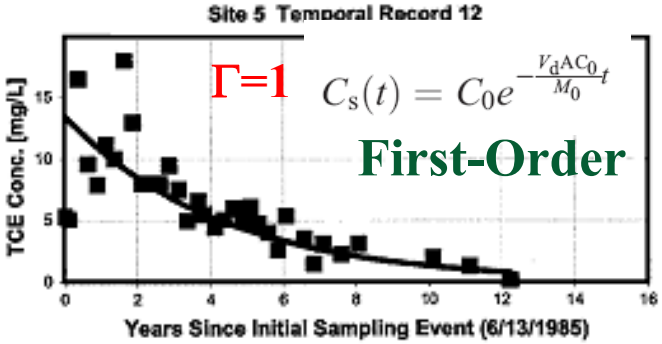
$$C_s(t) = C_0 - \frac{V_d A C_0^2}{2 M_0} t$$

Γ = 0

$$C_s(t) = C_0$$

Source Mass Estimation

Fit monitoring well data to standard functions to estimate a value of Γ



Method A: Requires only MW data

1. Monitoring well data over time fitted with an exponential to estimate k.
2. Now, $M_{t=a} = V_d A C_{t=a} / k$
3. Here, a = time from which sampling data available
4. Thus:

$$M_{t=now} = M_{t=a} \exp\left(-k t_d\right)$$

Method B: Requires mass discharge (M_D) and plume mass (M_P)

$$M_D(t) = M_{D,0} \exp\left(-\frac{M_{D,0}}{M_0} t\right)$$

$$M_P(t) = \int_0^t M_{D,0} \exp\left(-\frac{M_{D,0}}{M_0} t\right) dt$$

Two equations and two unknowns – solve for $M_{D,0}$ and M_0

Estimate present source mass using

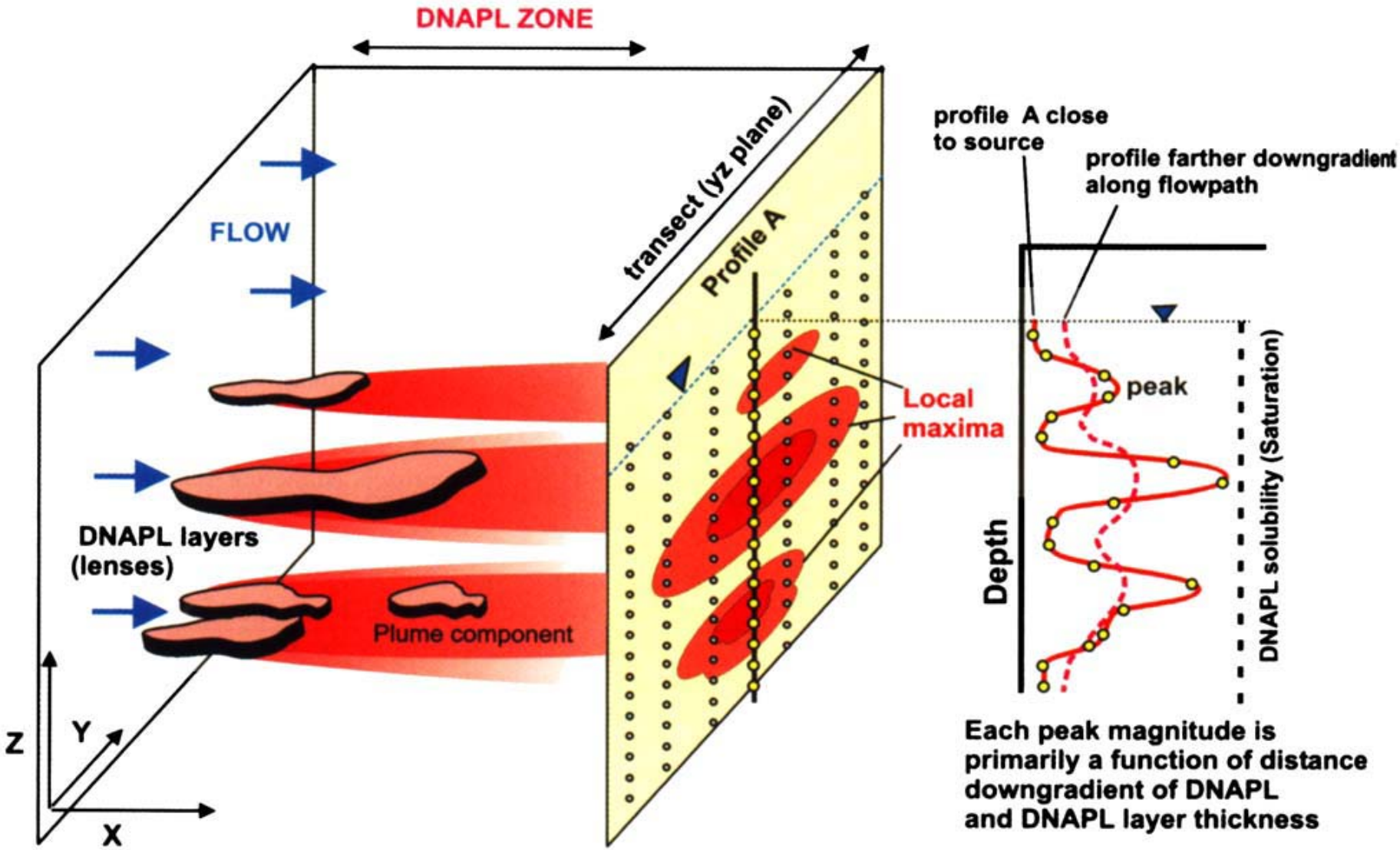
$$M_{t=now} = M_0 \exp\left(-\frac{M_{D,0}}{M_0} t\right)$$

We can improve on our mass balance through Mass Flux Characterization

Methods Currently in Use

- Transect of fully screened wells and hydraulic tests
- Transect of multilevel samplers with measured K field
- Integral pumping test (Tübingen)
  - Bockelmann et al. JCH 2001
- Transect of passive flux meters (Florida)
  - Hatfield et al. JCH 2004
- Direct push techniques across control plane

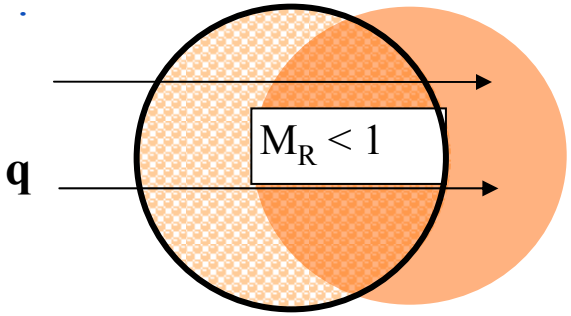
Multilevel Sampler Network Flux Control Plane



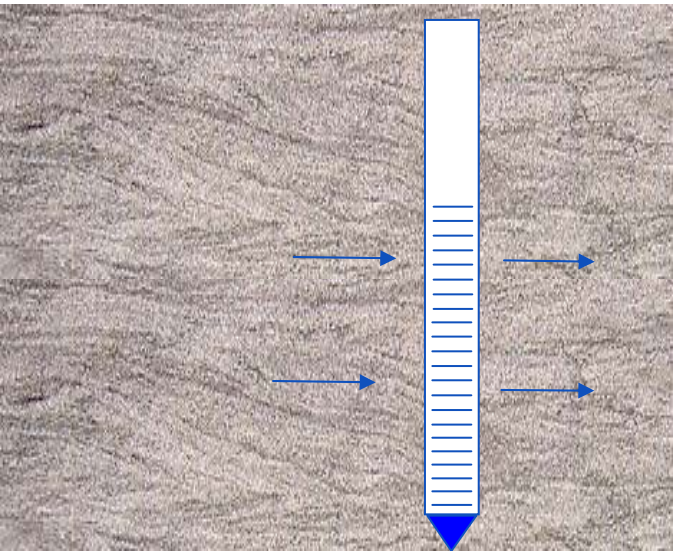
Guilbeault et al. GROUND WATER 43(1): 70-86, 2005

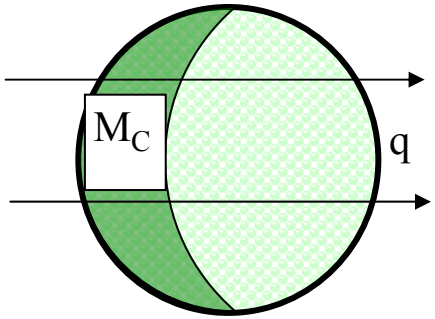
Passive Flux Meter

Groundwater & Contaminant Fluxes



Displaced resident tracers for groundwater flux



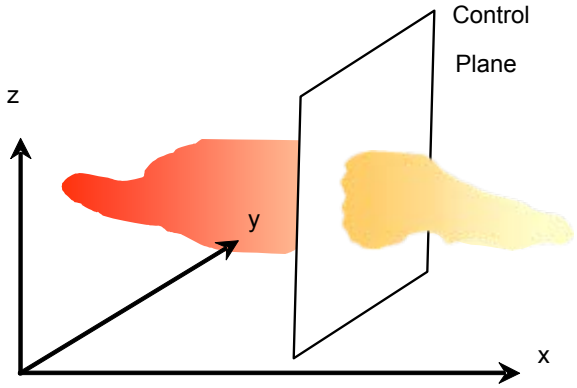


Captured contaminants for contaminant fluxes

Hatfield et al., 2004 JCH

Utility of Flux Data

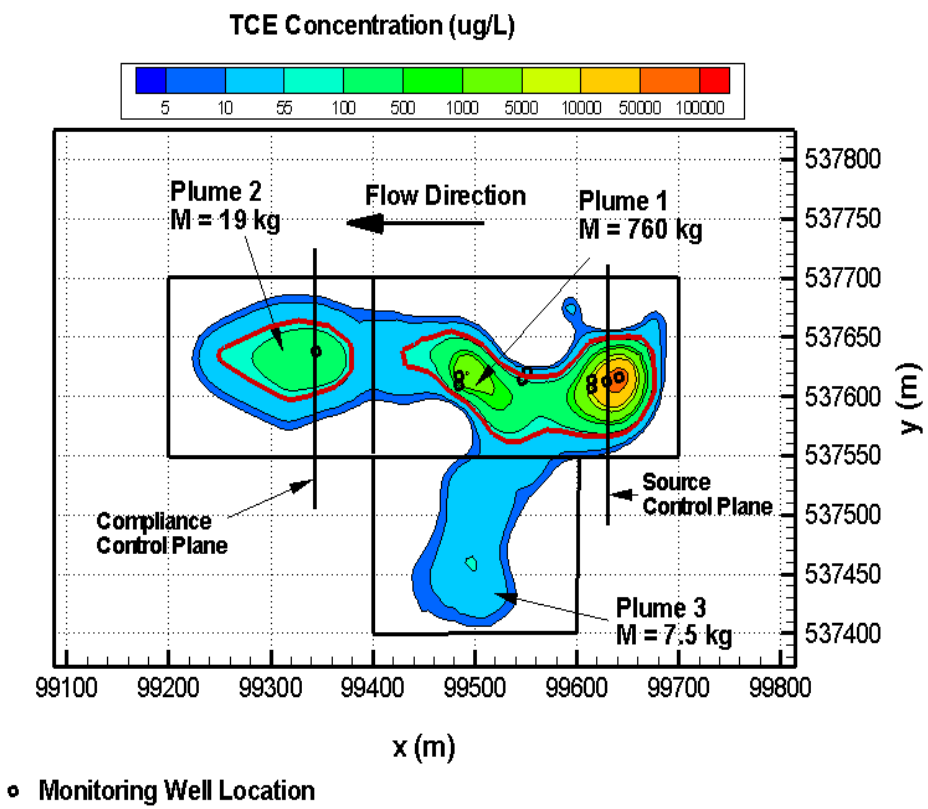
- Site mass balance
- Remedial performance
- Long term predictions
- Flux based target objectives (Assimilative capacity of the aquifer)



Remedy Options?
Look at some Case Studies

Options	Stable $M_D(t) = \lambda(t)$	Advancing $M_D(t) > \lambda(t)$	Shrinking $M_D(t) < \lambda(t)$
1. **No remediation (MNA?)**	• if $\lambda(t)$ is constant (?), eventually all plumes start shrinking • requires long term stewardship for at least a century • $M_D(t)$ decreases over time (exponential ?);		
2. Reduce Source Mass (and, as a result, also decrease source flux & longevity)	• Plume "pinched off" at the head; • tail starts shrinking when reduced flux front reaches it	• Plume "pinched off" at the head, but tail continues to move forward • split plumes?	• Plume shrinks inwards from both ends
3. Reduced Source Flux	• Plume response similar to 2; • since the source mass hasn't been reduced, the source treatment has to be maintained for a very long time		
4. Integrated "Treatment Train" Approach: (2) + (3) → Implement "aggressive" short-term action to deplete most of the source mass (say, ~80%?), and then use the "passive" source treatment (e,g., nZVI or eZVI) to sustain essentially zero source flux, or a low-grade "chaser" (e.g., chem ox)			

Case Study I: TCE plume in US



500 m x 120 m x 16 m

Sandy aquifer; v = 0.14 m/day

What do we need to know?

Source strength

Natural Attenuation rate

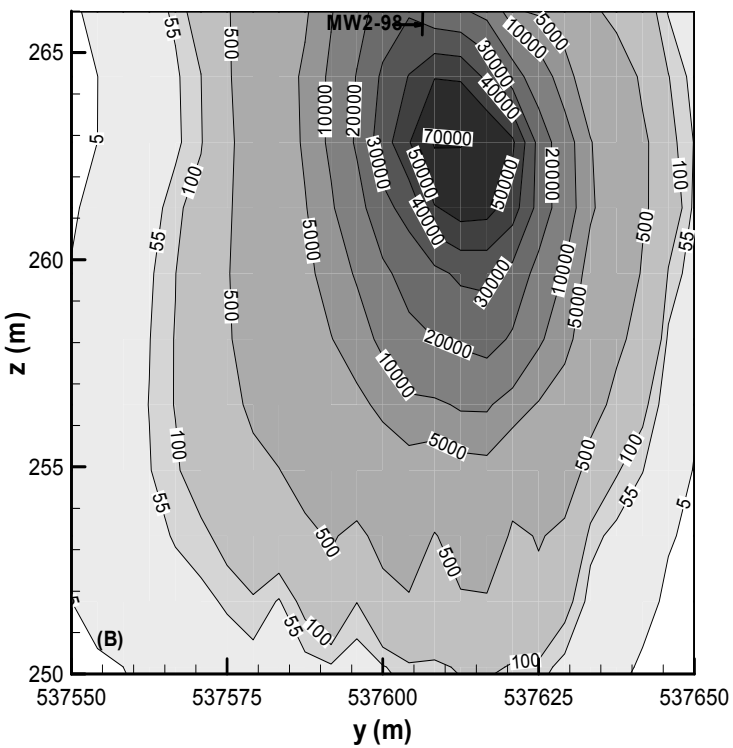
Remedial performance metrics

Basu, N. B. et al. 2006a. "Flux-Based Assessment At A Manufacturing Site Contaminated With Trichloroethylene." *Journal of Contaminant Hydrology,* 86 (1-2), 105-127

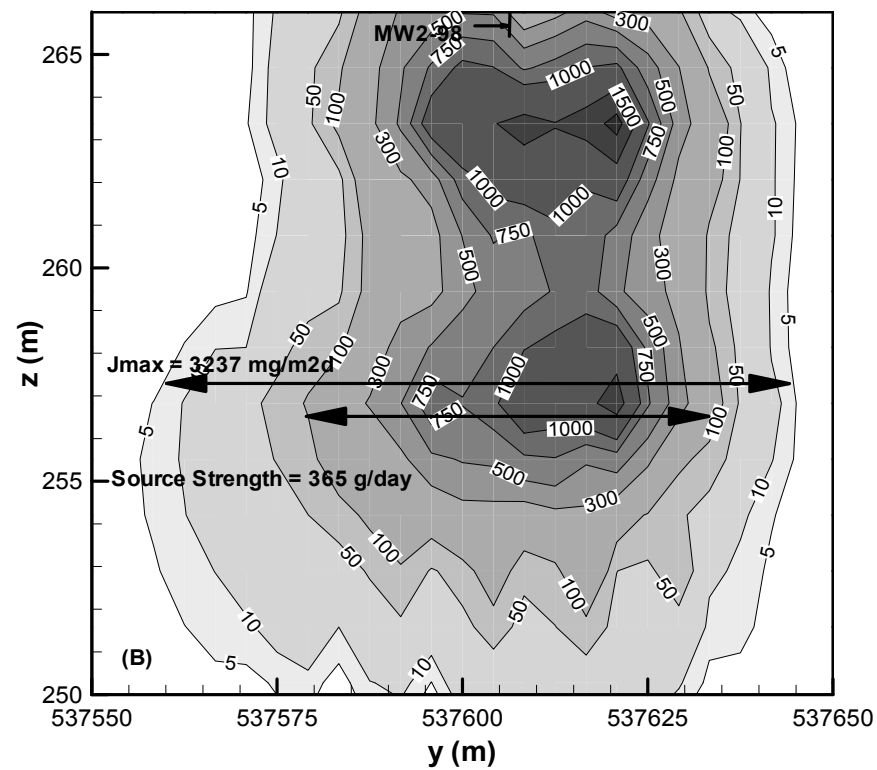
Source Strength

Source Strength= 365 g/day

Concentration contours: µg/L

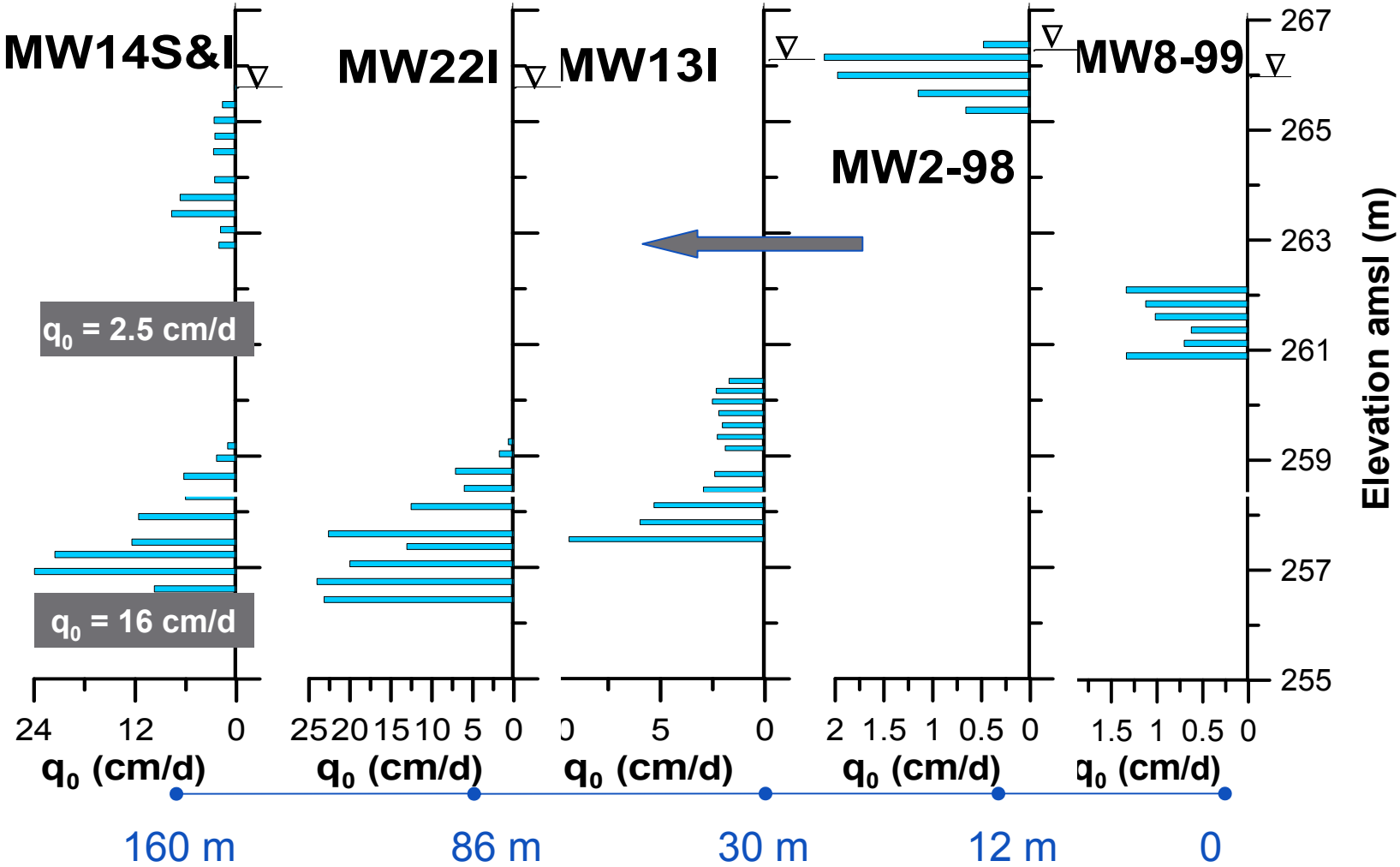


Flux contours: mg/m^2 day



Basu, N. B. et al. 2006a. "Flux-Based Assessment At A Manufacturing Site Contaminated With Trichloroethylene." *Journal of Contaminant Hydrology*, 86 (1-2), 105-127.

Groundwater Fluxes along Plume Centerline: TCE Site in Midwestern US



Basu, N. B. et al. 2006a. "Flux-Based Assessment At A Manufacturing Site Contaminated With Trichloroethylene." *Journal of Contaminant Hydrology,* 86 (1-2), 105-127.

Natural Attenuation Rate

$$M_{CP(2)} = M_{CP(1)} \exp\left(-\frac{\lambda x}{v}\right)$$

λ Evaluated through changes in mass discharge with x

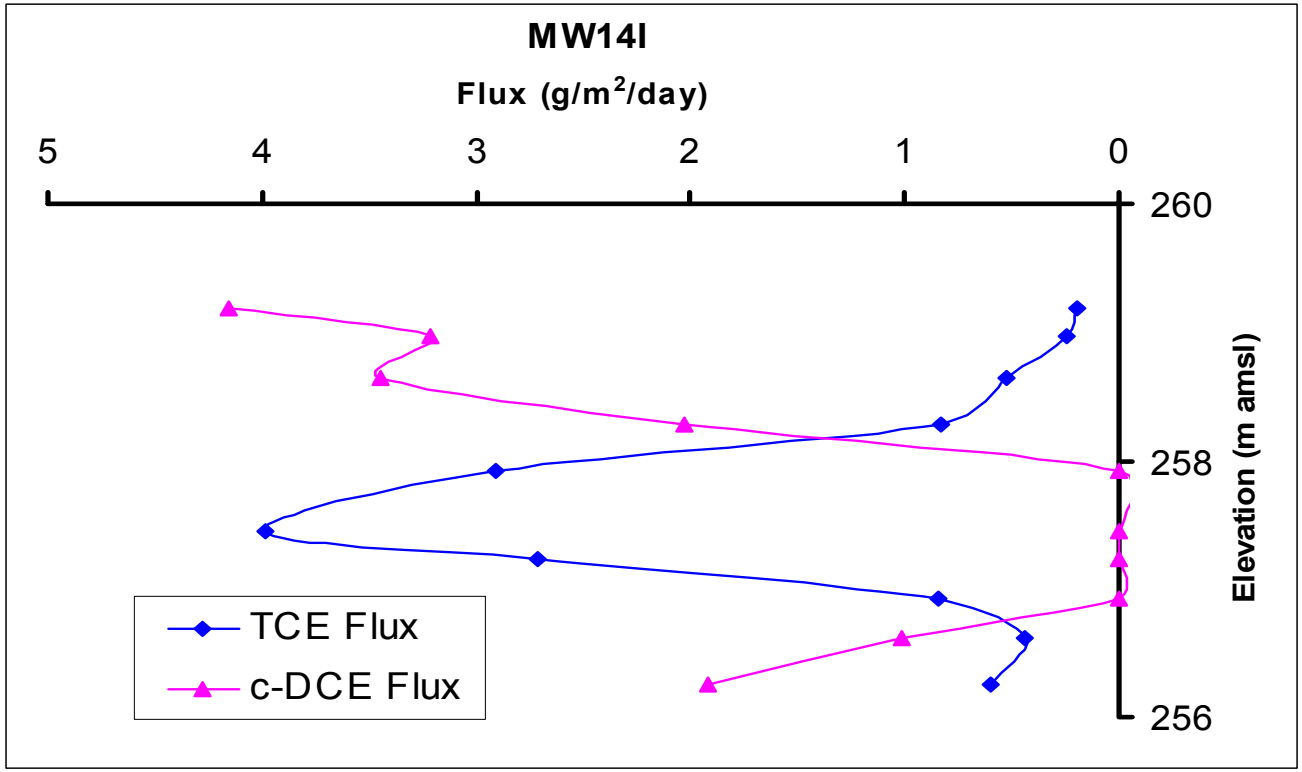
$\lambda = 0.52\ yr^{-1}$

Total Plume Mass

TCE = 788 kg

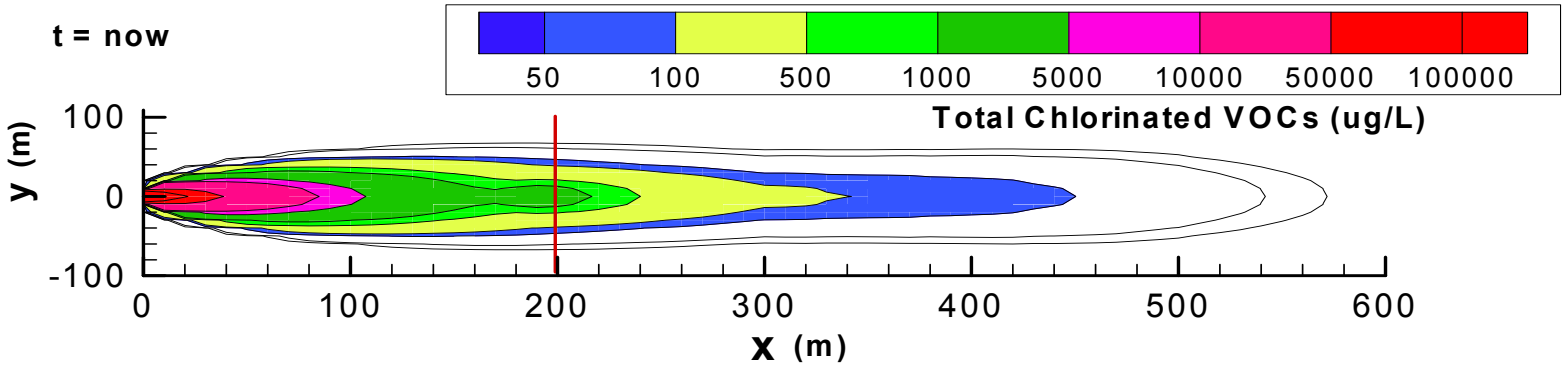
DCE = 26 kg

VC = 1.4 kg



Remedial Design

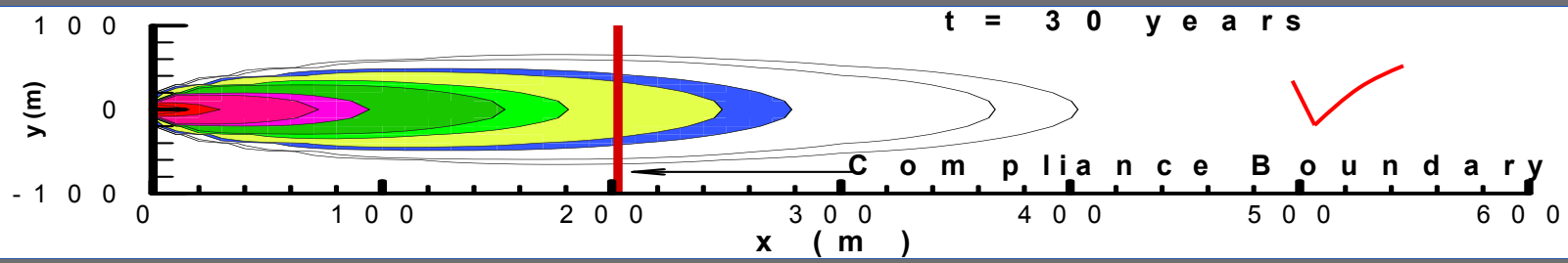
Estimated Source Mass: 40,000 kg
Estimated Source Load: 365 g/day
Estimated Source Flux: 0.11 g/m^2 d



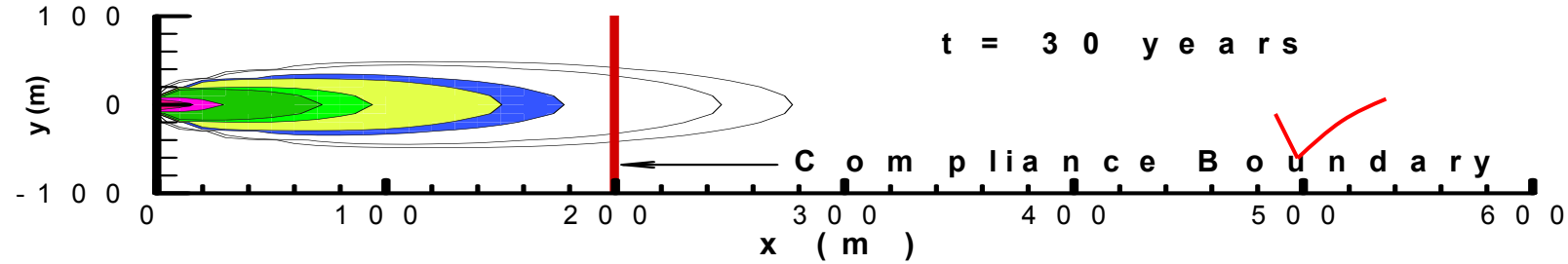
<u>Objective</u>: To shrink the plume within the property boundary by 30 years (Plume defined by the 55 ug/L contour)

Use REMCHLOR simulations to explore options

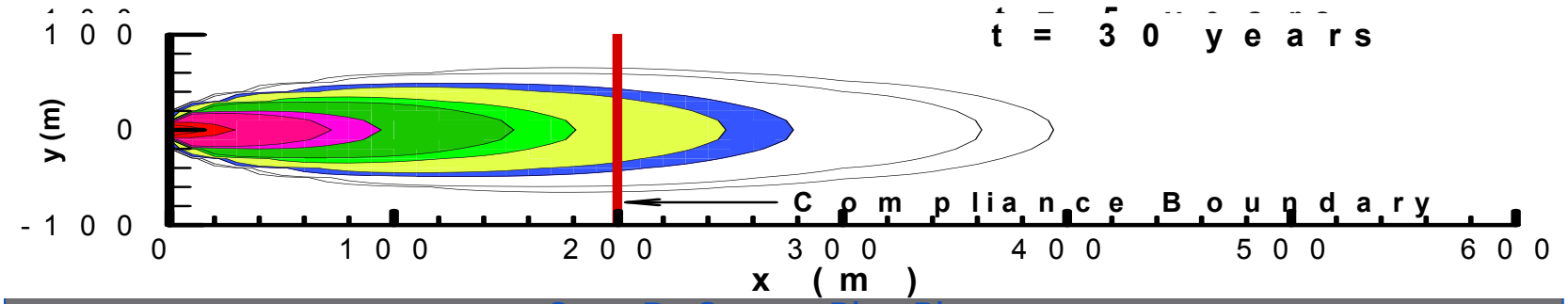
Case A: No Treatment



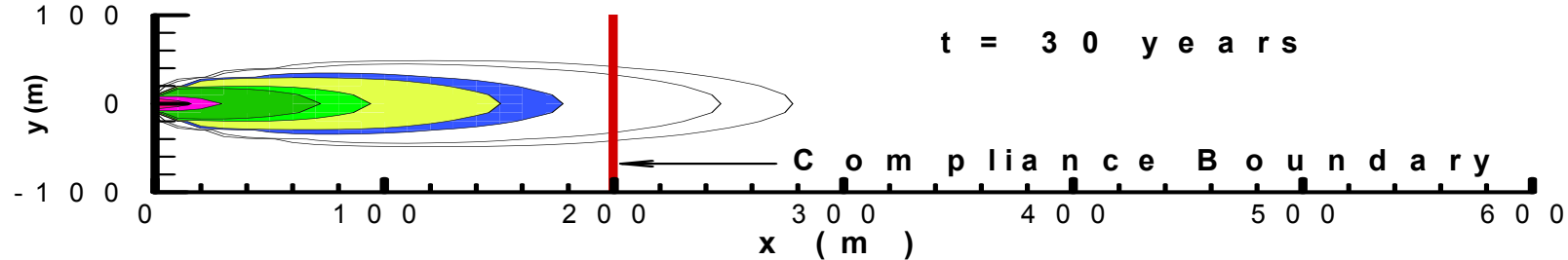
Case B: 90 % source depletion



Case C: λ↑ by a factor of 3 (10 years)

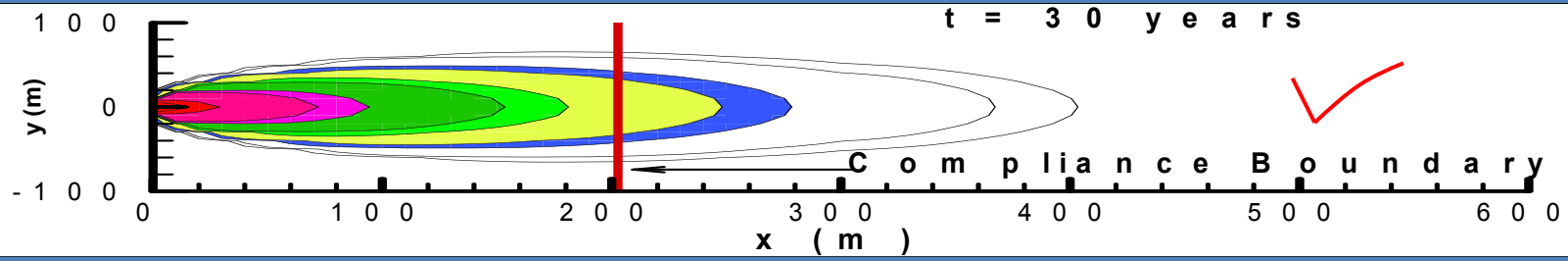


Case D: Source Plus Plume

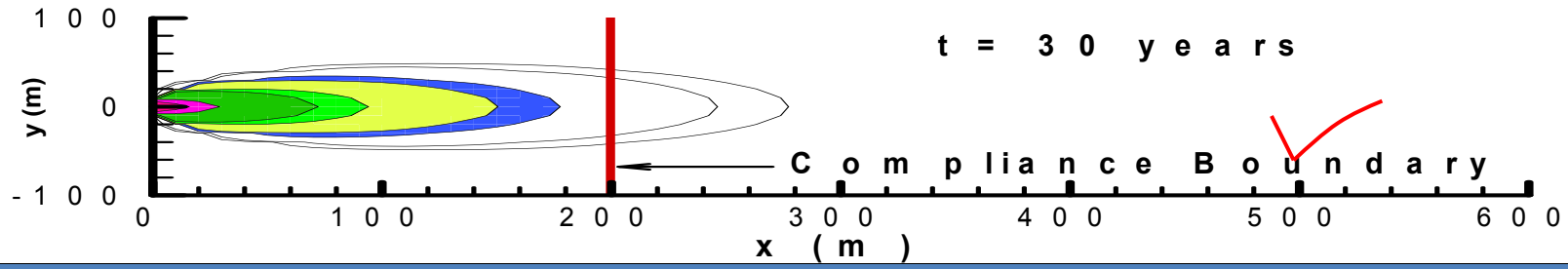


Preliminary unpublished data not for distribution

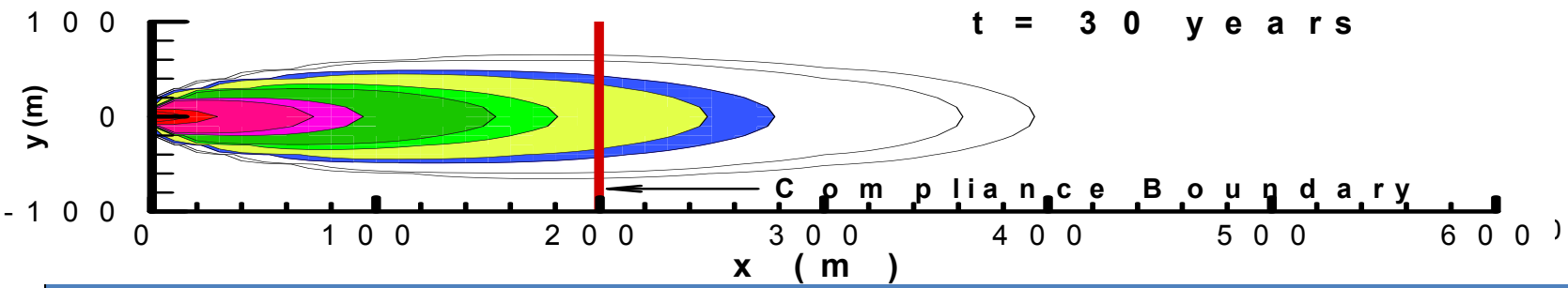
Case A: No Treatment



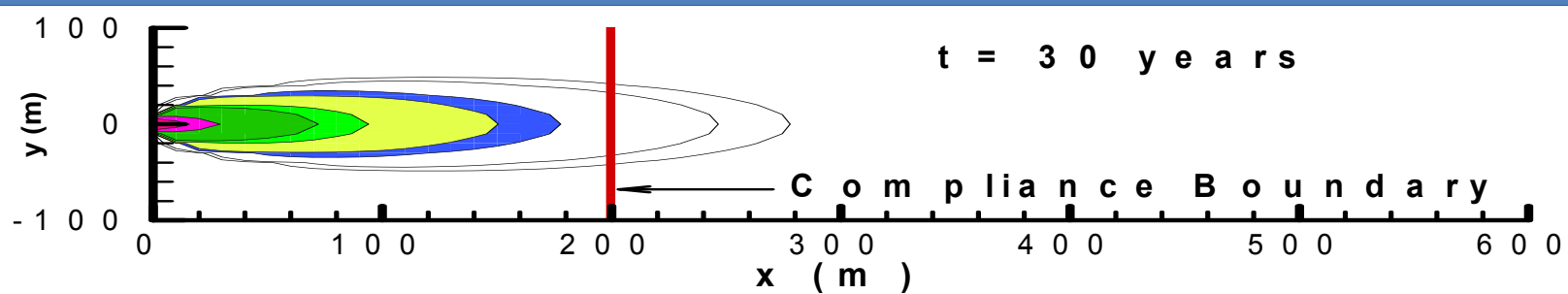
Case B: 90 % source depletion



Case C: λ↑ by a factor of 3 (10 years)



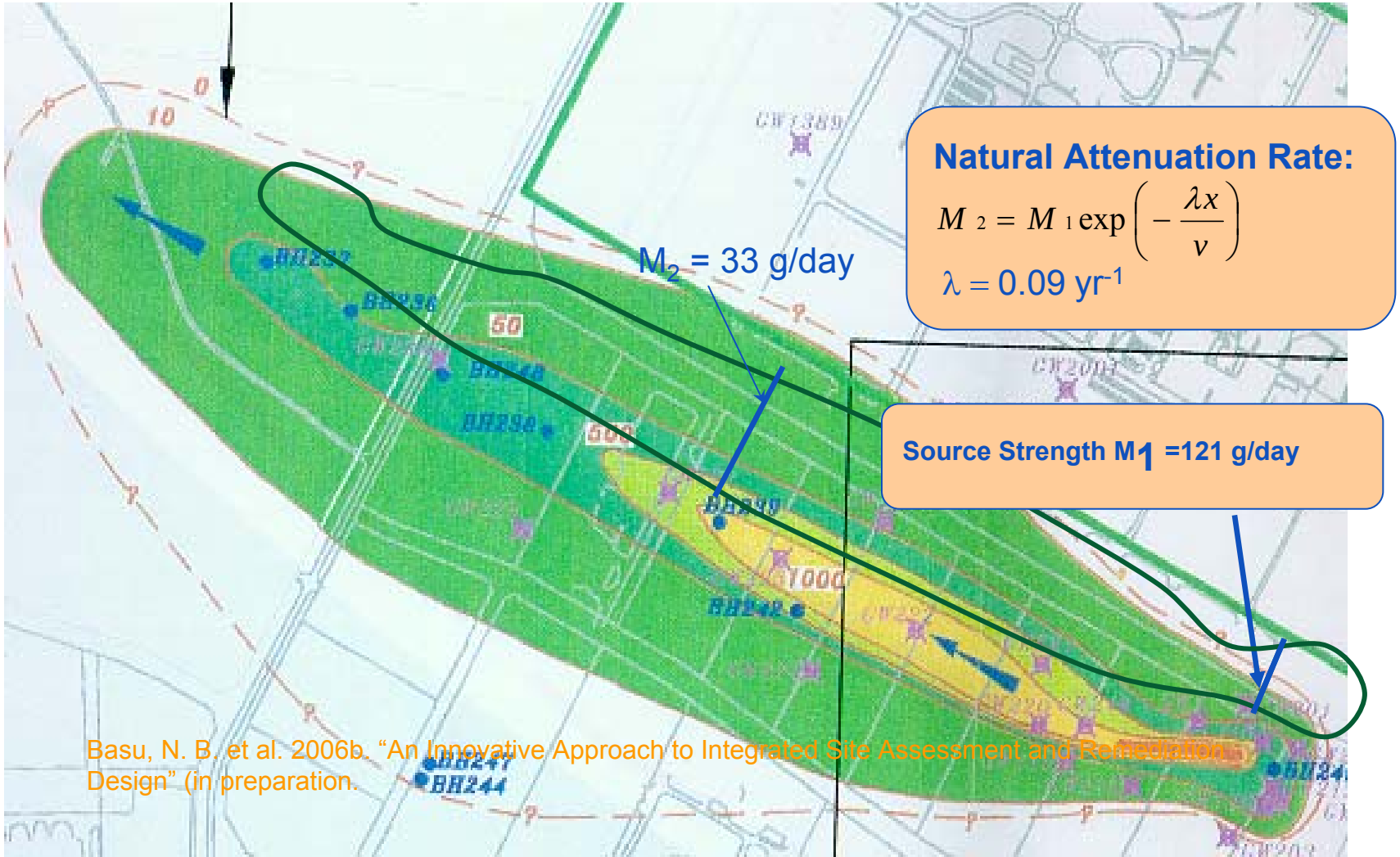
Case D: Source Plus Plume



Preliminary unpublished data not for distribution

Case Study II Industrial Site in Australia

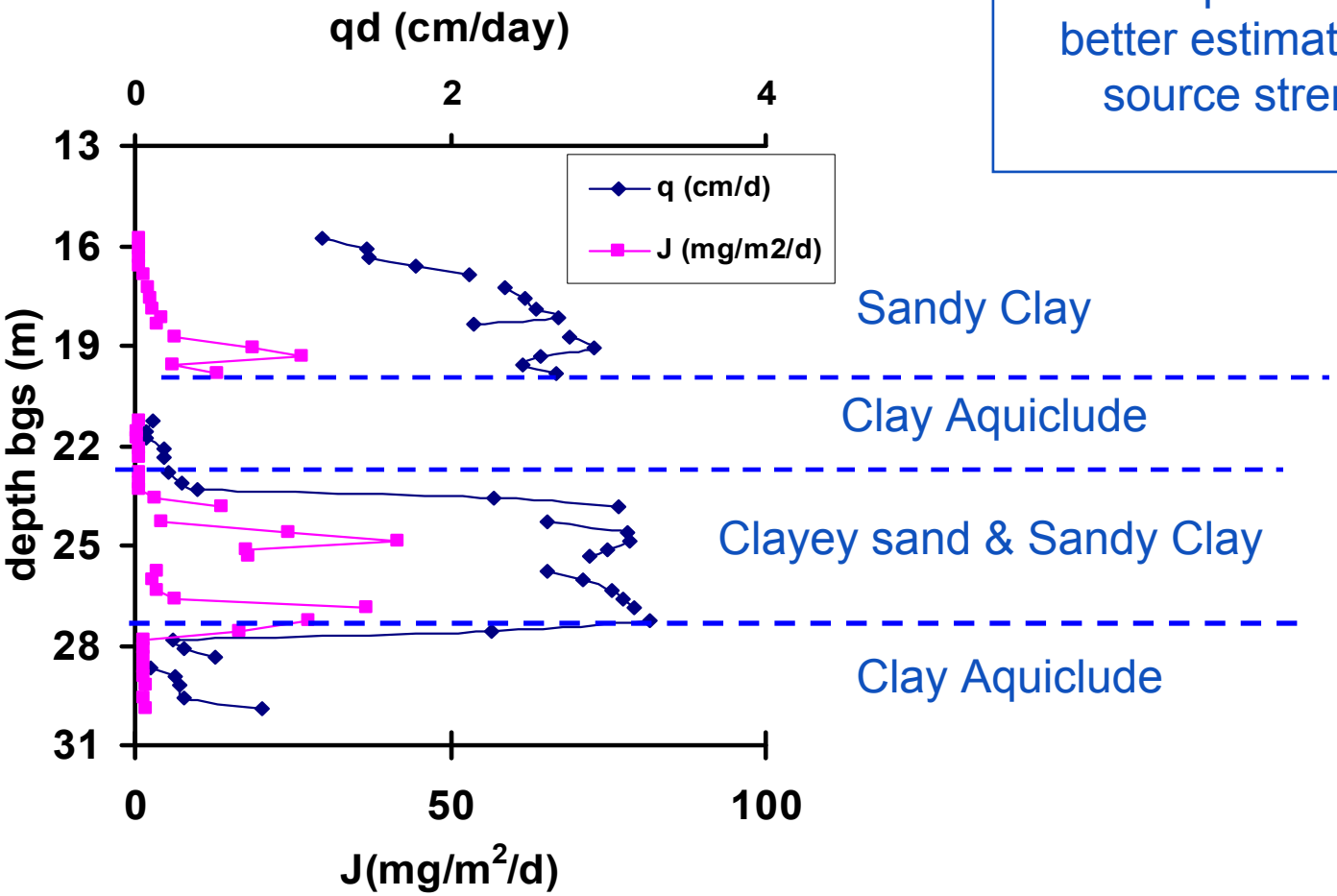
Estimated Source Mass: 3,000 kg
Estimated Source Load: 121 g/day
Estimated Source Flux: 0.04 g/m^2 d



Basu, N. B. et al. 2006b. "An Innovative Approach to Integrated Site Assessment and Remediation Design" (in preparation.

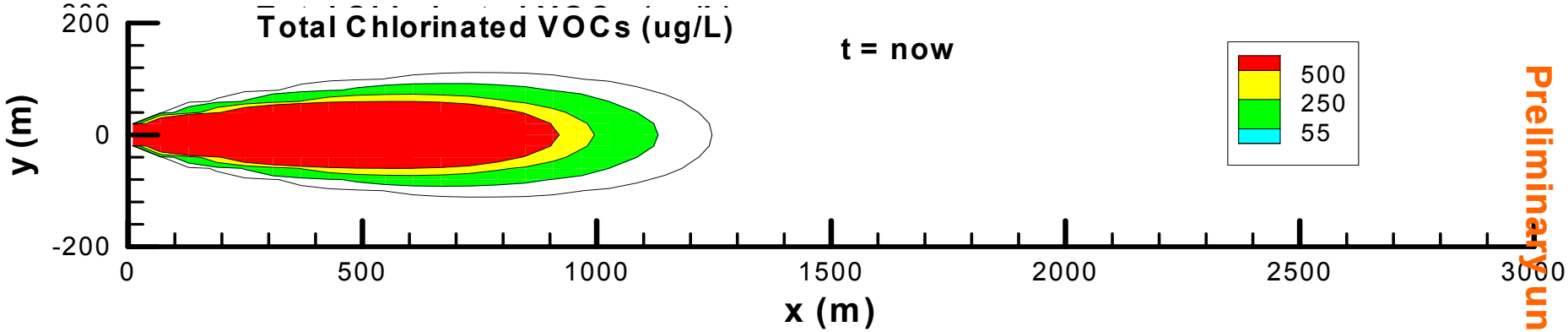
Flux Profile within Well Screens

Required for better estimation of source strength

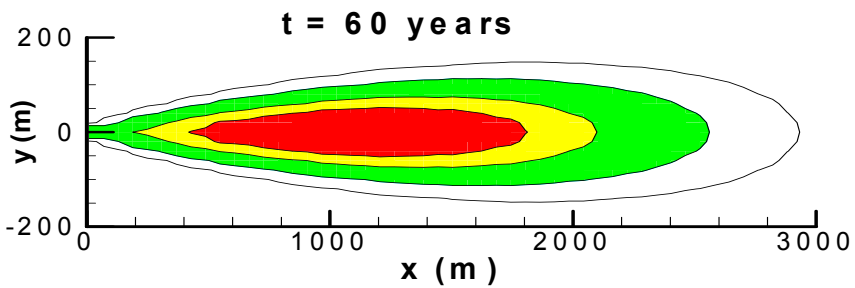


Case Study II: Remedial Design

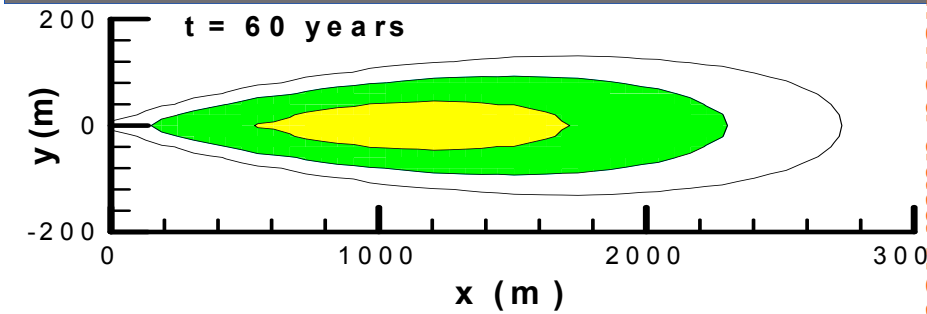
Objective: Reduction of Total Chlorinated VOCs to 55 ug/L within 60 years



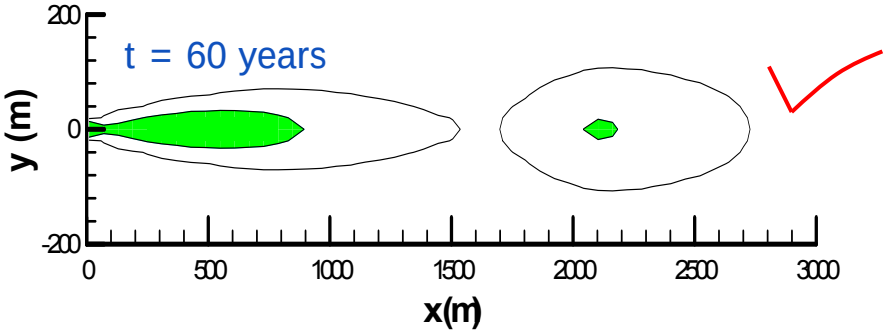
Case A: No Treatment



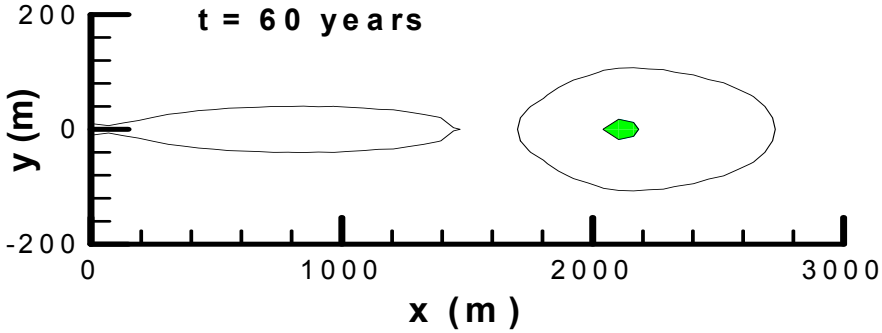
Case B: 90 % source depletion



Case C: $\lambda\uparrow$ 0.06 yr^{-1} to 1 yr^{-1} (10 years)

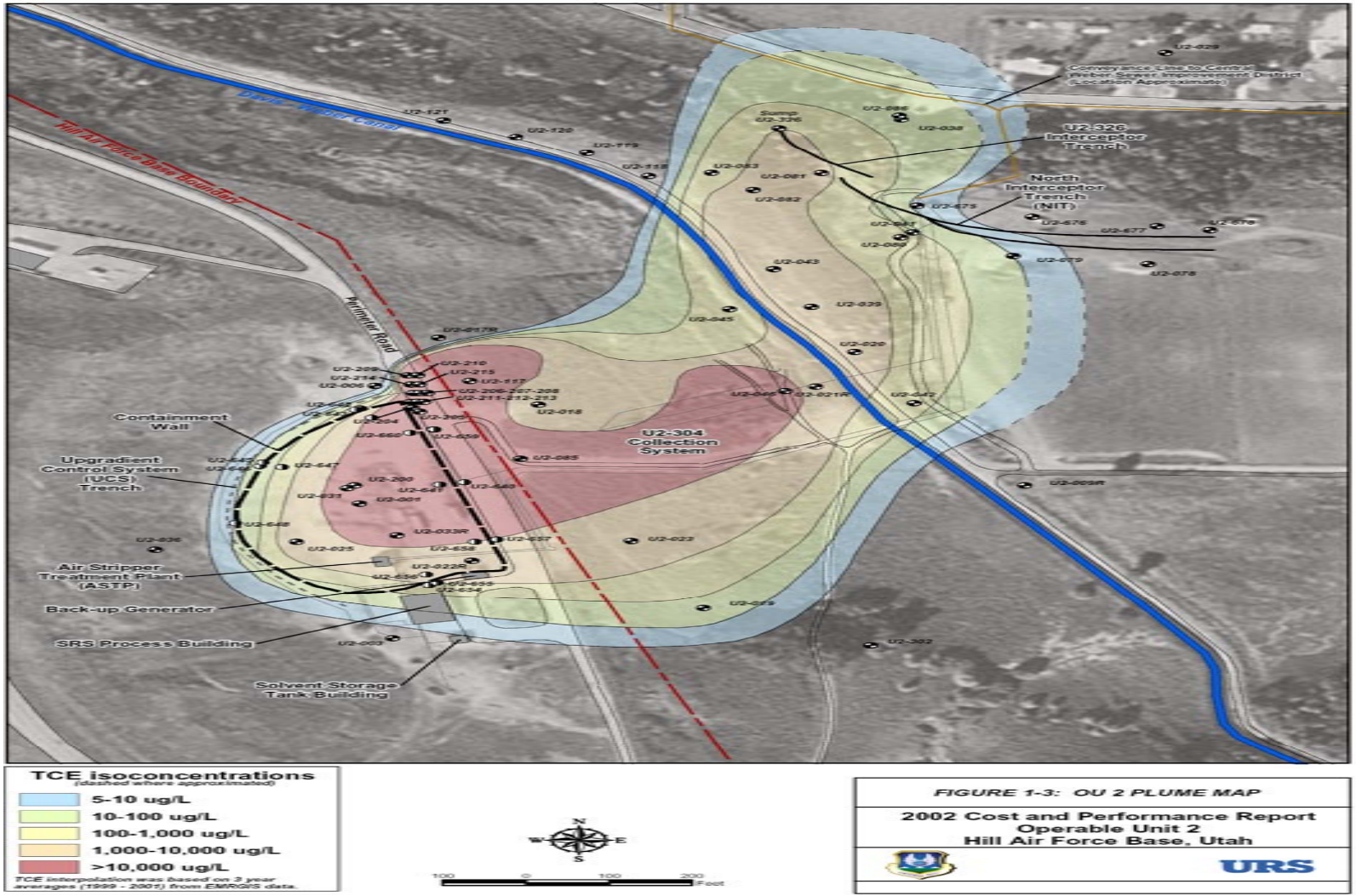


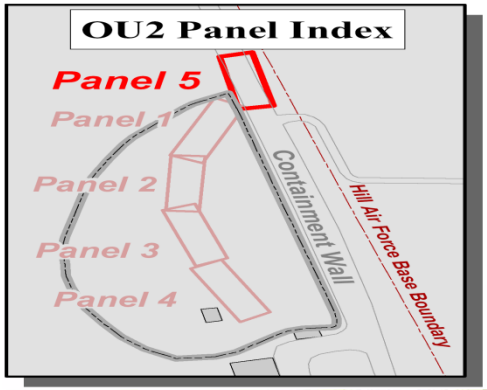
Case D: Source Plus Plume (Case B + Case C)

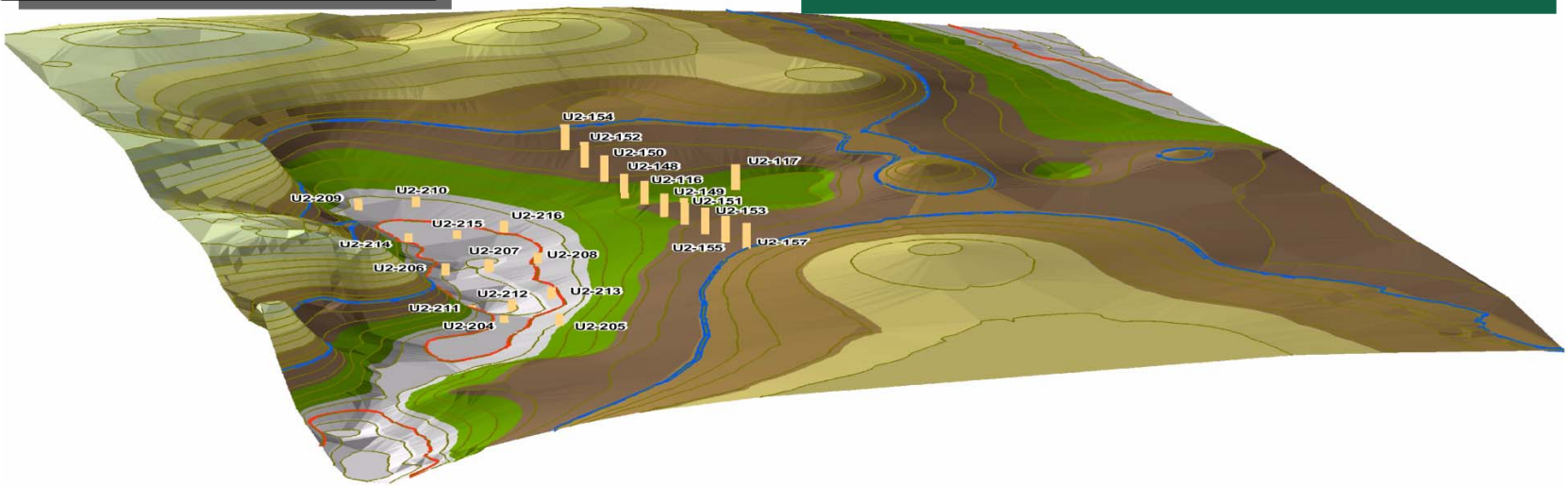


Preliminary unpublished data not for distribution

Case Study III: TCE Plume at the OU2 site, Hill AFB, Utah







Well Screen Interval

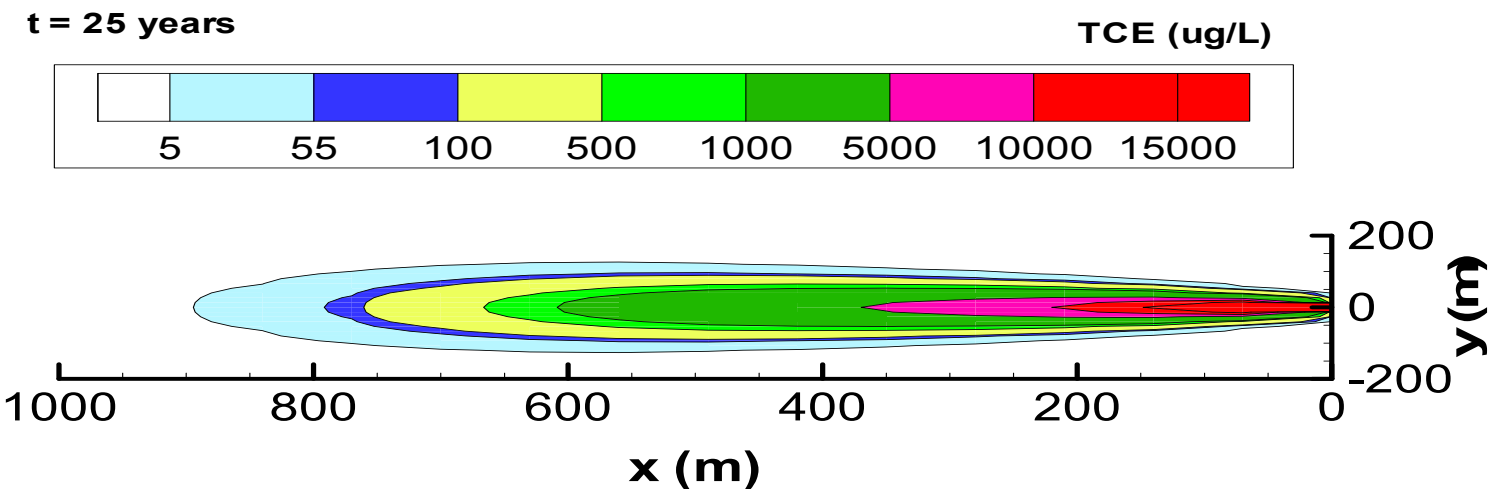
Historical Maximum DNAPL Elevation (4,654 ft amsl)

Seasonally High Groundwater Elevation (4,666 ft amsl)

Operable Unit 2 Hill AFB, Utah	Panel 5 Clay Aquitard Surface	Figure 1 URS

Remedial Design

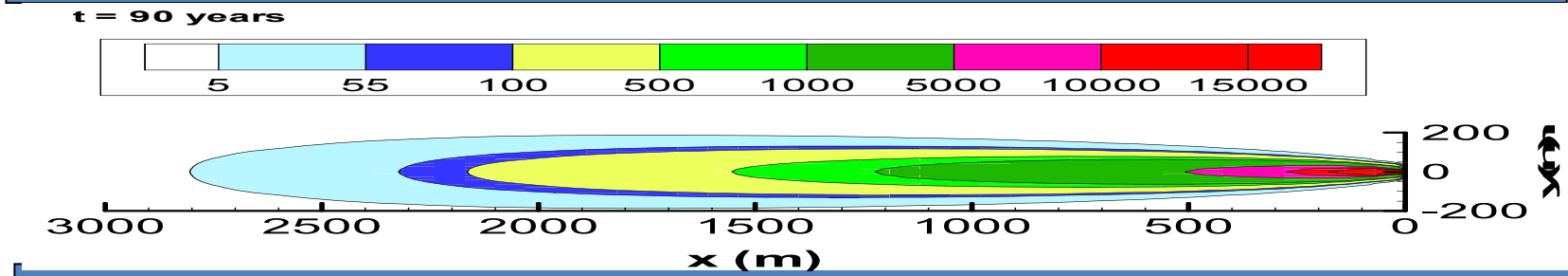
Estimated Source Mass: 250,000 kg
Estimated Source Load: 500 g/day



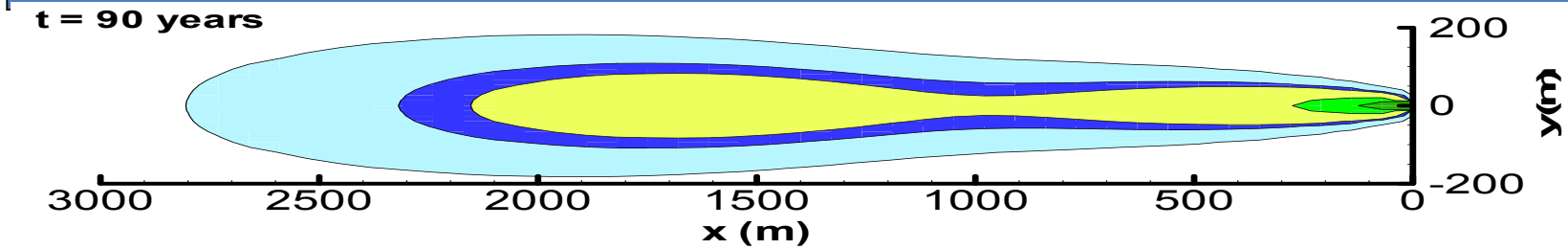
Objective: To shrink the plume within 1000 m by 65 years (Plume defined by the 55 ug/L contour)

Basu, N. B. et al. 2006b. "An Innovative Approach to Integrated Site Assessment and Remediation Design" (in preparation.

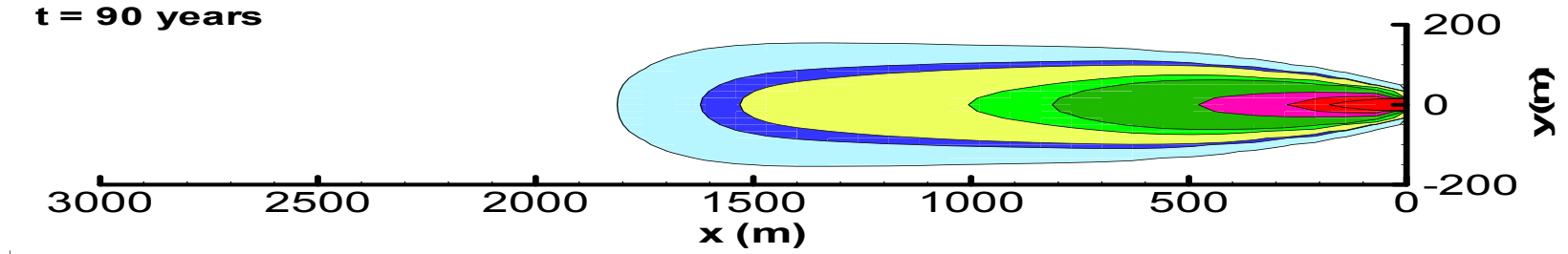
Case A: No Treatment



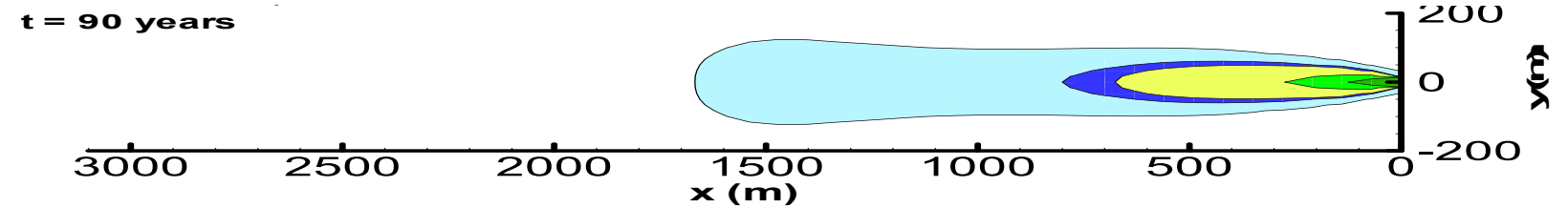
Case B: 95 % source depletion



Case C: λ↑ for 40 years



Case D: Source Plus Plume



Preliminary unpublished data not for distribution

Impact of Source Treatment on Flux?

Journal of Contaminant Hydrology 102 (2008) 140–153

Contents lists available at ScienceDirect

Journal of Contaminant Hydrology

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

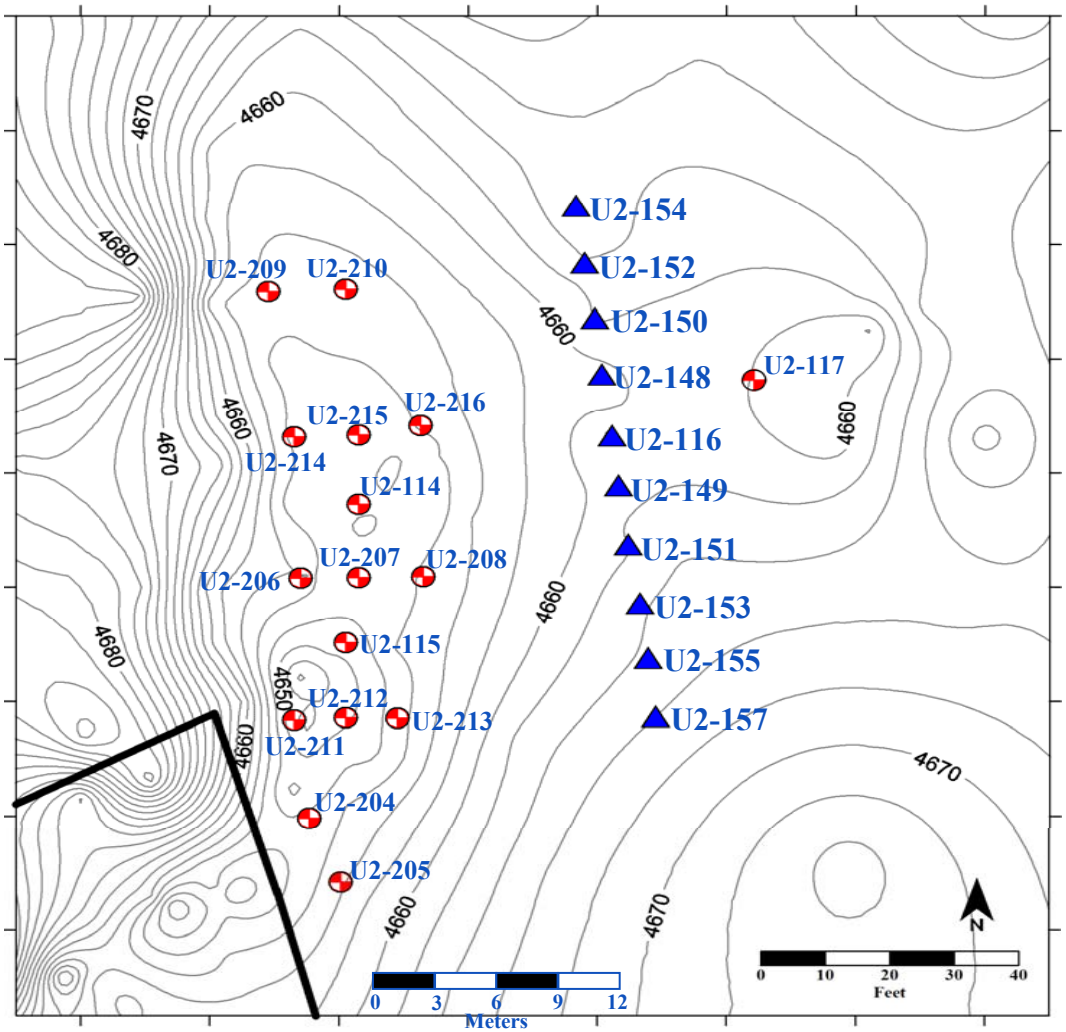
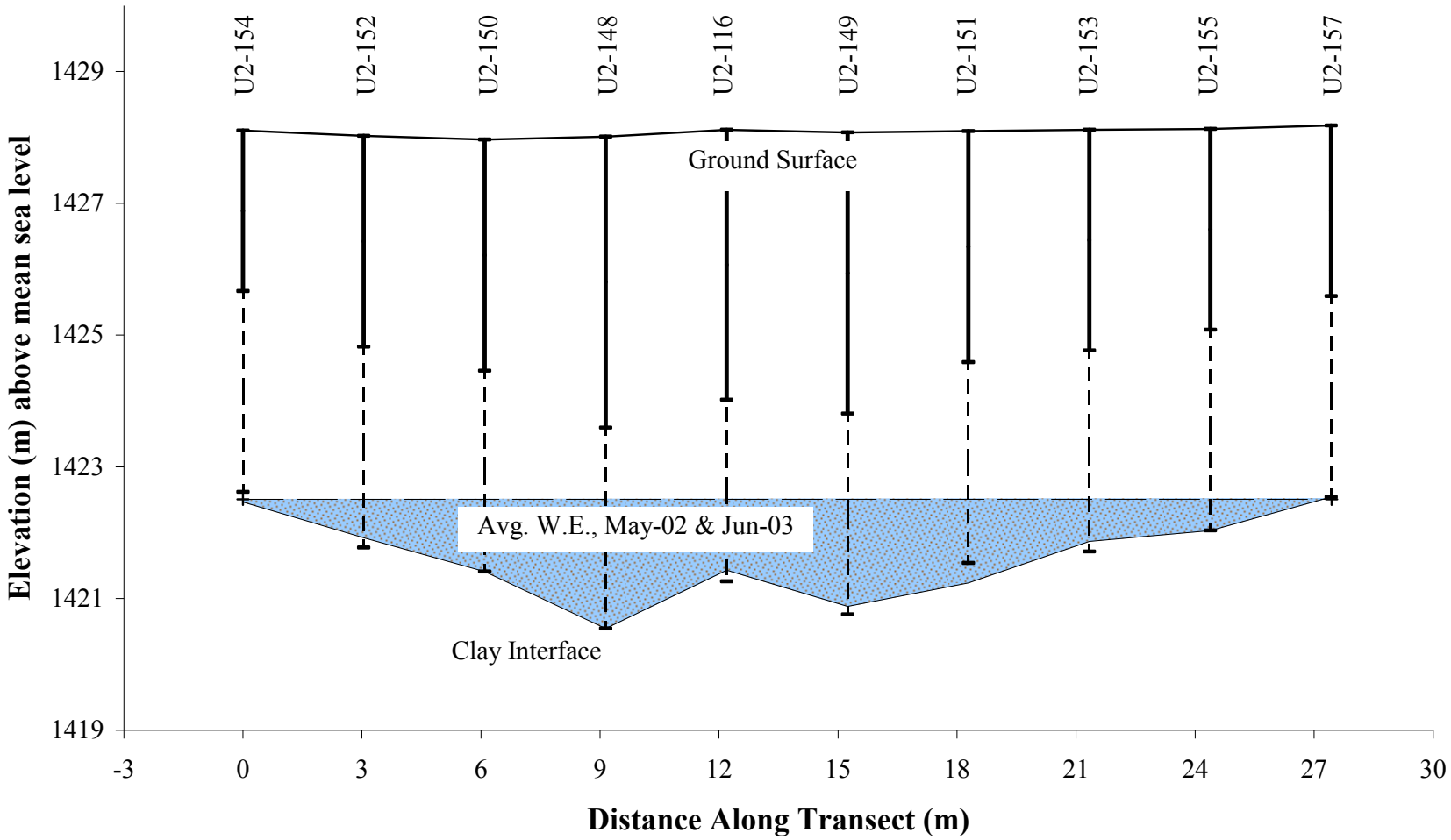


Figure 1. Plan view of the Panel 5 area at Hill AFB. The thick black line in the lower left corner represents the containment wall installed around OU2. The triangular symbols represent wells used for mass flux measurements. The grey contour lines represent the surface of the clay unit (contours in feet)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

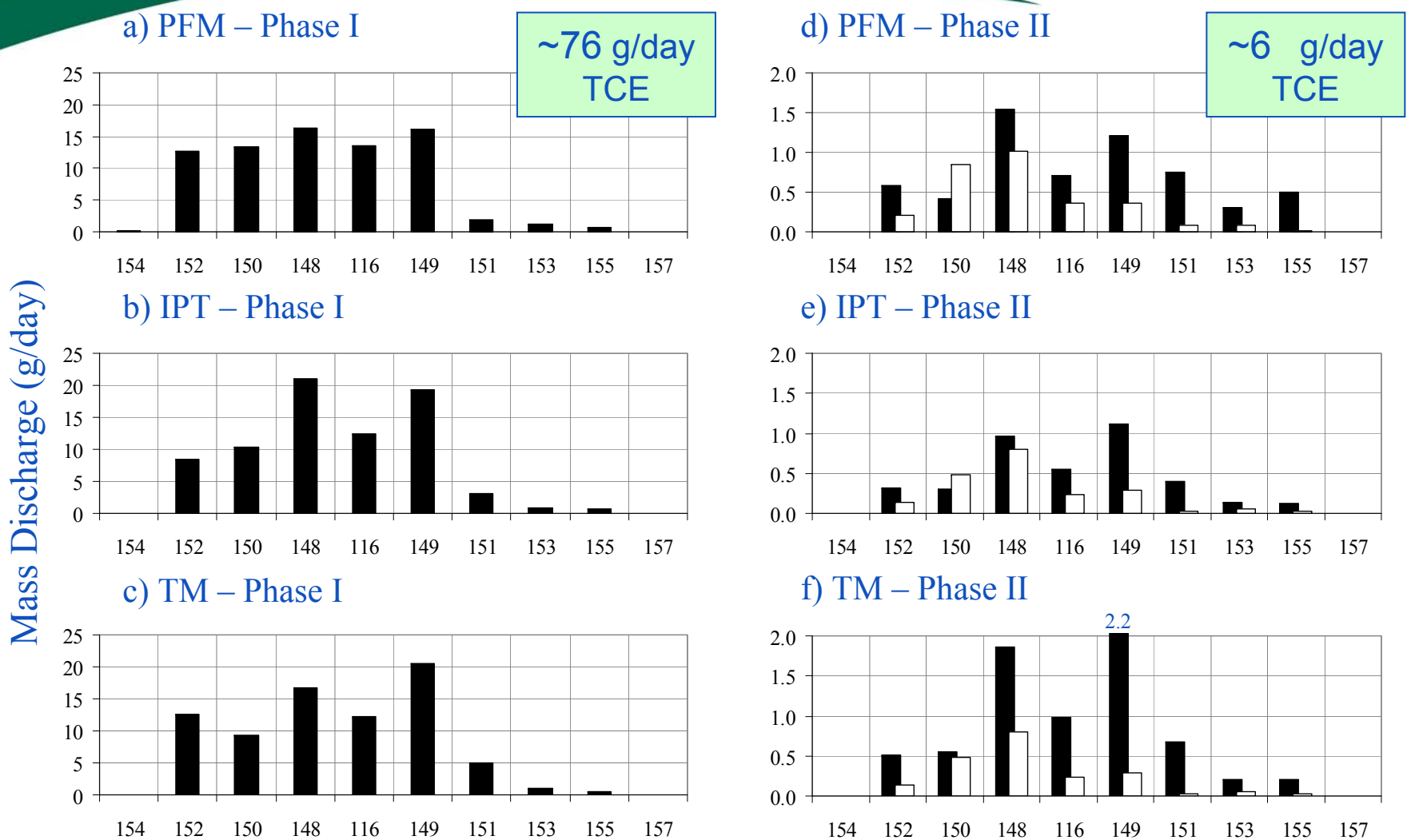


Figure 6. Average mass discharge (g/day) for each well at Hill AFB, as measured in Phase I (May-02) by a) PFM, b) IPT, and c) TM methods; and as measured in Phase II (Jun-03) by d) PFM, e) IPT, and f) TM. TCE is shown in black and *cis*-DCE in shown in white. Note the change in scale on the y-axis to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

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

Fort Lewis

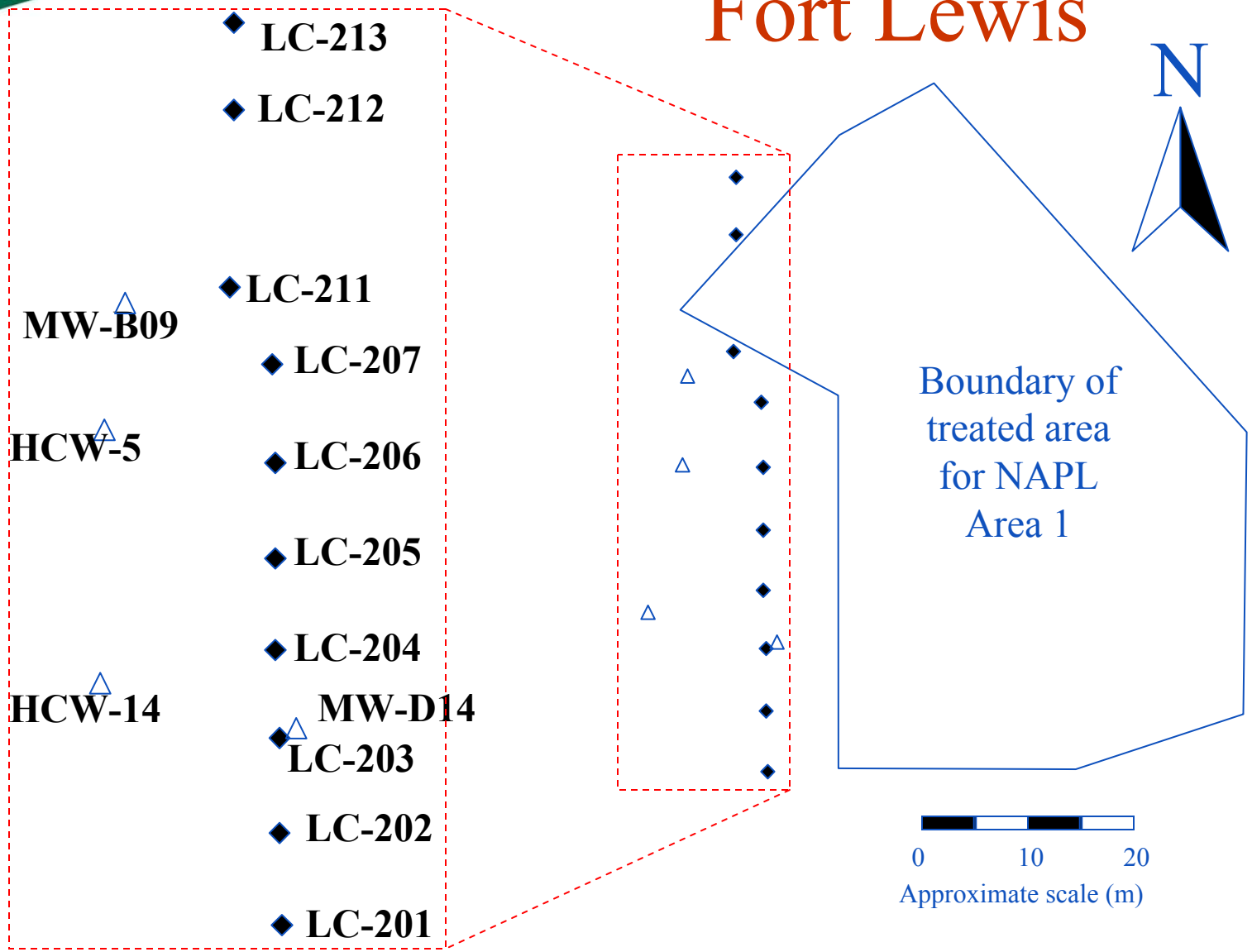
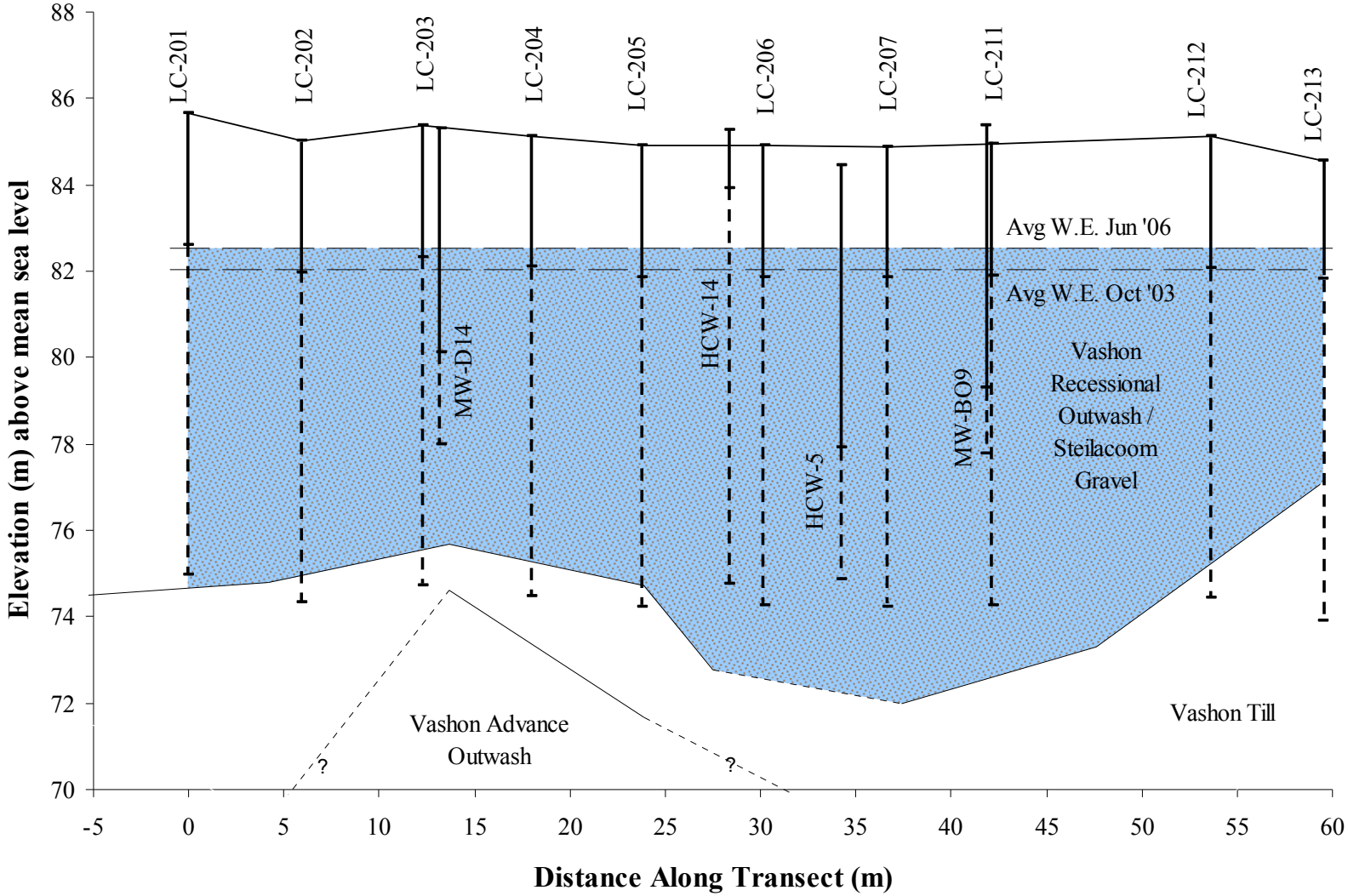


Figure 3. Plan view of the NA1 source area at the East Gate Disposal Yard site at Fort Lewis, and the downgradient flux well transect. The diamonds represent flux wells and the triangles represent hydraulic monitoring points.

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

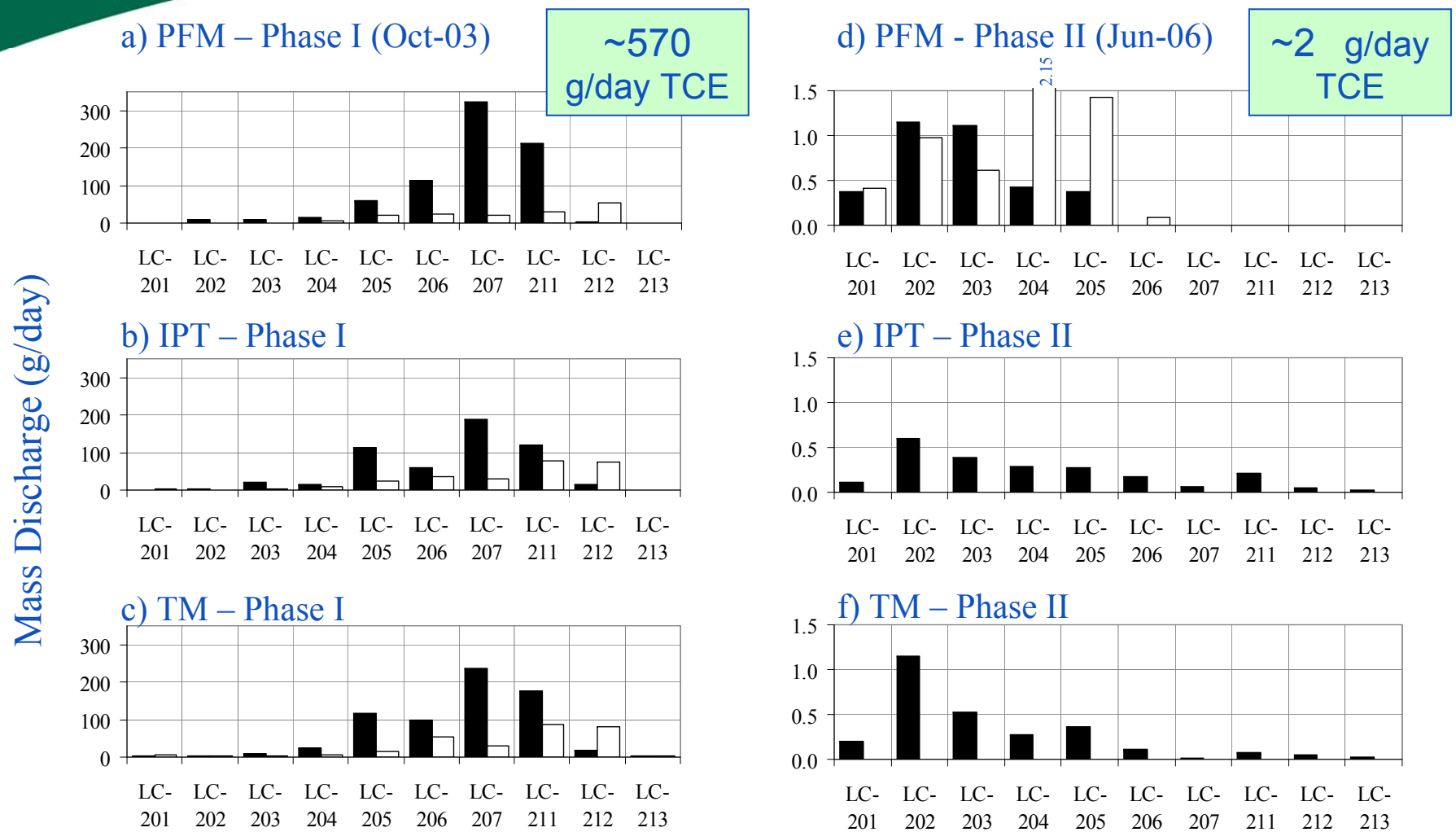


Figure 7. Average mass discharge (g/day) for each well at NA1 Fort Lewis, as measured by a) PFMs, b) IPT, and c) TM for Phase I tests (Oct-03); and as measured by d) PFMs, e) IPT, and f) TM for Phase II tests (Jun-06). TCE is shown in black, and *cis*-DCE in shown in white. Note the change in scale on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

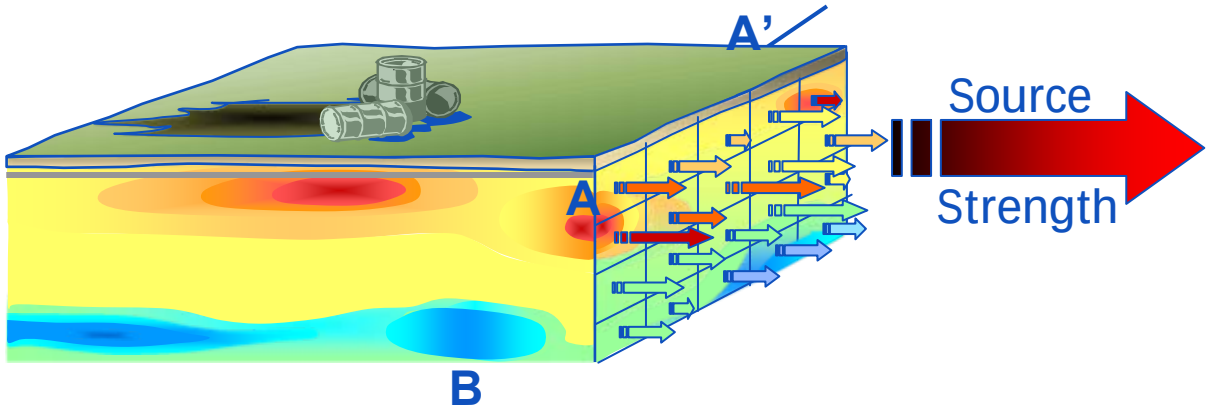
Brooks et al., JCH, 102(2008), 140-153

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.

Summary

- Mass Balance and Source Strength Function Assessment Provides Improved Site Management Data
- Source Strength Functions Allow Improved Predictive Capabilities
- Mass Flux and Discharge Characterization can Improve Mass Balance and Age Estimates



MEASUREMENT AND USE OF MASS DISCHARGE AND MASS FLUX AT CONTAMINATED SITES

Start	End	Topic
8:30 AM	8:50 AM	Welcome & Introduction *(Dr. Hans Stroo)*
8:50 AM	9:40 AM	Flux-Based Site Management and Case Studies *(Dr. Michael Annable)*
9:40 AM	9:50 AM	Questions and Open Discussion
9:50 AM	10:10 AM	Break
10:10 AM	11:00 AM	Quantifying Mass Flux and Discharge *(Dr. Charles Newell and Dr. Shahla Farhat)*
11:00 AM	11:30 AM	Case Study Review *(Mr. Alec Naugle)*
11:30 AM	11:50 AM	Case Study Review – Field Measurement of Mass Discharge *(Mr. Murray Einarson)*
11:50 AM	12:00 PM	Questions and Open Discussion
12:00 PM		Adjourn

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12:00 PM		Adjourn

MEASUREMENT AND USE OF MASS DISCHARGE AND MASS FLUX AT CONTAMINATED SITES

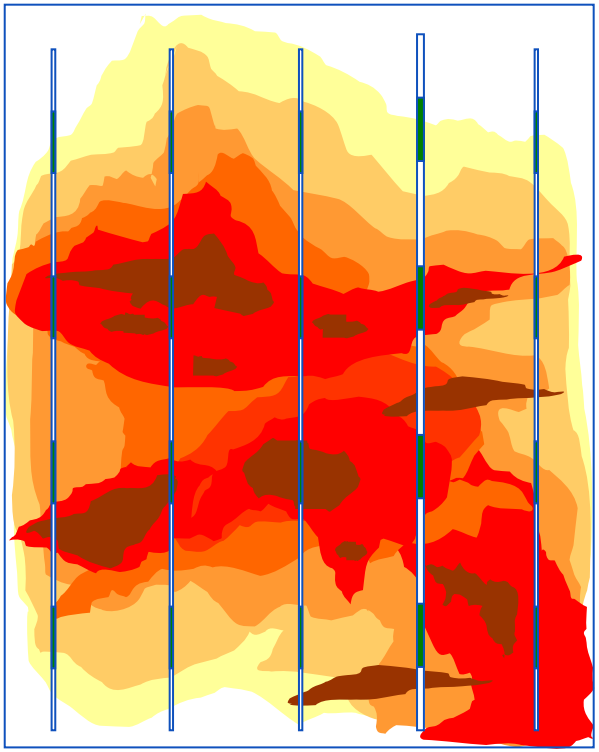
Start	End	Topic
8:30 AM	8:50 AM	Welcome & Introduction *(Dr. Hans Stroo)*
8:50 AM	9:40 AM	Flux-Based Site Management and Case Studies *(Dr. Michael Annable)*
9:40 AM	9:50 AM	Questions and Open Discussion
9:50 AM	10:10 AM	Break
10:10 AM	11:00 AM	Quantifying Mass Flux and Discharge *(Dr. Charles Newell and Dr. Shahla Farhat)*
11:00 AM	11:30 AM	Case Study Review *(Mr. Alec Naugle)*
11:30 AM	11:50 AM	Case Study Review – Field Measurement of Mass Discharge *(Mr. Murray Einarson)*
11:50 AM	12:00 PM	Questions and Open Discussion
12:00 PM		Adjourn

Quick Review of Definitions

Mass flux, J
($g/m^2/day$)

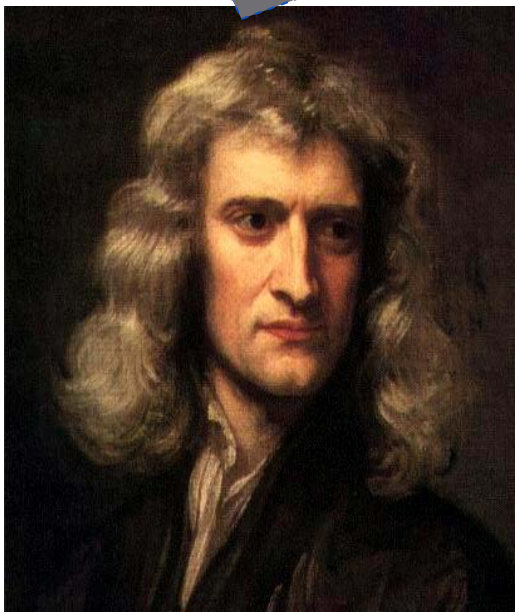
Integrate

Mass discharge, M_d
(g/day)



$$\int$$

"This plume has a mass discharge of 1.5 grams per day."



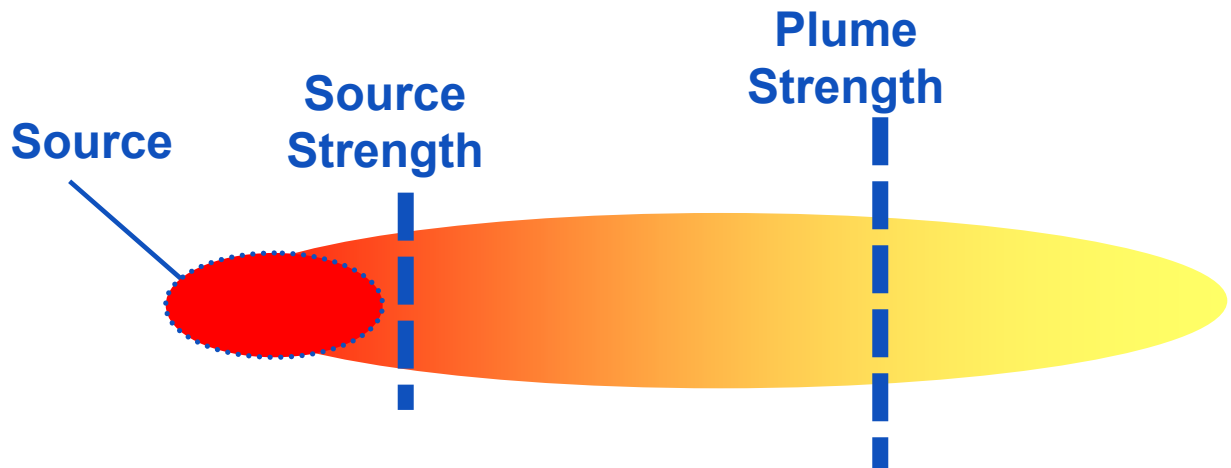
Sir Isaac Newton:

"Method of Fluxions"

Five Methods for Mass Discharge

- *Method 1:* Transect Method (Sect. 4.1)
- *Method 2*: Well Capture/Pumping Methods (Sect. 4.2)
- *Method 3:* Passive Flux Meters (Sect. 4.3)
- *Method 4*: Using Existing Data (Isocontours) (Sect. 4.4)
- *Method 5*: Solute Transport Models (Sect. 4.5)

All methods are "ready to go"



Calculating Mass Discharge: Transect Method Simple Example

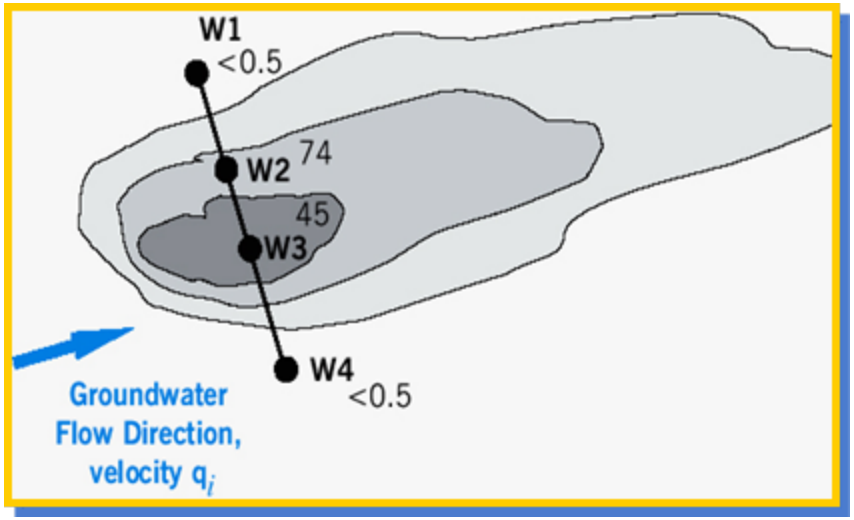
Nichols and Roth, 2004

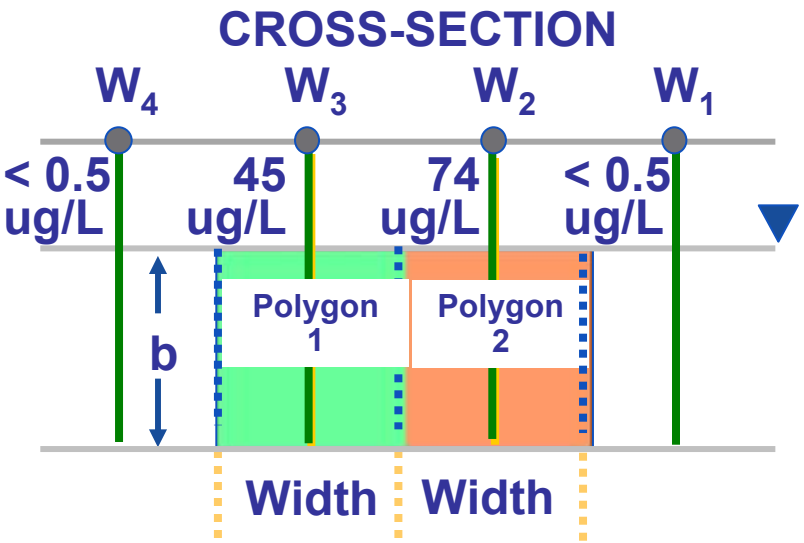
Step-by-step approach assuming uniform groundwater velocity

1. Characterize plume (C)
2. Characterize flow (q)
3. Select transect: with simple approach, just build cross-sectional polygons ("window panes") for each well across flow
4. Determine area (W • b = A)
5. Multiply and sum together:

$$M_d = \Sigma\,(C_n \bullet A_n \bullet q)$$

M_d = Mass discharge
C_n = Concentration in polygon n
A_n = Area of segment n





Calculating Mass Discharge: Groundwater Darcy Velocity Term (q)

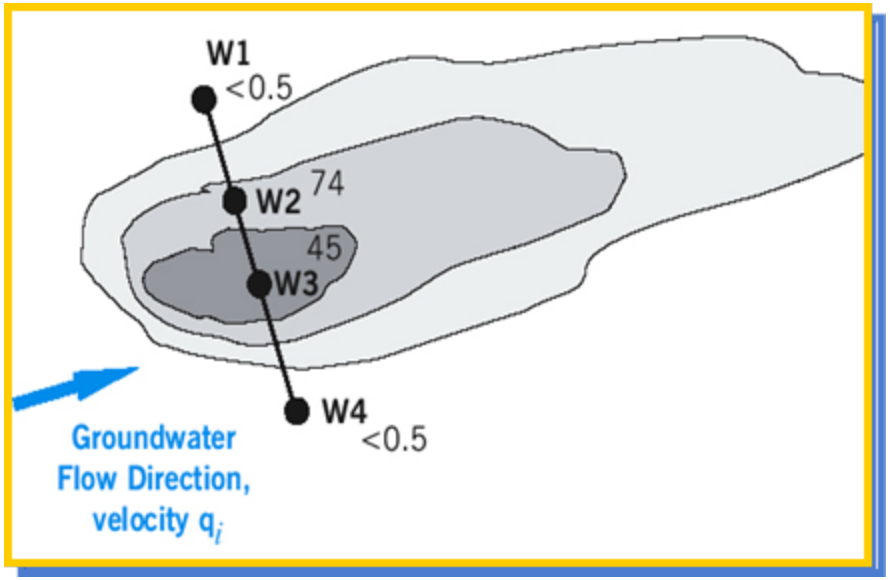
$$M_d = \Sigma (C_n \bullet A_n \bullet q_n)$$

Calculation of Darcy Velocity

$$q = K \bullet i$$

q = Groundwater Darcy velocity
i = Hydraulic gradient
K = Hydraulic conductivity*

* Hydraulic conductivity can be determined by pumping test, slug test, or estimated based on soil type



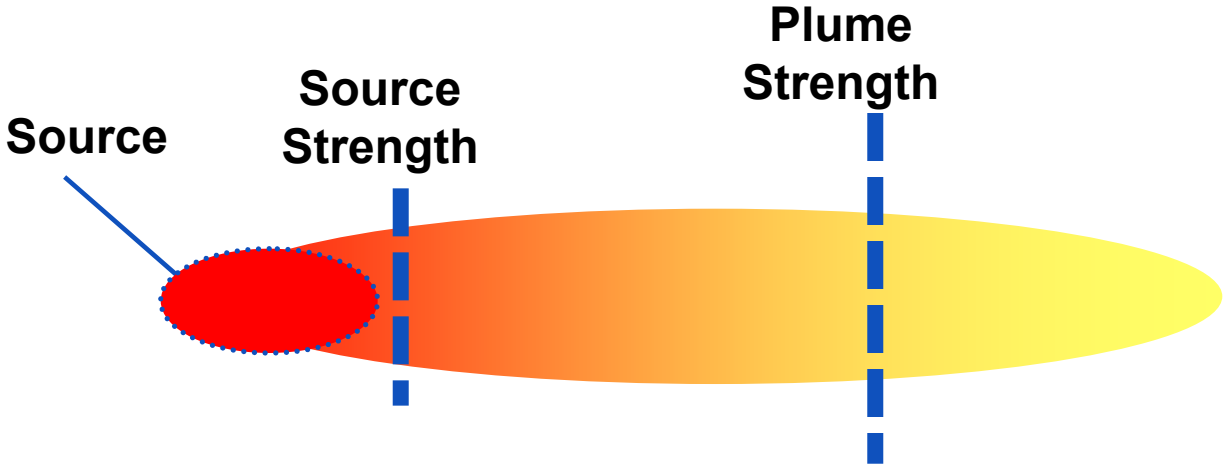
Variability in groundwater velocity - most applications of the transect method to date have assumed a uniform groundwater Darcy velocity for the entire transect. However, different values for q may be used for different polygons if sufficient data are available.

Class Exercise

Calculate Mass Discharge by Hand

Building Transects: General Rules

- Can be permanent or temporary installations
- No special well or sampling points needed
- Can be based on longer single screen wells or multilevel observations
- Transect must be perpendicular or close to perpendicular to groundwater flow

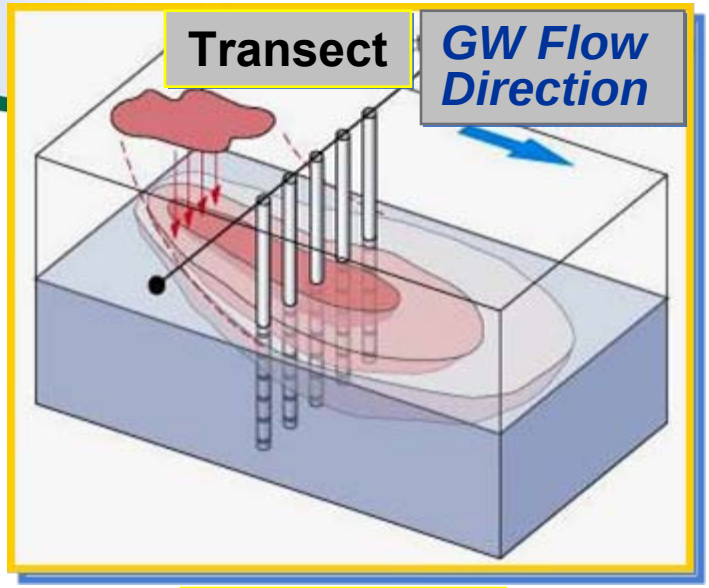


Transect Method: Using High Resolution

Nichols and Roth, 2004

- Multi-level sampling means multiple level polygons
- Sum up all cells to get Mass Discharge (M_d) in units of
  - Grams per day (g/day)

    or
  - Kilograms per year (kg/yr)



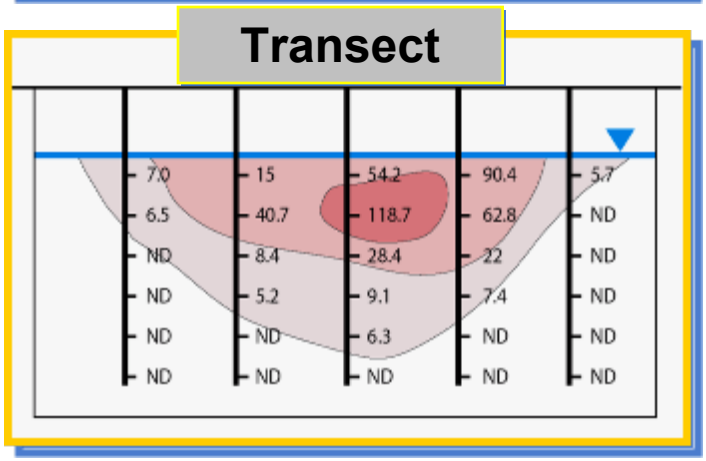


Figure 4-1

	w_1	w_2	w_3	w_4	w_5
b_1	7.0	15	54.2	90.4	5.7
b_2	6.5	40.7	118.7	62.8	0
b_3	0	8.4	28.4	22	0
b_4	0	5.2	9.1	7.4	0
b_5	0	0	6.3	0	0
b_6	0	0	0	0	0

In this case

- **M_d = 488 g/day**

  or
- **M_d = 178 kg/yr**

How Many Points? Depends on Use

Information from Table 1.1

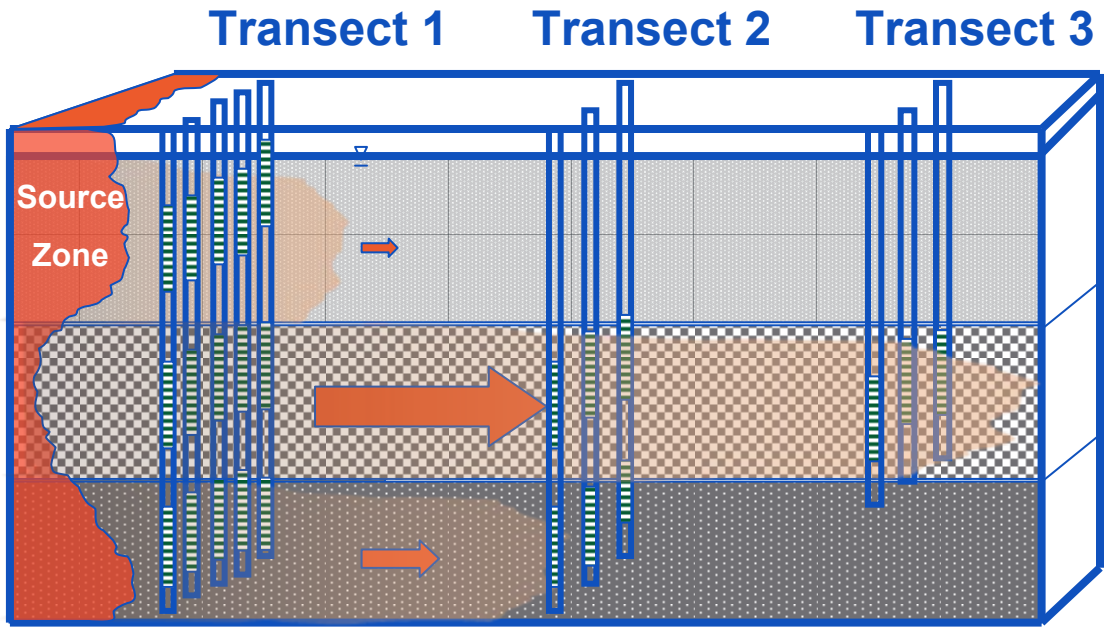
Remedial Applications	Mass Flux Data Use	Relative Data Density Needed
Active remediation or MNA	Estimate source strength	Low
	Estimate plume stability	High*
	Estimate mass balance-natural attenuation capacity	Medium to High*
Evaluate risk to receptor(s)	Estimate risks and exposures at various points of potential exposure	Low to Medium
Select appropriate technology	Determine remedial action objectives	Low to High
	Determine appropriate remedial technology(ies)	
Develop/optimize remedial design	Evaluate heterogeneities in source architecture	High
	Estimate source strength reductions necessary to transition technology (e.g., in situ biorem. or MNA)	Low
	Estimate distribution of contaminants	High
Evaluate remedial performance	Compare actual mass removal to design. Compare electron acceptor to electron donors	Low to High**
Evaluate compliance / LTM	Determine mass discharge or flux limits to achieve remedial goals	Low to Medium

*If using multiple plume transects

**Depending on system design and treatment volume(s)

Use of Multiple Mass Transects

Design Tailored to Site Conditions and Goals



Mass Discharge *vs. Distance*

Mass Discharge *vs. Time*

For more info see: "EPA's Calculation and Use of First-Order Rate Constants – MNA" EPA/540/S-02/500

Two Related Concepts

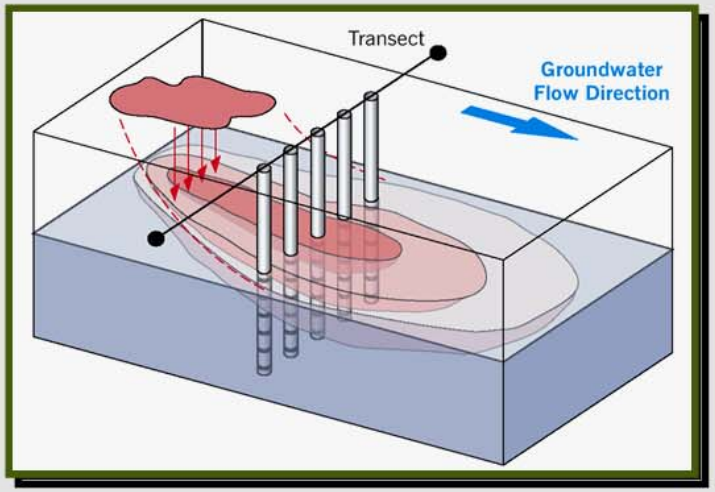
- Pre-characterization
  - One option is to use Membrane Interface Probes (MIPs) or some other screening tools to determine where mass discharge is located
  - Then design a mass discharge monitoring system with more focused sampling on high mass flux areas
- *Site characterization* is different than *long-term monitoring*

Tools for Transect Method: Calculator

Lead author: Shahla Farhat, Ph.D.
free at www.gsi-net.com
Microsoft Excel-based

Mass Flux Toolkit

To Evaluate Groundwater Impacts, Attenuation, and Remediation Alternatives



Calculate Flux

Impact of Flux

Learn About Flux

About | Help

Version 1.01

Input Data and Grid

Data Input Instructions:
10.80 → Enter value directly.
10.80 → Value calculated by model.

Site Location and I.D.: Texas
Description: MTBE

4. CHOOSE

6. ENTER TI
Distanc
D

Hydraul
Uniform
Uniform

20E-02 (cm/sec)
00E-03 (cm/cm)

Mon
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

Key Features of Mass Flux Toolkit

- Streamlines the data input process
- You pick interpolation method
- It does the calculations
- Uncertainty/sensitivity analysis
- Graphical output
- How to use mass discharge data
- Overall resource for mass flux

7. CHOOSE GRID

Orig mean cell width (x-axis) (ft) 14.0
Orig cell thickenss (y-axis) (ft) 1.5
→
Refine cell width by 1
Refine cell thickness by 1

8. SELECT CONSTITUENT FOR CALCULATIONS

MTBE | Constituent B

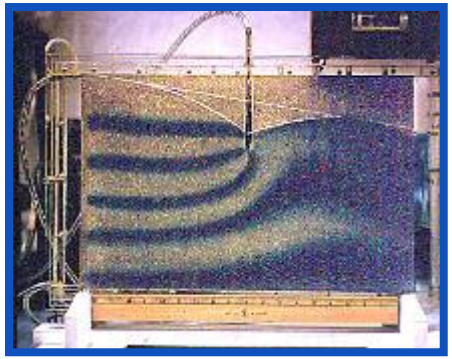
Next Step: Complete Grid | Go Back | Clear Screen | Paste Example | See Saved Grids | Print | HELP

Software Demonstration

Mass Flux Toolkit Demonstration

Method 1 – Transects Advantages and Limitations

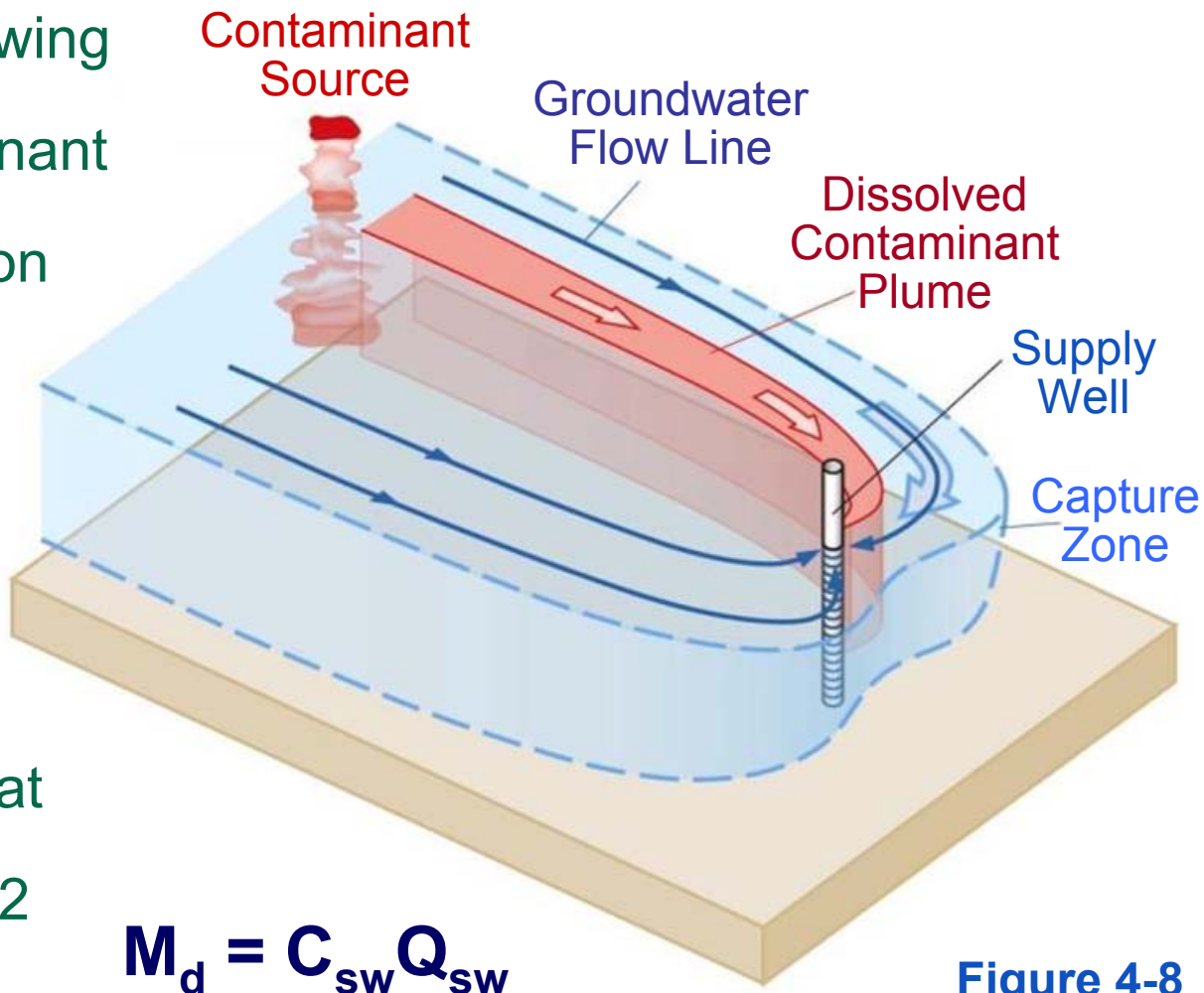
- Advantages
  - Commonly used – many applications
  - Direct measurement
  - Extension of accepted technology
- Limitations
  - High resolution data can be costly
  - Calculations can be time consuming



Method 2 – Well Capture/Pump Tests

Nichols and Roth, 2004

- Instead of plume flowing downgradient you capture the contaminant plume and measure flow, concentration on surface, but
  - Pumping should not induce dissolution at the source
  - Pumping needs to reach steady state
  - High confidence that plume has been captured
- Some pump and treat (P&T) systems can be ideal for Method 2



$$M_d = C_{sw}Q_{sw}$$

Figure 4-8

Well Capture Mass Discharge Calculation

Nichols and Roth, 2004

Figure 4-8

Measure Q, C_{well} from well

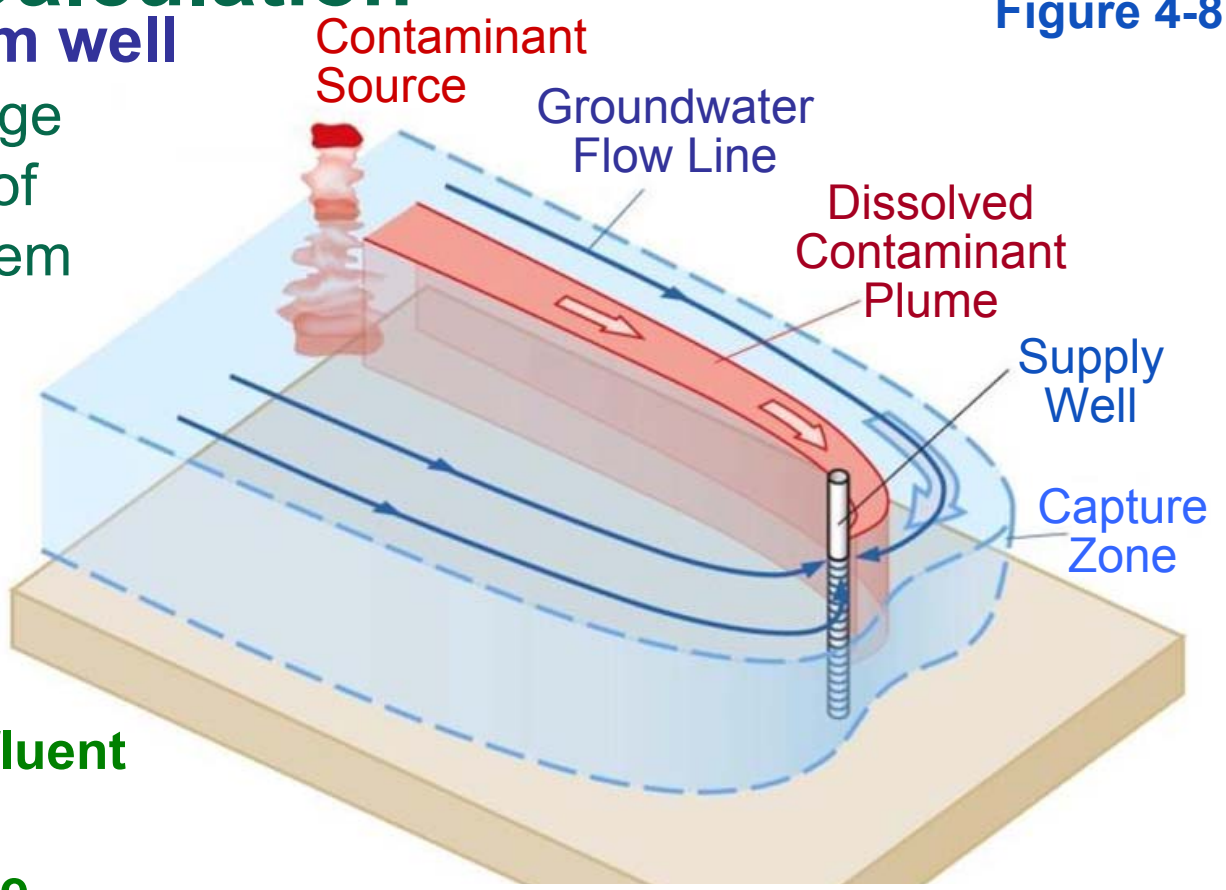
Calculate mass discharge based on total capture of plume by pumping system

$$M_d = Q \times C_{well}$$

M_d = Mass discharge (grams per day)

C_{well} = concentration in recovery well effluent (grams per liter)

Q = Well pumping rate (liters per day)



$$\frac{\text{grams}}{\cancel{\text{liters}}} \times \frac{\cancel{\text{liters}}}{\text{day}} = \frac{\text{grams}}{\text{day}}$$

More Sophisticated Version Method 2

- Integral Pump Tests (IPT)
  - Steady state flow conditions, but handles changing heterogeneous concentrations in plume

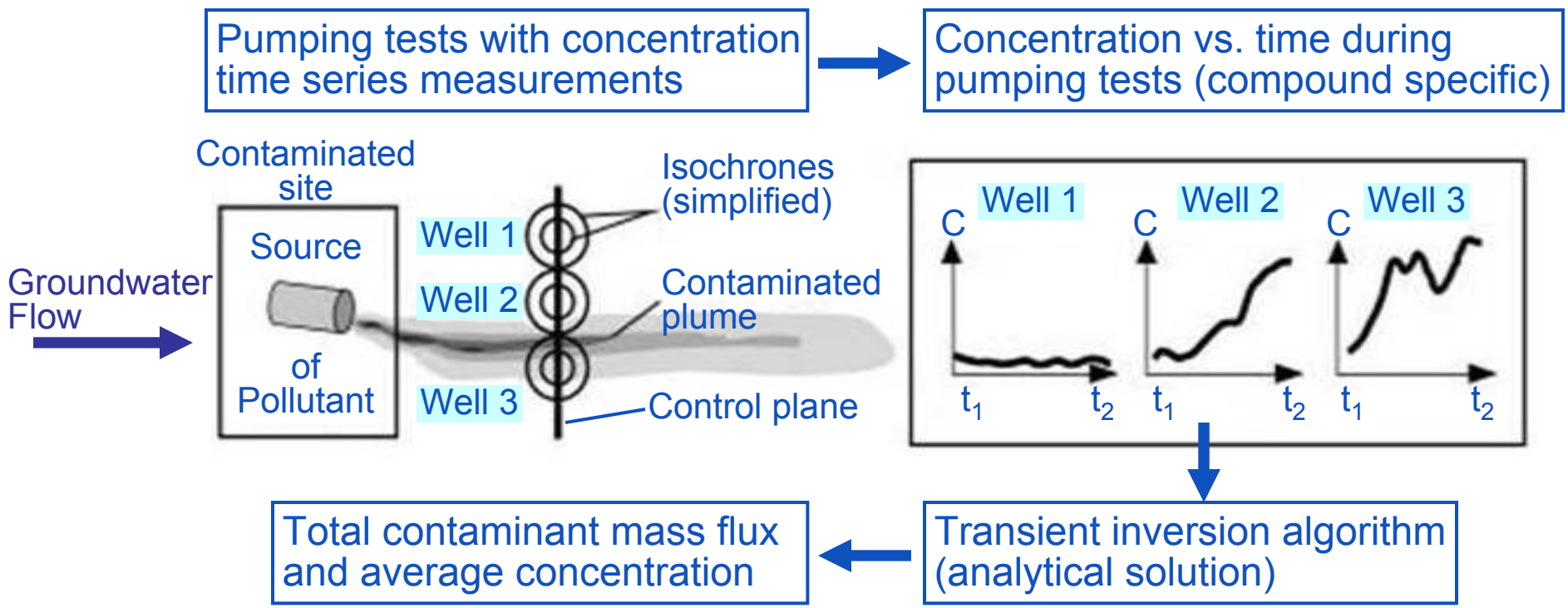
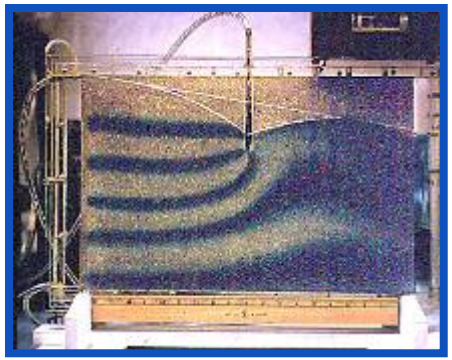


Figure 4-9. Estimating Mass Flux Using Integral Pump Test Series Data

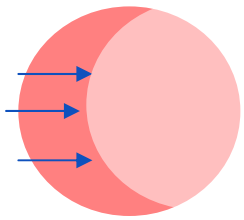
Well Capture Methods Advantages and Limitations

- Advantages
  - Fewer wells
  - Better integration of flow and concentration data
  - Can use existing pumping system
- Limitations
  - No mass flux data
  - Large volumes of water that need disposal/treatment
  - Possible to change plume characteristics
  - Difficult to assure full plume capture

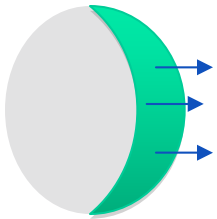


Methods 3 – Passive Flux Meter

- Permeable sorbent
  - Accumulates contaminant based on flow and concentration



- Soluble tracers
  - Loses tracer based on groundwater velocity and flux convergence calculations



1. Contaminant adsorbed onto passive flux meter over time to get Concentration

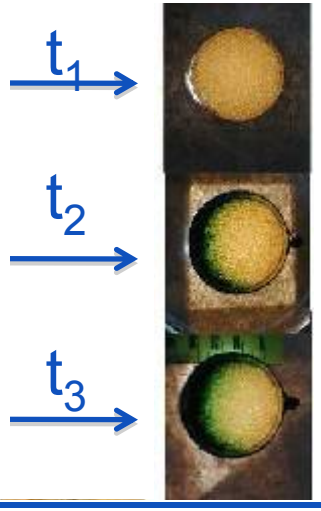
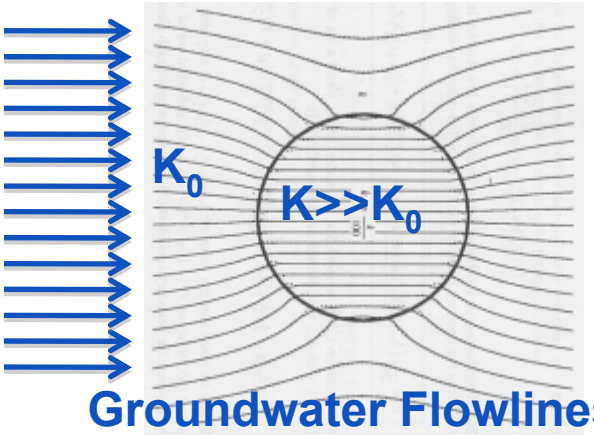


Photo: Dye intercepted in a meter

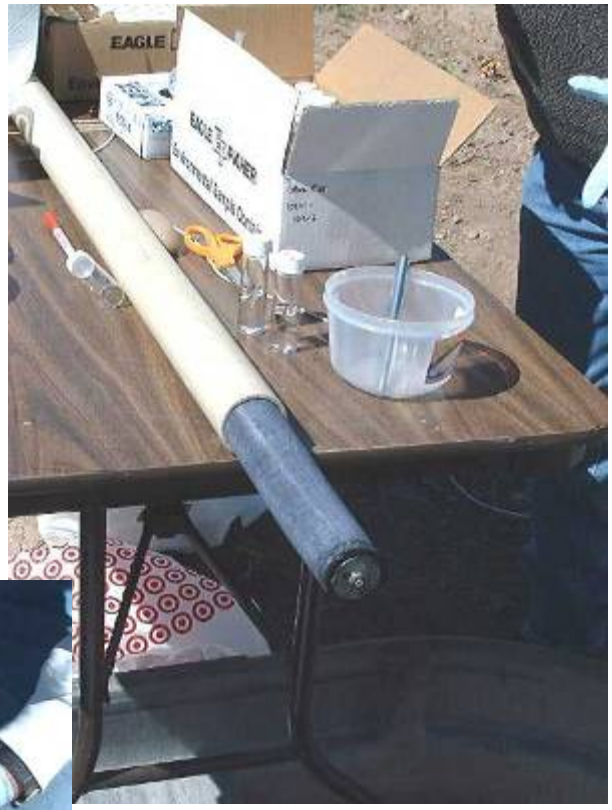
2. Tracer desorbs from passive flux meter over time to get Flow (Q)



Source: Hatfield and Annable

Passive Flux Meter

Installation



Sampling

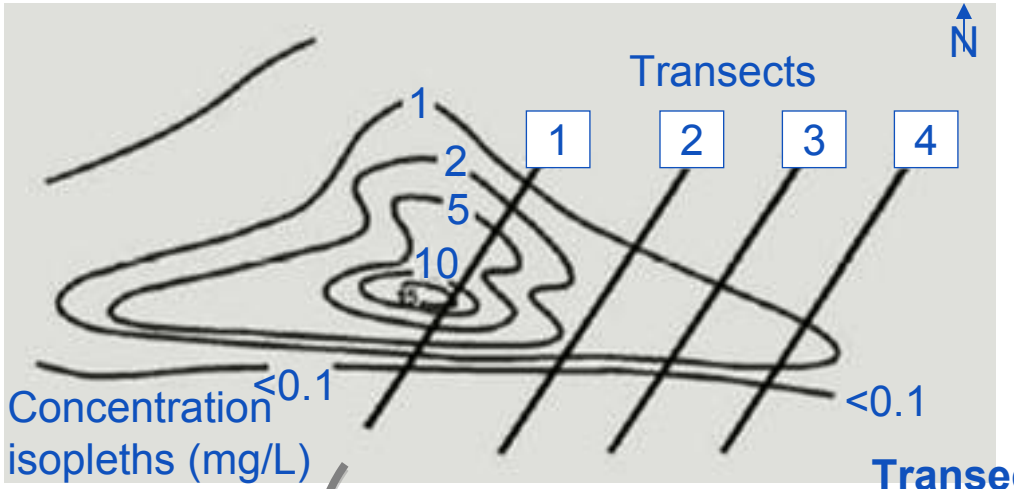
Vendor: http://www.enviroflux.com/pfm.htm

Passive Flux Meter Advantages and Limitations

- Advantages
  - “One stop shop” for both flow and concentration
  - Easy to install in the field
  - No waste generated
  - Vendor available to implement this method
- Limitations
  - Some method-specific issues (lower measurement in pushed wells, slight biodegradation of tracer at one site, competitive sorption under some conditions)
  - Relies on well convergence calculations

Methods 4 – Use Existing Data (Transect Based on Isocontours)

- Uses existing well network and plume map
- Combine with flow data



Scale (ft)
0 1000

Dover Air Force Base Delaware

Two dimensional transect based on isocontour data

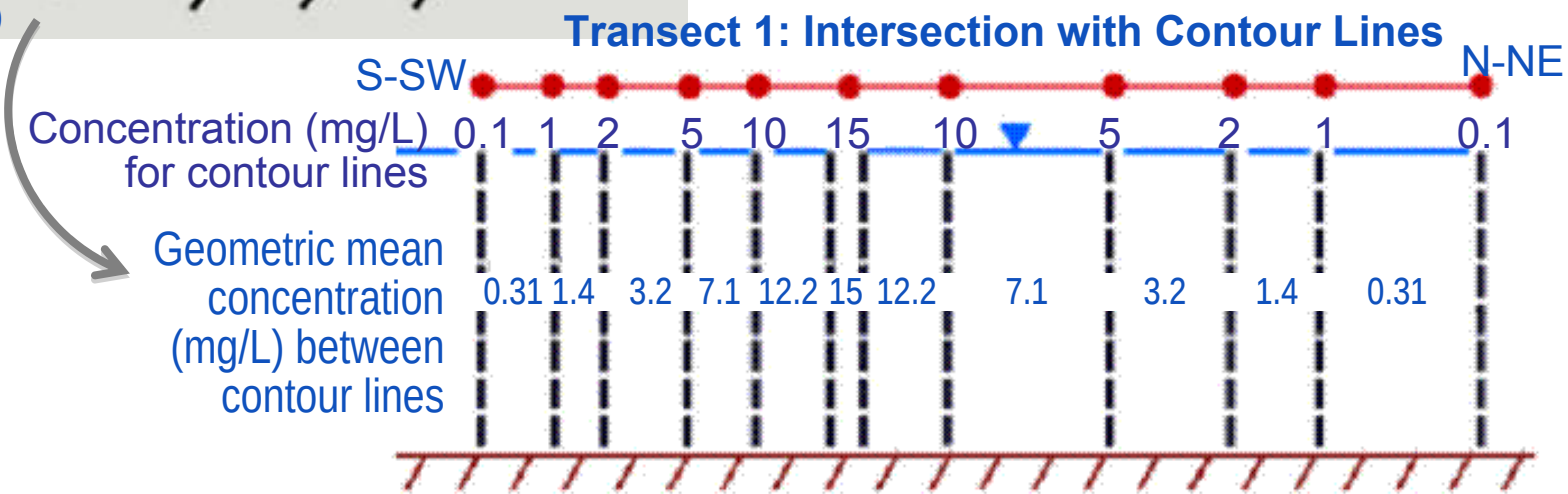
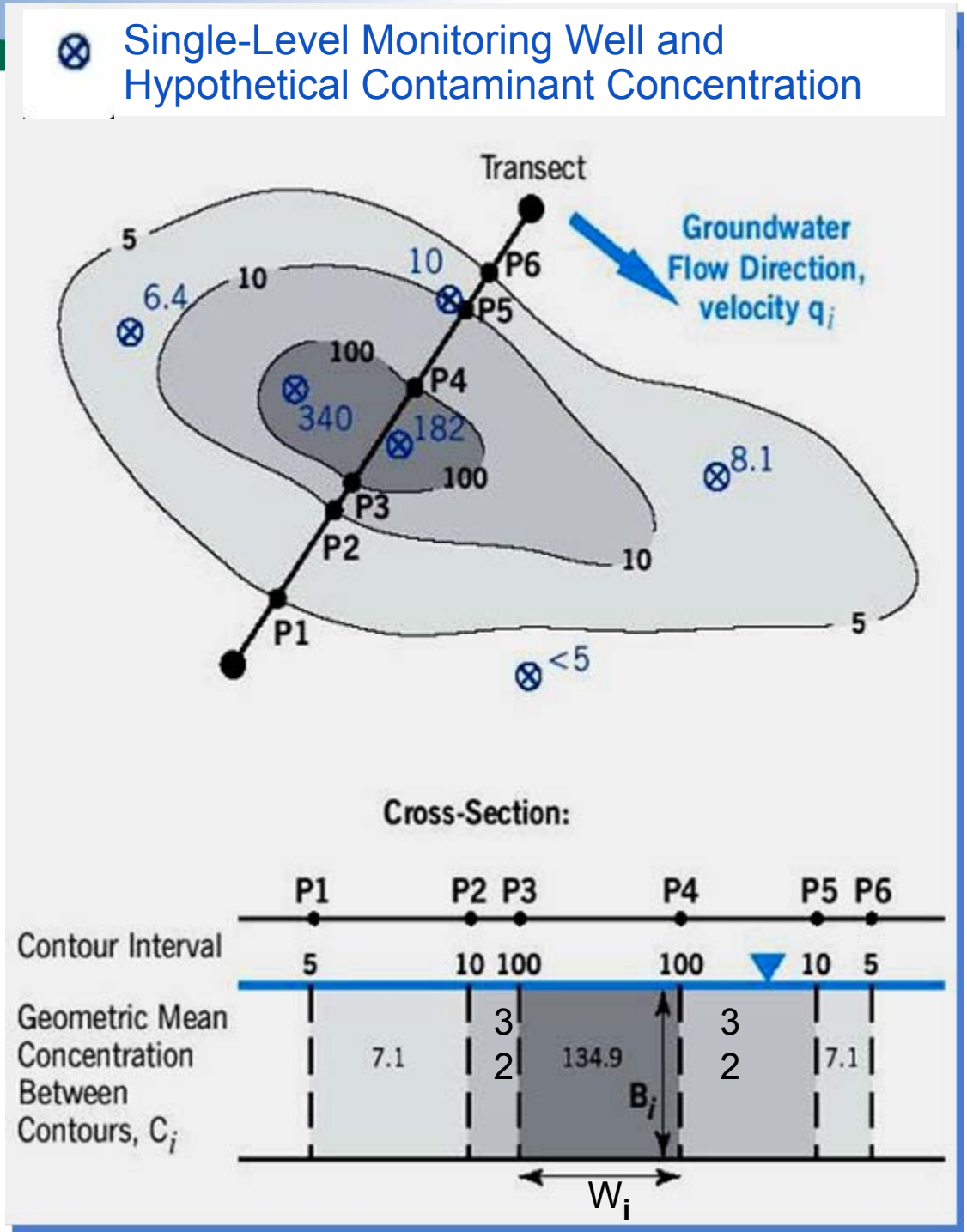


Figure 4-12

Calculating Mass Discharge from Isocontours

Plume Contour Data

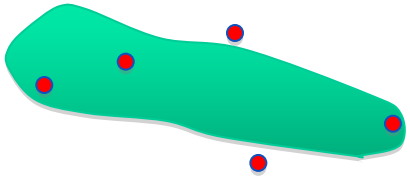
1. Get isocontours from existing plume map
2. Build transect using points where isocontours intersect transect line (you can add actual wells if close to contour)
3. Apply Transect Method (Method 1) Calculations



Nichols and Roth, 2004

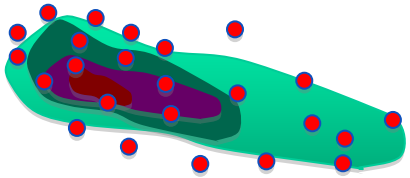
Isocontour Method Advantages and Limitations

- Advantages
  - Does not need special field study. Can use existing, historical data from existing monitoring system
  - Limited additional expense
- Limitations
  - Wide range of opinion about usefulness of this method
  - Can be inaccurate if plume map is built with only a few wells. For example consider:
    - Gas station site with 5 wells throughout entire plume: **not likely** to provide high quality mass flux/mass discharge data



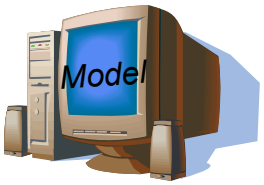
versus

    - Well characterized site with 40 wells in source zone: **likely** to provide higher quality data



Measurement Method 5 – Computer Models

- Using computer models



Models Integrate Flow and Concentration

1. Calibrate model
2. Get flow and concentration data across transect
3. Example Below from BIOSCREEN

DISSOLVED HYDROCARBON CONCENTRATIONS IN PLUME (mg/L at Z=0)

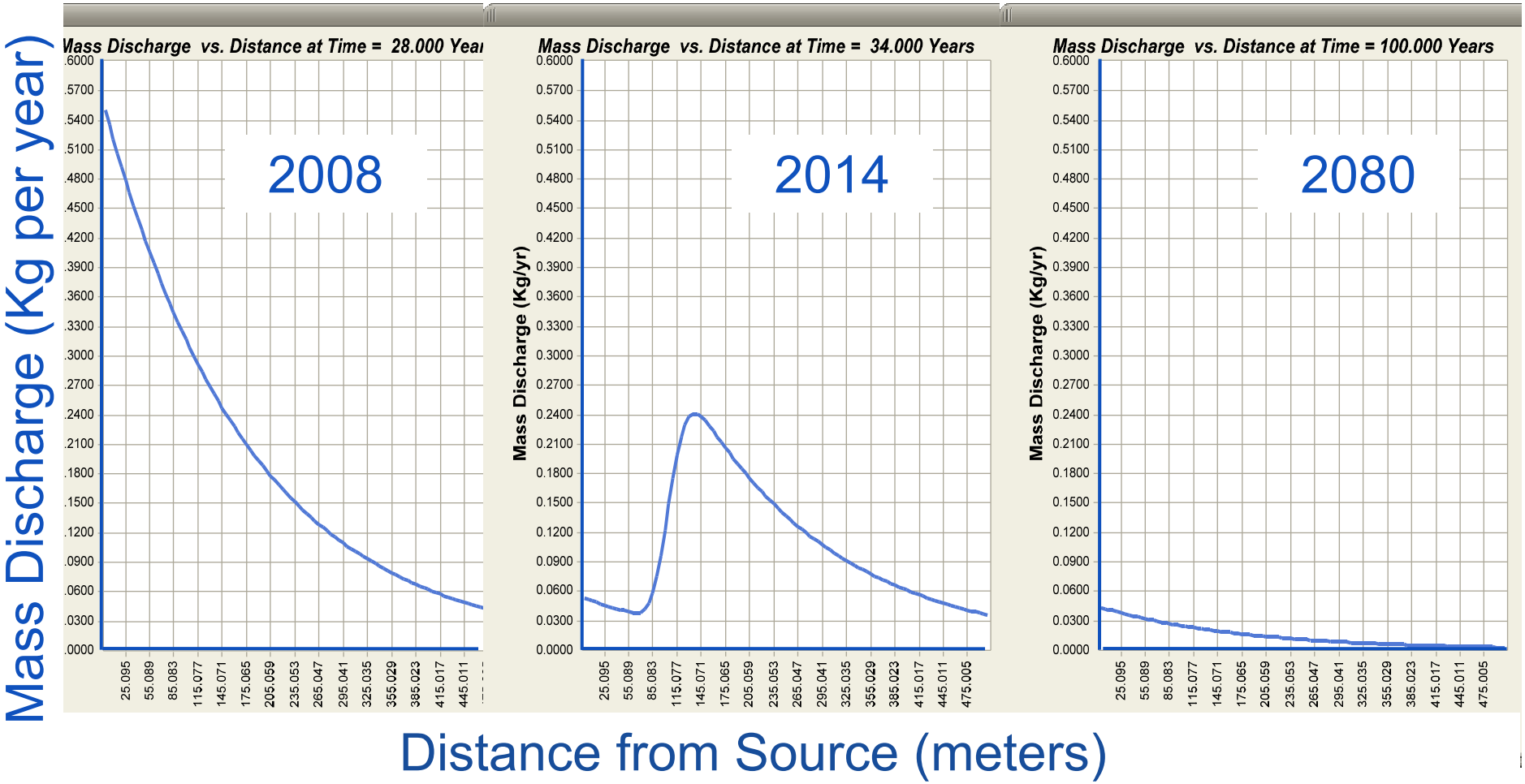
Transverse Distance (ft) ↓	*Distance from Source (ft)* 0	145	290	435	580	725	870	1015	1160	1305	1450
160	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
80	0.070	0.538	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0	9.000	8.466	7.407	6.350	5.268	4.192	3.152	2.168	1.245	0.385	0.000
-80	0.070	0.538	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-160	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
MASS FLUX (mg/day)	3.3E+5	2.4E+5	1.8E+5	1.6E+5	1.3E+5	1.0E+5	7.9E+4	5.4E+4	3.1E+4	9.6E+3	0.0E+0

Time: **5 Years** Target Level: **0.005** mg/L Displayed Model: **Inst. Reaction**

REMChlor Model of Source Remediation

Source: Ron Falta, Clemson Univ.

Remove 90% of mass in 2010.
REMChlor shows mass discharge vs. distance in future years



Measurement Method 5
Models with Mass Discharge

Model	Model application and type
BIOSCREEN	Fuel Hydrocarbon MNA, Analytical
BIOCHLOR	Chlorinated Solvent MNA, Analytical
BIOBALANCE	Chlorinated Solvent MNA, Analytical
MODFLOW/MT3DMS	General. Numerical
MODFLOW/RT3DMS	General, Sequential Degradation, Numerical
MODFLOW/MT3D	General. Numerical
MODFLOW/RT3D - rtFlux	General. Numerical
REMChlor *New!*	Hydrocarbon, Chlorinated Solvent

From Table 4-3

Computer Model Method Advantages and Limitations

- Advantages
  - Does not need special field study. Can use existing, historical data from existing monitoring system
  - Models are designed to combine flow, concentration data
- Limitations
  - Helpful to have experience/training in using models
  - Need good data – both flow and concentration
  - Amount of data depends on what the information is being used for
    - For example - need absolute or relative number?
    - Table 1.1 in Guide (shown under Transect Section) provides more detail

Five Methods for Mass Discharge

- *Method 1:* Transect Method (Sect. 4.1)
  - Commonly used. Based on familiar technology.
- *Method 2:* Well Capture/Pumping Methods (Sect. 4.2)
  - Many pump and treat systems doing this now.
- *Method 3:* Passive Flux Meters (Sect. 4.3)
  - New technology, easy to install, one device for flow and concentration.
- *Method 4:* Using Existing Data (Isocontours) (Sect. 4.4)
  - Uses existing data. Cost effective, but requires good monitoring network.
- *Method 5:* Solute Transport Models (Sect. 4.5)
  - Combines flow and concentration data. Helpful to have experience.

Method	Comparison Based on Two Sites
TM and MIPT	▶Relative difference 3% to 46% ▶(TM – MIPT)/TM
TM and PFM	▶Relative difference -21% to 17% ▶(TM – PFM)/TM
PFM and MIPT	▶Relative difference 0% to 35% ▶(PFM – MIPT)/PFM

TM = Transect method PFM = Passive flux meter
MIPT = Modified integral pumping test

Brooks et al. (2008)

Comparison of Methods *(cont'd)*

Method		Implement-ability	Regulatory Considerations	Availability	Cost
Transect	TM	1	1	1	4
	PFM	3	2	2	4
Pumping	IPT	3	3	2	2

1 = best; 4 = worst

TM = Transect method

PFM = Passive flux meter

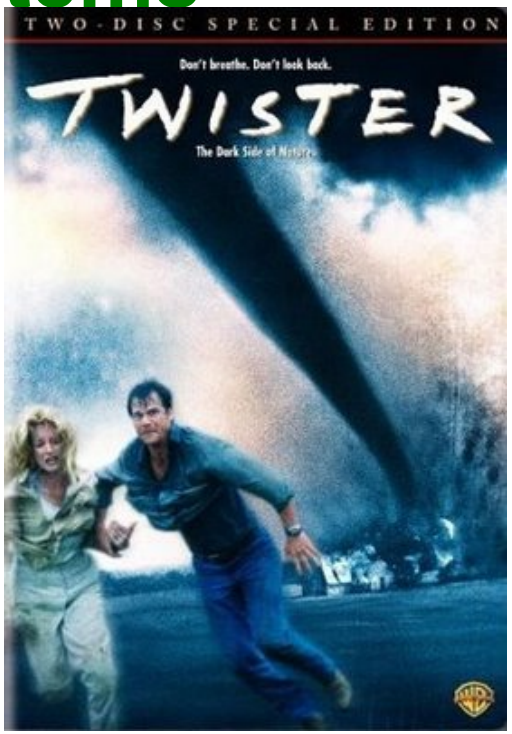
IPT = Integral pump test method

Goltz et al. (2007)

Scientific Classification Systems

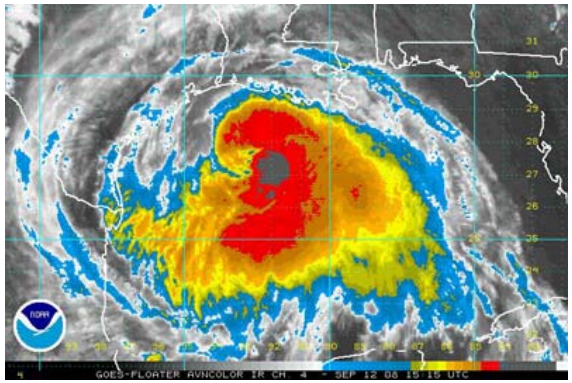
Use in Science

- "The act of distributing things into classes or categories of the same type"
- Key part of science



Good Examples

- *Remediation*: Chlorinated Solvent MNA Scenarios Tool
- *Other Fields:* Richter scale, volcanoes, star brightness etc.



OoM: *"Order of Magnitude"*

- **Concentration, hydraulic conductivity have a log-normal distribution**

- **Log-normal distribution: by a factor of 10.**
  - **We discuss K as "10^{-1} cm/sec" or "10^{-6} cm/sec"**
  - **Concentrations: from 0.001 mg/L to 1000 mg/L**

- **Remediation: "Well implemented in-situ remediation remedies are likely to reduce source zone groundwater concentrations by about *one order-of-magnitude* (90% reduction) from pre-treatment levels."**

Source: Sale and Newell, 2010

Site Prioritization Using Mass Discharge

Site	COC	Pre-Treatment Mass Discharge (g/day)
Unidentified Site	Total COC	56,000
Thermal Treatment Site 5	Total COC	1,874
Ft. Lewis Before Treatment	TCE	596
St. Joseph, MI	Total Ethenes	425
Midwestern US	TCE	389
Dover AFB, DE	CVOC	280
Long Island	MTBE	250
Thermal Treatment Site 2	Total COC	164
Unidentified Site	Unknown	160
Port Hueneme, CA	MTBE	150
Thermal Treatment Site 1	Total COC	141
Thermal Treatment Site 3	Total COC	134
Florida	TCE	102
Borden Site	TCE	93
Thermal Treatment Site 4	Total COC	87
Strasbourg	CH	86
Hill AFB Before Treatment	TCE	77
Neckar Valley, Germany	PCE	77
Ontario	PCE	56.2

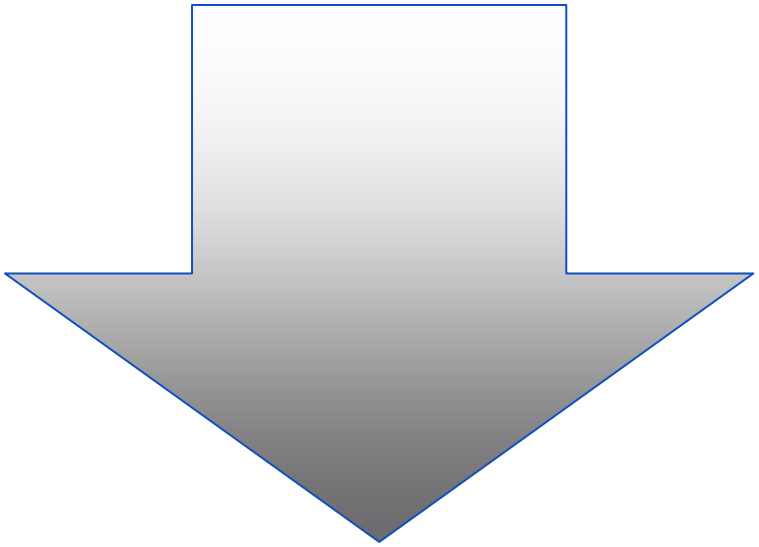
56,000 Grams Per day

0.00078 Grams Per day

Site	COC	Pre-Treatment Mass Discharge (g/day)
Site 1, Alameda Naval Air Station	cis-1,2-DCE	31
Testfeld Site, Germany	PAH	30
Thermal Treatment Site	Total COC	26
Thermal Treatment Site 13	Total COC	25
Thermal Treatment Site 6	Total COC	13
Elizabeth City, NJ	MTBE	7.6
Thermal Treatment Site 8	Total COC	7
Unnamed	MTBE	4
Thermal Treatment Site 14	Total COC	3.6
Thermal Treatment Site 12	Total COC	3.4
Australia	TCE	3
Landfill Site, Heidelberg, Germany	TCE	2.5
Thermal Treatment Site 9	Total COC	1.1
Borden Site Chemox Treatment	PCE	0.88
Sampson County, NC	MTBE	0.77
Unidentified Dry Cleaner Site	PCE	0.4
Thermal Treatment Site 11	Total COC	0.3
Unidentified Site	RDX	0.3
Vandenberg AFB, CA	MTBE	0.029
Thermal Treatment Site 10 – Shallow Plume Only	Total COC	7.80E-04

Mass Flux Calculations for Various Sites

Smallest: 0.00078 grams per day



Largest is 72,000,000 times larger than smallest

Log (72,000,000) = 7.9

Equal to ~8 OoMs

Largest: 56,000 grams per day

"Plume Magnitude Classification System"

Mass Discharge (grams/day)	Plume Category
< 0.001	"Mag 1 Plume"
0.001 to 0.01	"Mag 2 Plume"
0.01 to 0.1	"Mag 3 Plume"
0.1 to 1	"Mag 4 Plume"
1 to 10	"Mag 5 Plume"
10 to 100	"Mag 6 Plume"
100 to 1,000	"Mag 7 Plume"
1,000 to 10,000	"Mag 8 Plume"
10,000 to 100,000	"Mag 9 Plume"
>100,000	"Mag 10 Plume"

Newell et al., accepted Journal of Ground Water

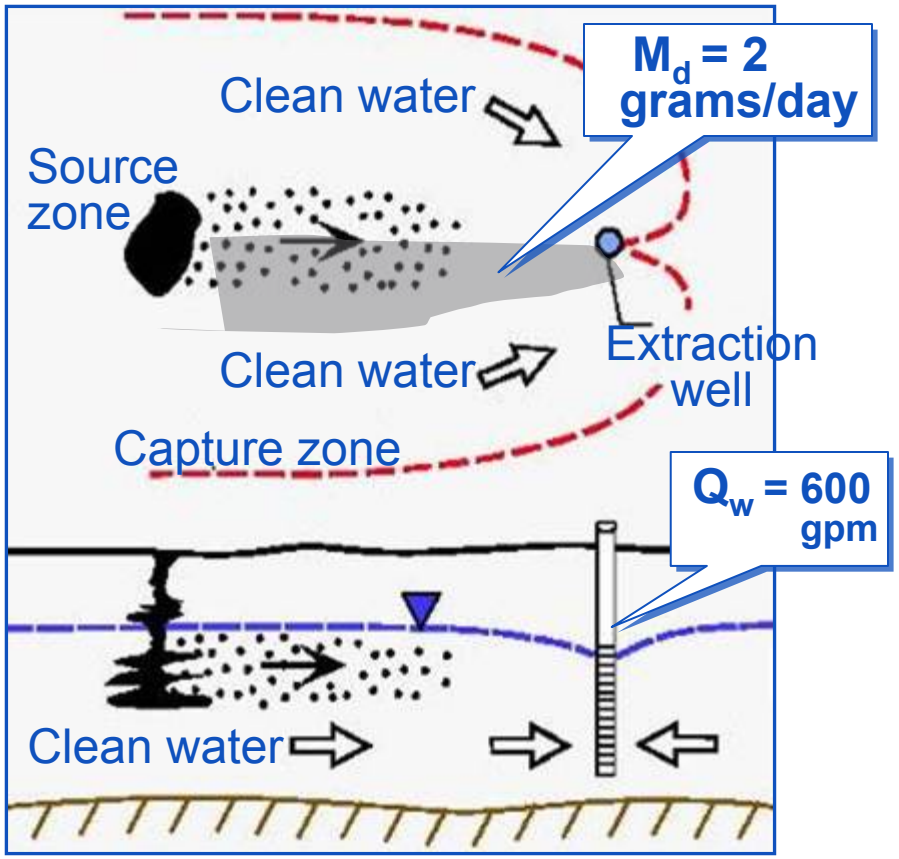
Using Mass Discharge: Estimating Well Impacts

Einarson and Mackay, 2001

Use mass discharge of plume to predict constituent of concern concentration in downgradient water supply well

$$C_{well} = M_d \div Q_{Well}$$

C_{well} = Concentration in extraction well
Q_{well} = Pumping rate for extraction well



$$2\ g/day \times \frac{1}{600\ gpm} \div 1440\ min \times \frac{1\ gal}{3.79\ L} \times \frac{10^6 ug}{g} = < 1\ ug/L$$

Using Mass Discharge: Estimating Well Impacts

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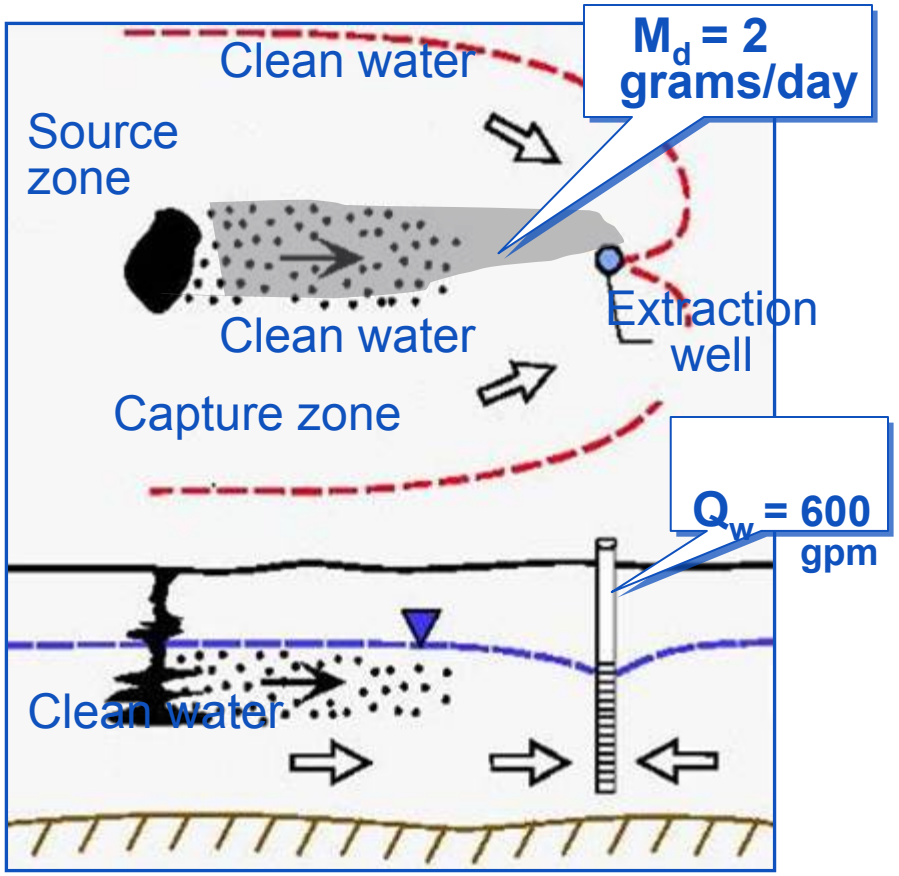

$$2\ g/day \times \frac{1}{600\ gpm} \div 1440\ min \times \frac{1\ gal}{3.79\ L} \times \frac{10^6 ug}{g} = < 1\ ug/L$$

What Mag Plume Does It Take for Impact?

For complete capture and MCL = 5 ug/L:

Mass Discharge (grams/day)	Plume Classification	This Mag Plume Could Impact:
0.001 to 0.01	**Mag 2** Plume	**Domestic well pumping at 150 gallons/day**
1 to 10	**Mag 5** Plume	**Municipal well pumping at 100 gallons per minute**
1,000 to 10,000	**Mag 8** Plume	**Stream with a mixing zone and base flow of 100 cubic feet per second**

Newell et al., accepted Journal of Ground Water

MEASUREMENT AND USE OF MASS DISCHARGE AND MASS FLUX AT CONTAMINATED SITES

Start	End	Topic
8:30 AM	8:50 AM	Welcome & Introduction *(Dr. Hans Stroo)*
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12:00 PM		Adjourn

Regulatory Perspective on the Use of Mass Flux & Mass Discharge

Dec 2, 2010

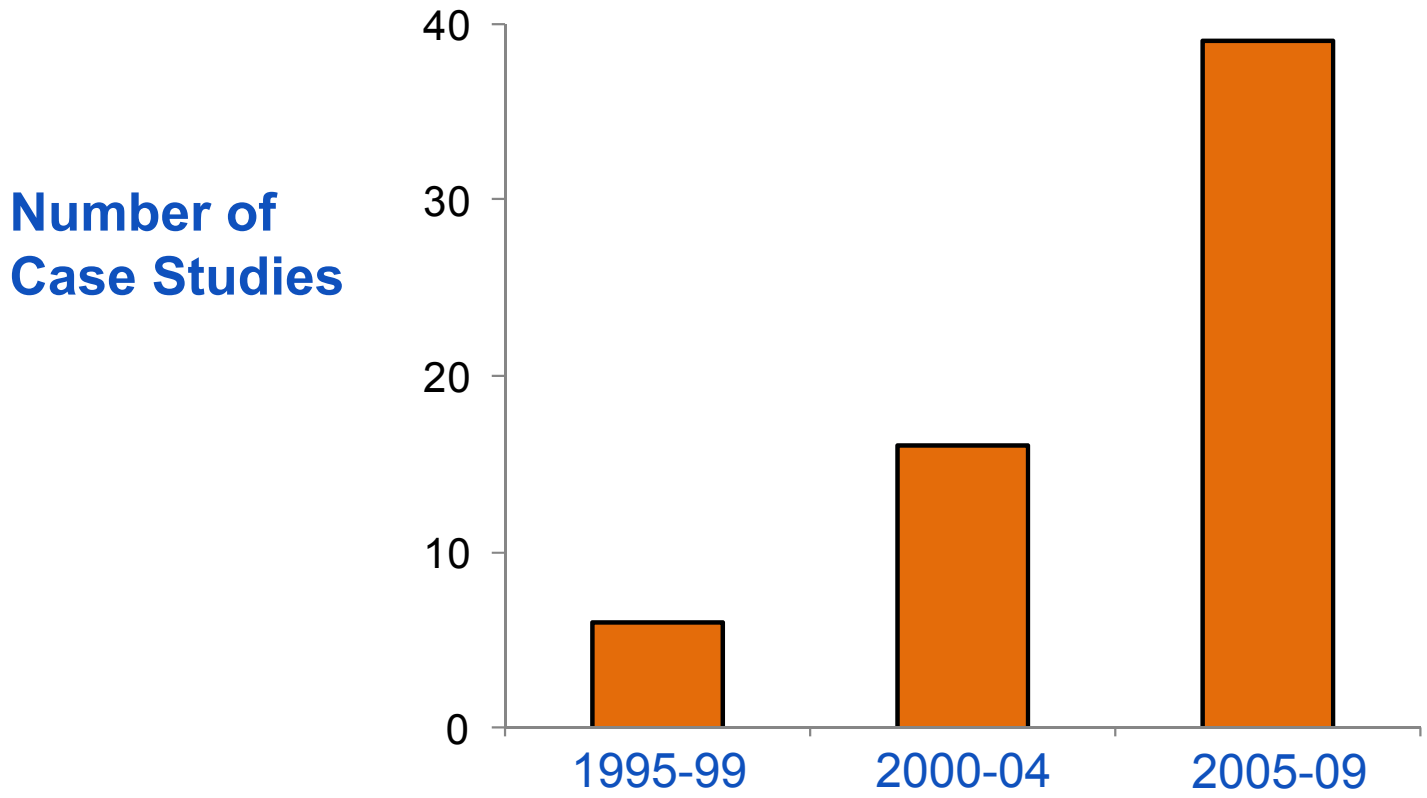
SERDP Workshop, Washington, DC

Alec Naugle, Sr. Engineering Geologist
anaugle@waterboards.ca.gov
(510) 622-2510

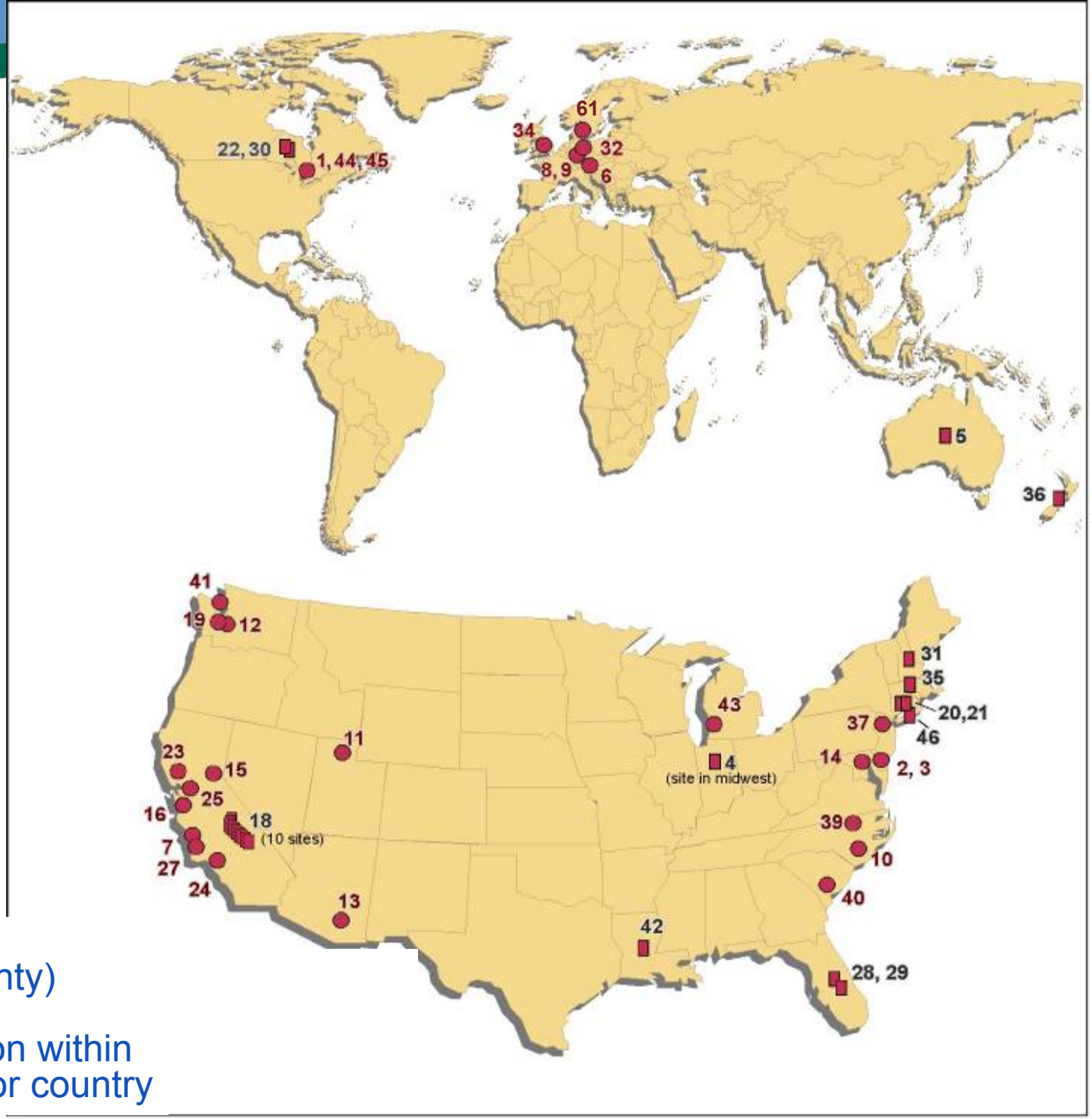
San Francisco Bay
Regional Water Quality Control Board

CALIFORNIA
Water Boards
STATE WATER RESOURCES CONTROL BOARD
REGIONAL WATER QUALITY CONTROL BOARDS

65 Case Studies show Increasing Use of Mass Flux/Discharge since 1995



Where Mass Discharge Has Been Used

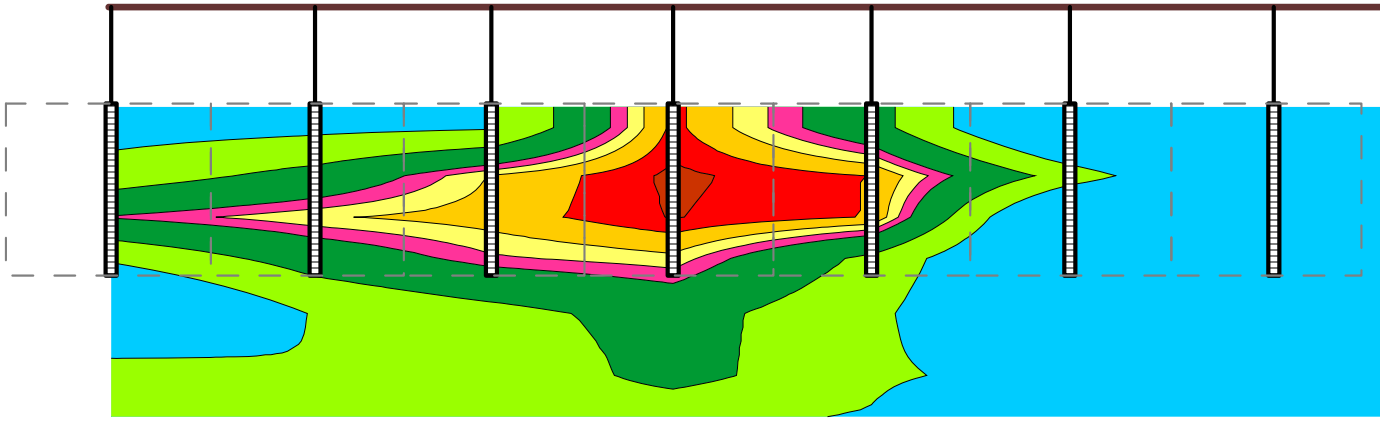


1 Specific location (known city or county)

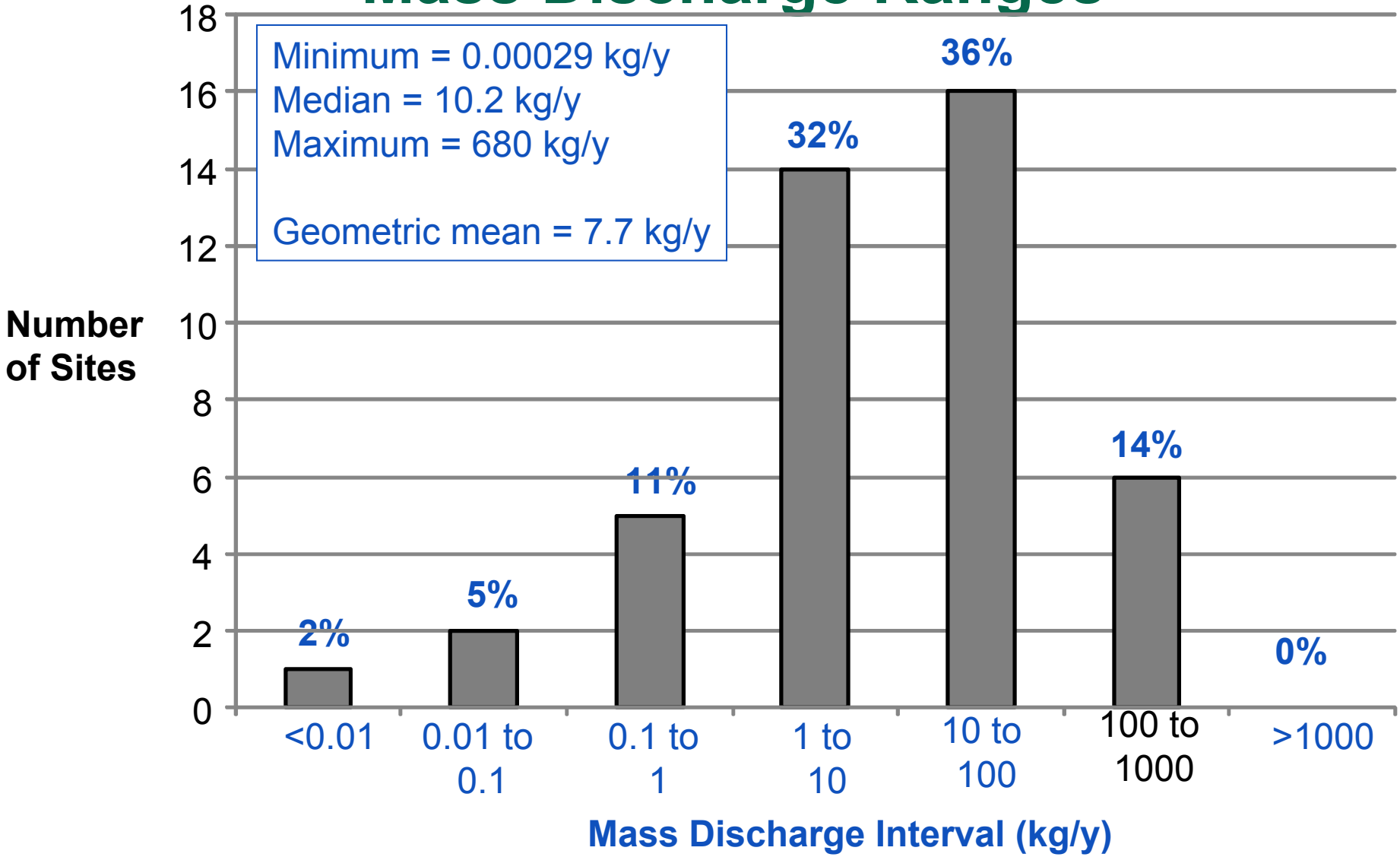
5 Unspecified location within a state, province, or country

Reasons for Increased Use

- New studies → heterogeneous mass flux from source zones (e.g. Guilbeault et al., 2005)
- Improved monitoring techniques
- Recent focus on improving remediation efficiency
- New databases comparing technology performance based on source strength reduction



Frequency of Sites with VOC/SVOC Mass Discharge Ranges



Mass Discharge Calculations for Various Sites

Site	Contaminant	Mass Discharge (g/d)	Reference
Sampson County, NC	MTBE	0.6 - 2	(Borden et al, 1997)
Vandenberg AFB, CA	MTBE	4 - 7	Unpublished
Unnamed Site	MTBE	4	Unpublished
Elizabeth City, NC	MTBE	7.6	Wilson, 2000
St. Joseph, MI	TCE	167	(Semprini et al, 1995)
Dover AFB, DE	CVOCs	630	(RTDF 1998)

Table adapted from Einarson and Mackay (2001) ES&T, 35(3): 67A-73A

Frequency of Method Applications

Mass Flux and Mass Discharge Measurement/Estimation Method	No. Sites Where Applied
Transects with groundwater sample collection	41
Integral Pump Test(s)	7
Transects with passive flux meters	5
Isoconcentration contours	2
Mass Balance	2
Solute Transport Model	1

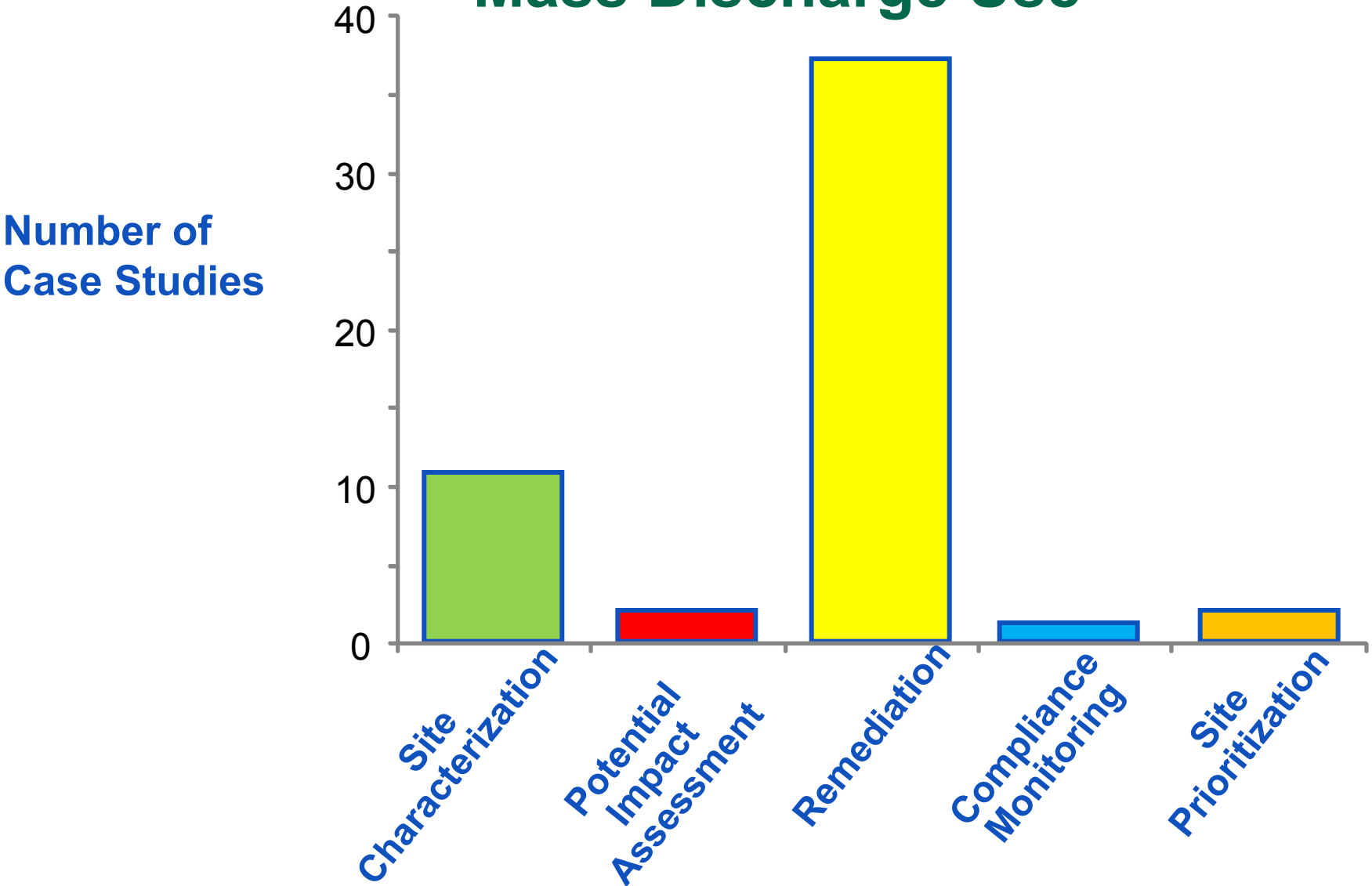
Six Use Categories from Case Studies

1. Site Characterization
2. Potential Impacts and Exposure Evaluation
3. Remediation Selection and Design
4. Performance Monitoring and Optimization
5. Compliance Monitoring
6. Site Prioritization

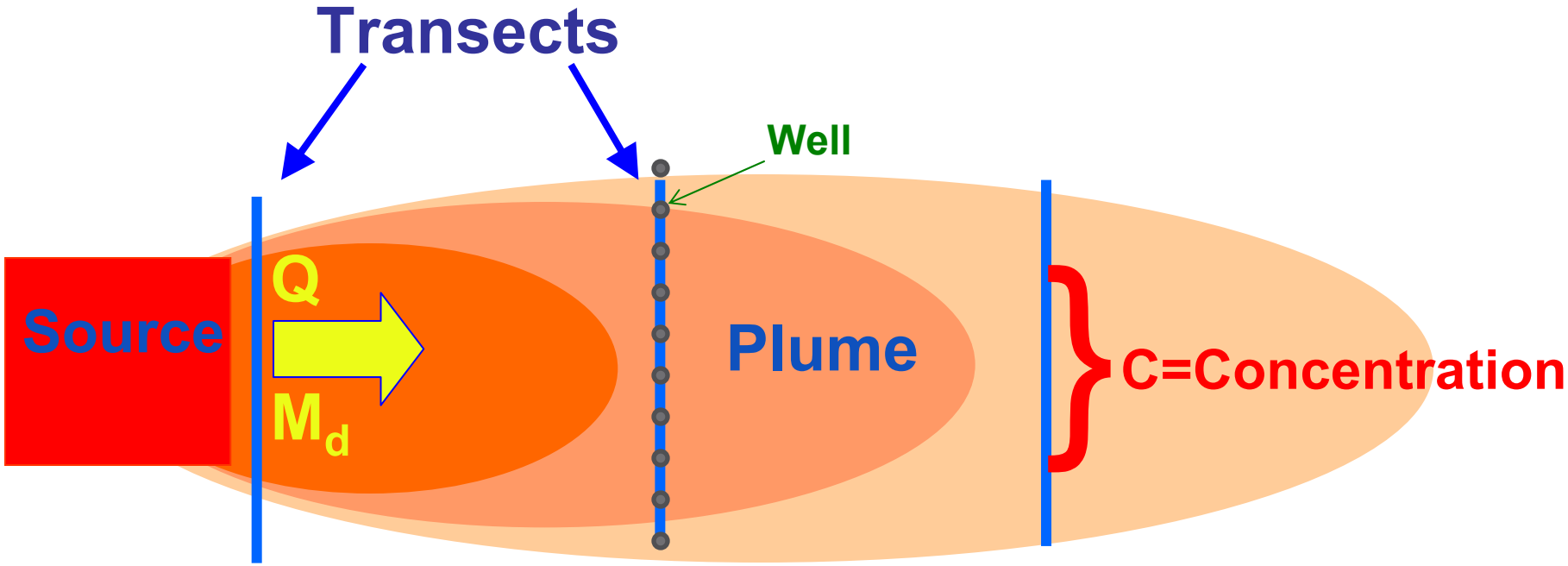
- Baseline mass discharge
- Identify hotspots
- Attenuation rates
- Low vs. high K
- Multiple sources

- Remedial action objectives (RAOs)
- Technology selection
- Remedial design
- Performance
- Optimization

61 Case Studies Documenting Mass Flux and Mass Discharge Use



Mass Discharge: Source or Plume Strength



Across any Transect, a Contaminant Plume Conveys:

Groundwater Discharge, **Q** (e.g., L/day)

Contaminant **Mass Discharge**, M_d (e.g., g/day or kg/year)

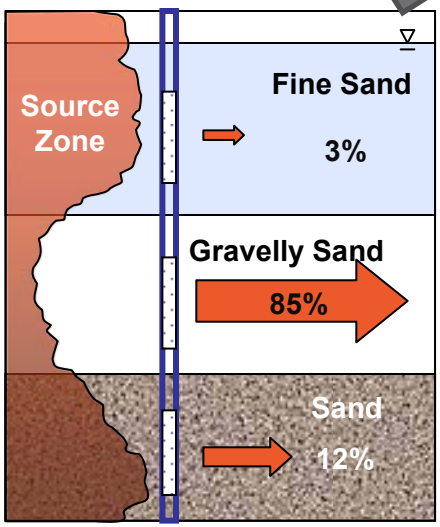
$$M_d = Q \times C \quad \text{(L/day x mg/L = mg/day)}$$

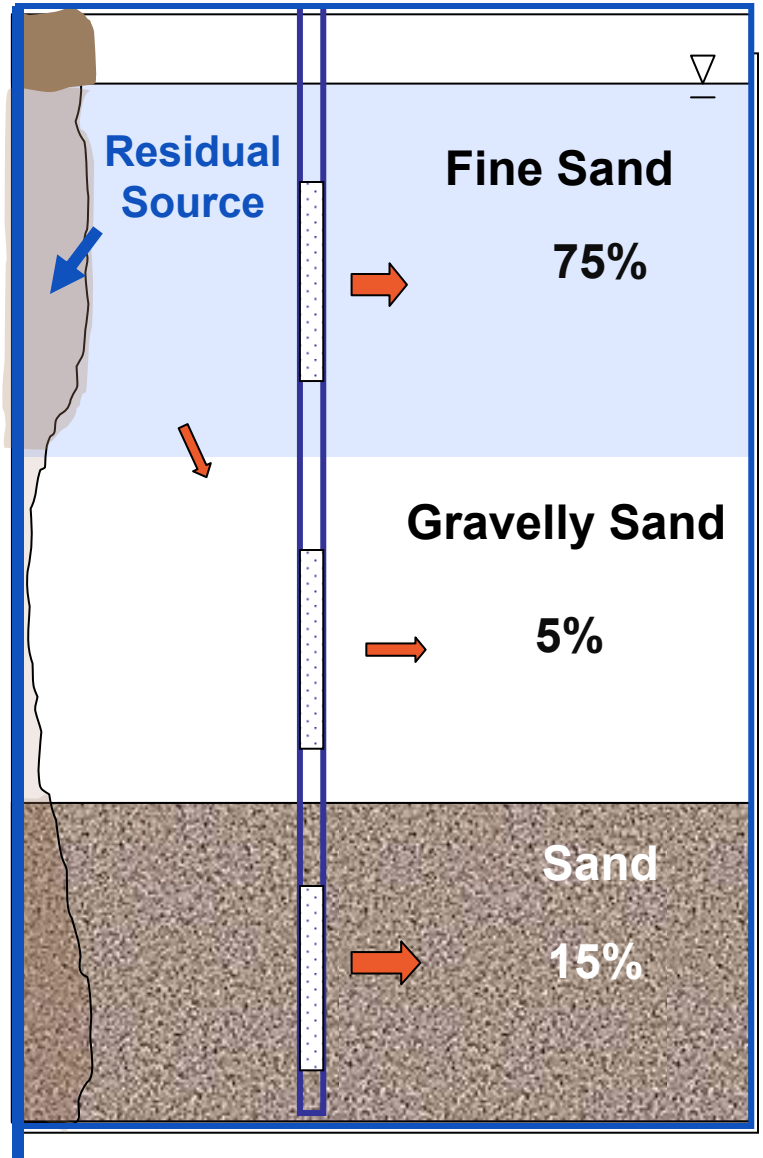
Figure 2-1

Example: Prioritizing Treatment Zones

As the source is depleted, more mass remains in less permeable regions.

This preferential depletion may alter the priorities for remediation.





Mass Flux (J) = KiC

K = 1.0 m/day
i = 0.003 m/m
C = 1,000 μg/L
Mass Flux = 37.5 mg/d/m²

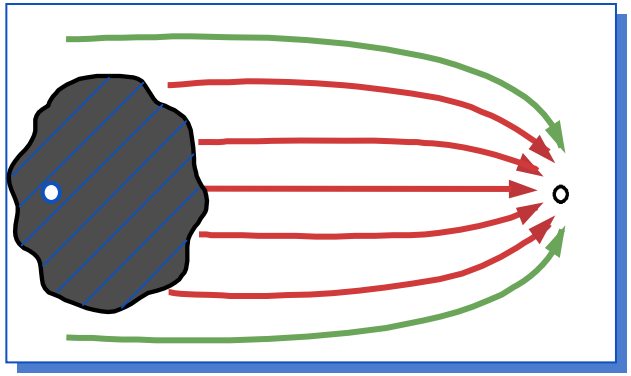
K = 33.3 m/day
i = 0.003 m/m
C = 50 μg/L
Mass Flux = 5 mg/d/m²

K = 5.0 m/day
i = 0.003 m/m
C = 500 μg/L
Mass Flux = 7.5 mg/d/m²

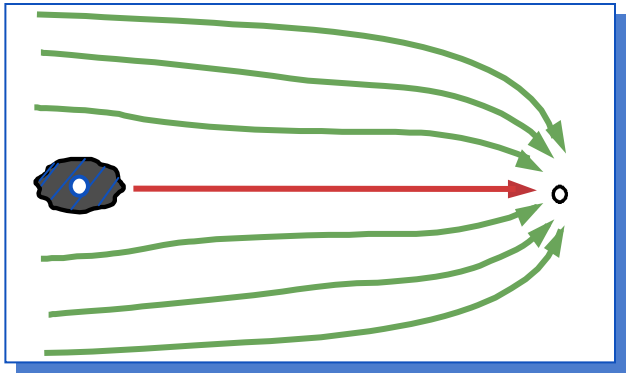
Mass Discharge and Concentration

- Concentration-based approach may not account for important site characteristics
  - Large vs. small releases
  - Pumping rate at the receptor well

Case A: Large Release
High Max. Conc. and High Md



Case B: Small Release
High Max. Conc. and Low Md



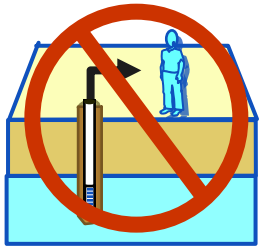
KEY POINT: **Evaluation of mass discharge (M_d) can increase understanding of site and be an important component of the site conceptual model**

Mass Flux/Discharge Applications

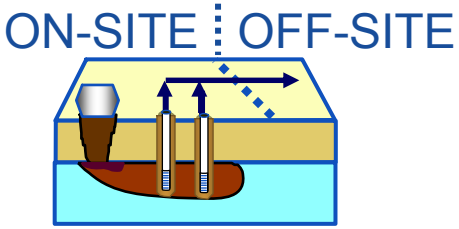
1. Site Characterization
2. Potential Impacts and Exposure Evaluation
3. Remediation Selection and Design
4. Performance Monitoring and Optimization
5. Compliance Monitoring
6. Site Prioritization

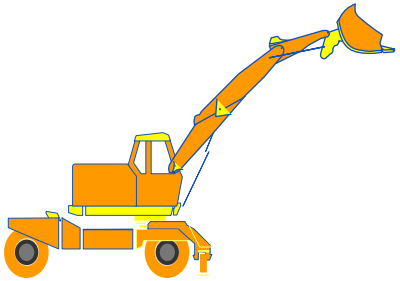
- Shows
  - Effect of natural attenuation

- Quantifies
  - Potential impacts to wells and streams

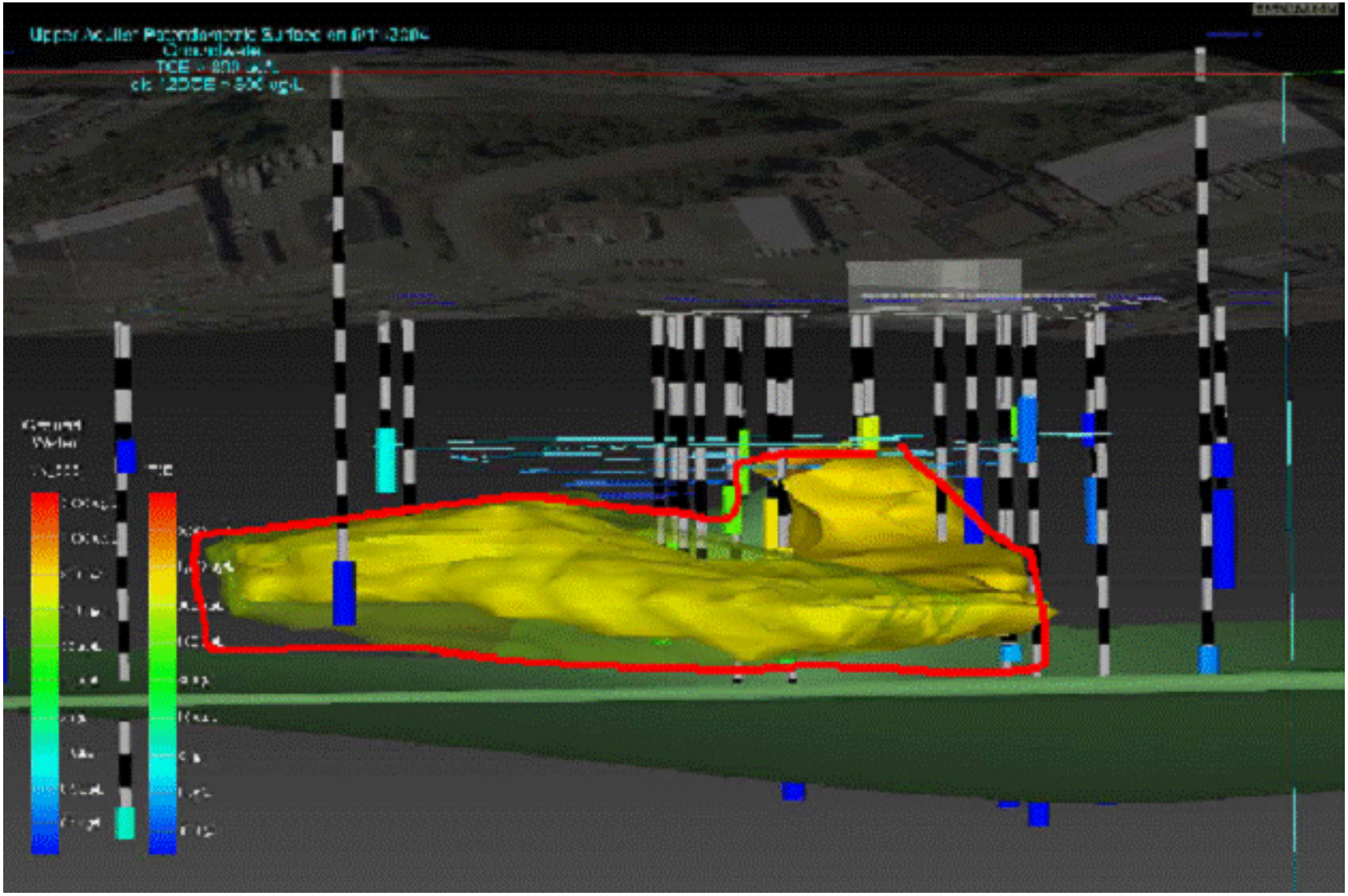


- Guides
  - Where remediation is needed

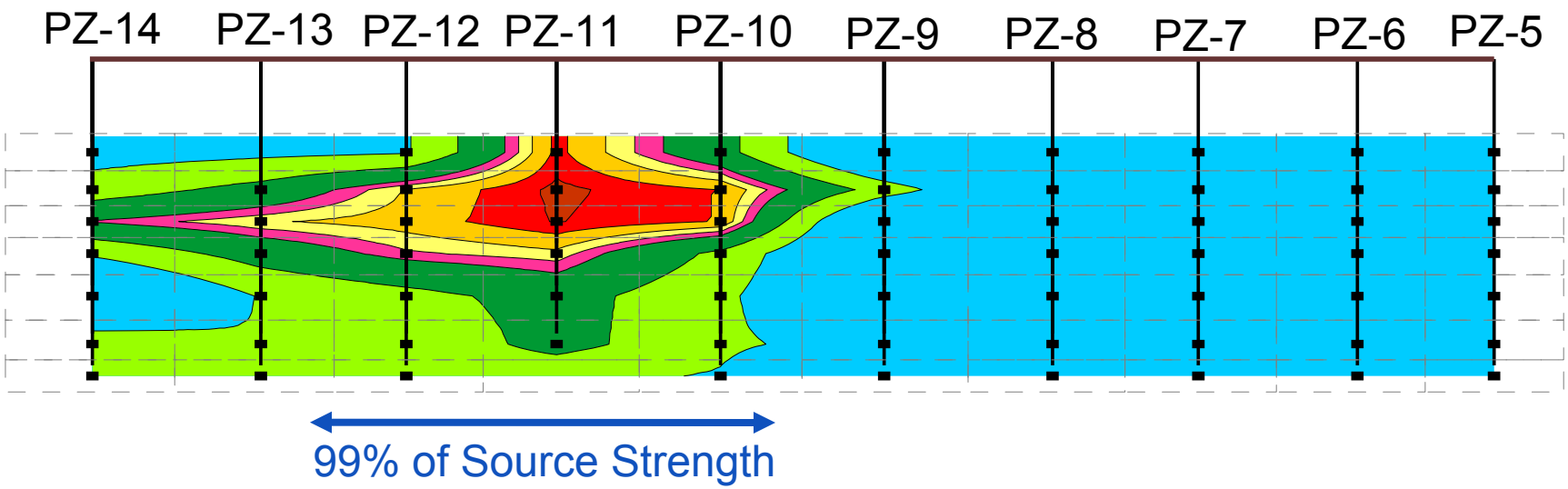




Case Examples

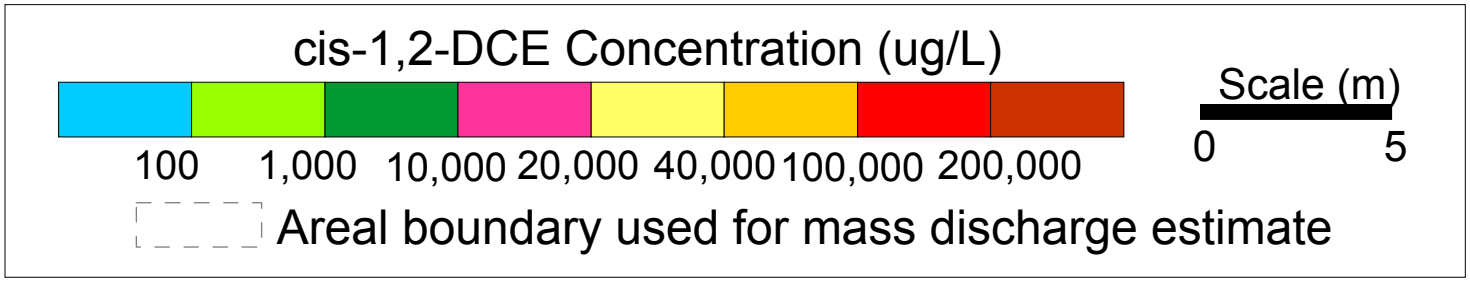


Example No. 1 Characterization and CSM
Alameda Naval Station, CA



- 80% of mass in 7% of transect area
- 90% of mass occurs where C > 20,000 ug/L

Data Source:
Einarson and MacKay, 2001



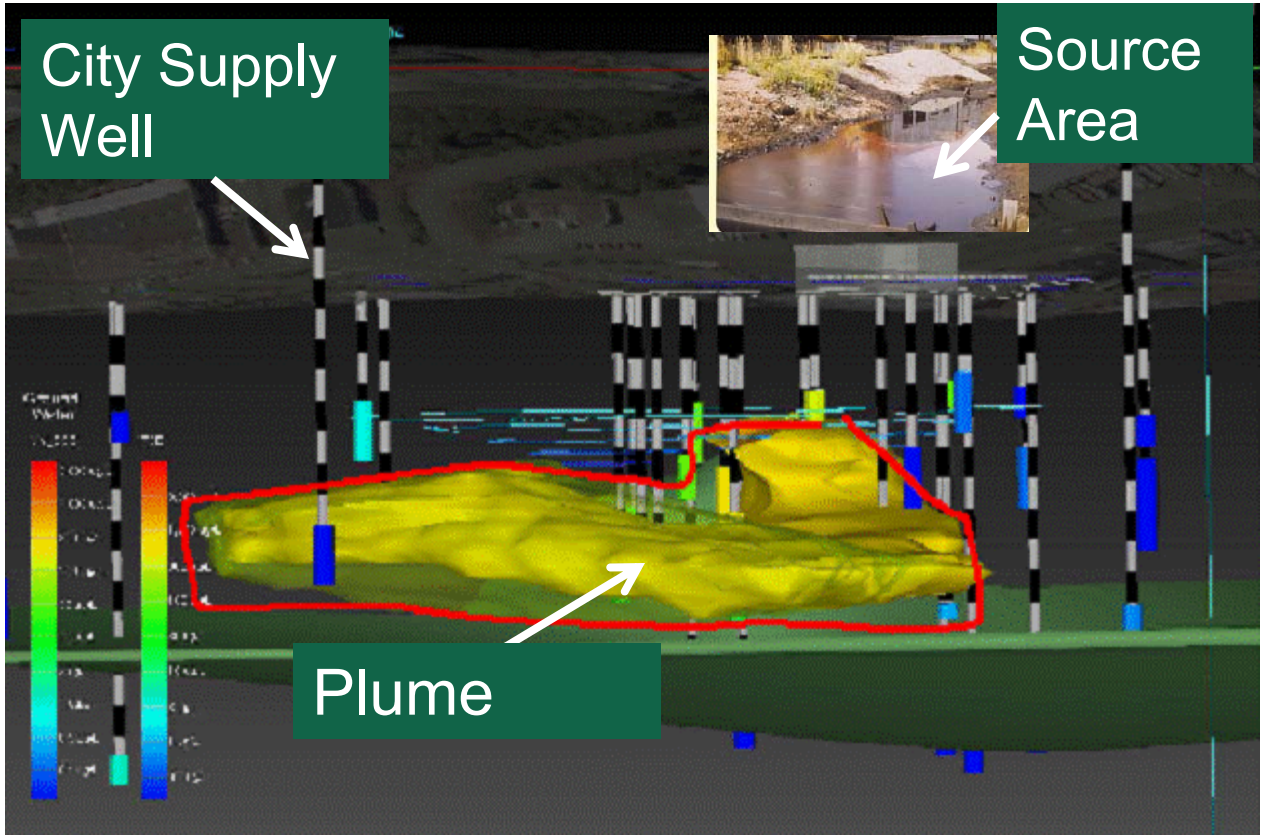
Example No. 2 – Mass Discharge (Md) as an Interim Remedial Goal Compliance

Mass flux and mass discharge

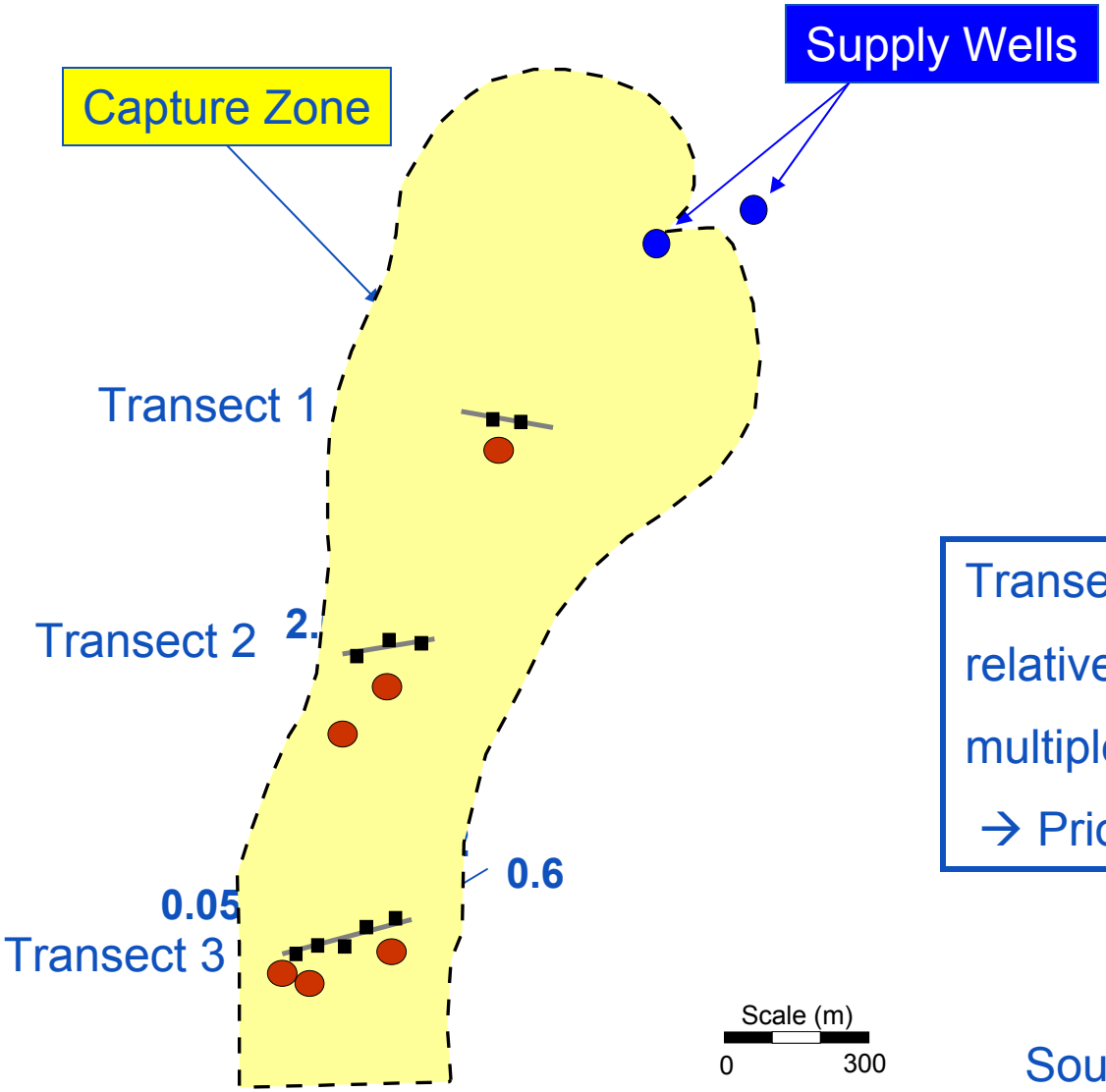
Focused Feasibility Study evaluation:
Reduce source strength (Md) by 90%, MNA sufficient to achieve compliance

ROD amendment:
Multi-component remedy- reduce source discharge Md by 90% & transition technology (if necessary)

- **Well 12A Superfund Site, WA**
  - Performance metric → remedy Operational and Functional



Example No. 3 – Site Prioritization



Potential Source Site

1.2 Md at pumping well (kg/year)

Transect

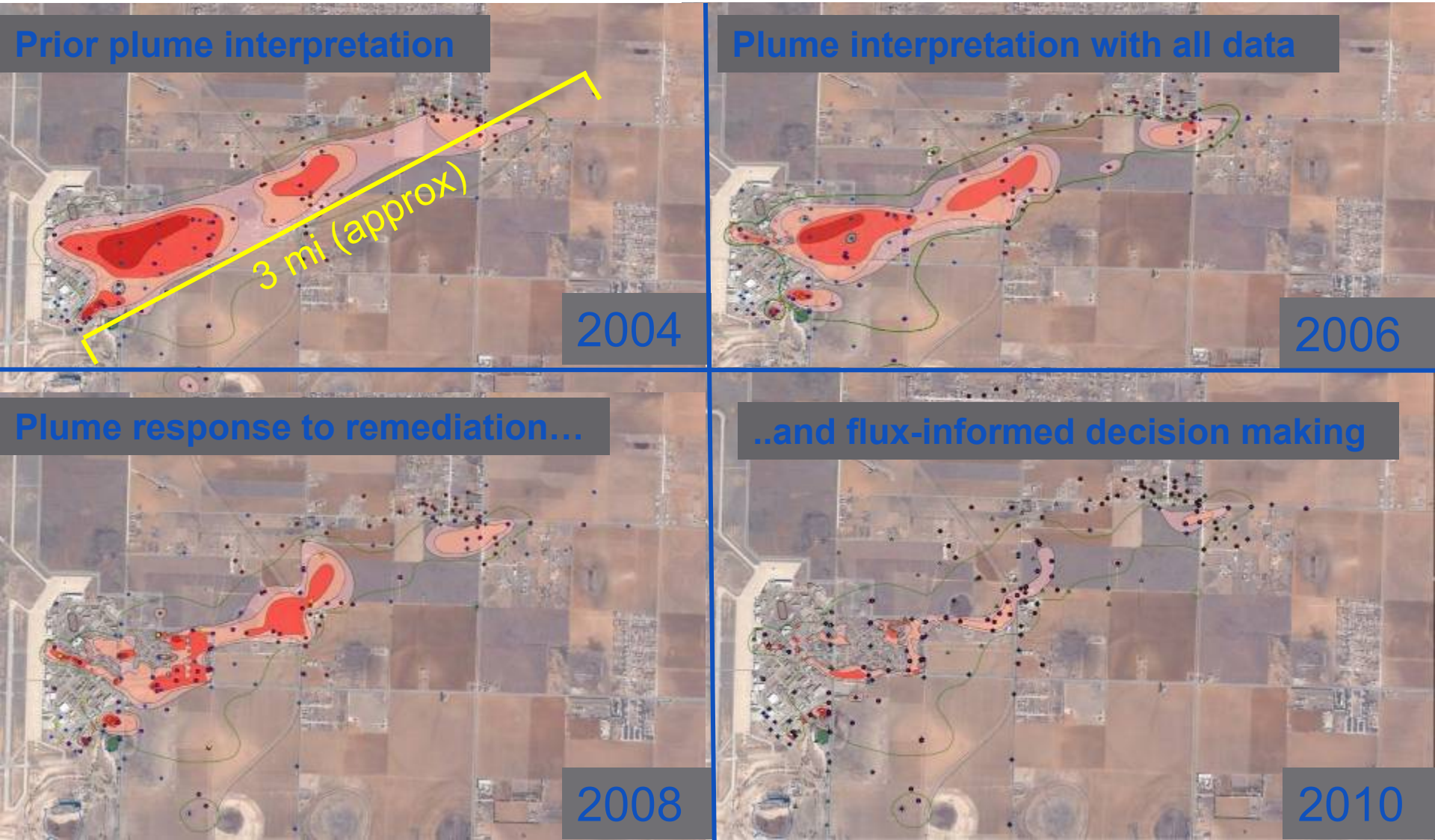
Transects used to determine relative contribution of multiple source areas

→ Prioritize remedial efforts

Source: Bauer et al., 2004

Mass Flux to Target Remediation: Reese Air Force Base

Case study from
F. Payne, ARCADIS



Case Studies Summary

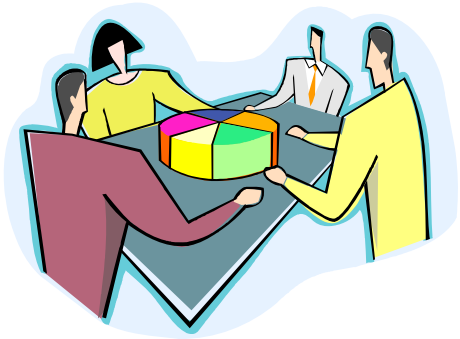
- Estimating mass flux/discharge may
  - Improve conceptual site models
  - Enhance remedial efficiency
  - Refinement of exposure assessment
- More effective site management
- Can use historical data and existing monitoring networks in some cases
- Can enhance compliance measurements

Regulatory Precedence

- Federal Superfund…signed Record of Decision (ROD) identifying a mass discharge interim goal [Well 12A site, WA, Oct 2009]
- Surface water regulation (e.g., Total Maximum Daily Loads (TMDL), National Pollutant Discharge Elimination System (NPDES)) is based on mass discharge
- Groundwater extraction gives estimate of mass discharge over capture zone
- Natural attenuation rate is estimated based on mass discharge reduction

Regulatory Acceptance – Needs

- More familiarity with mass flux and mass discharge concepts, methods, and uncertainties
- Better understanding of how mass flux and mass discharge relates to
  - Risk
  - Compliance
  - Typical regulatory metrics (e.g., concentration-based standards)



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Mass Flux/Mass Discharge Applications

Murray D. Einarson
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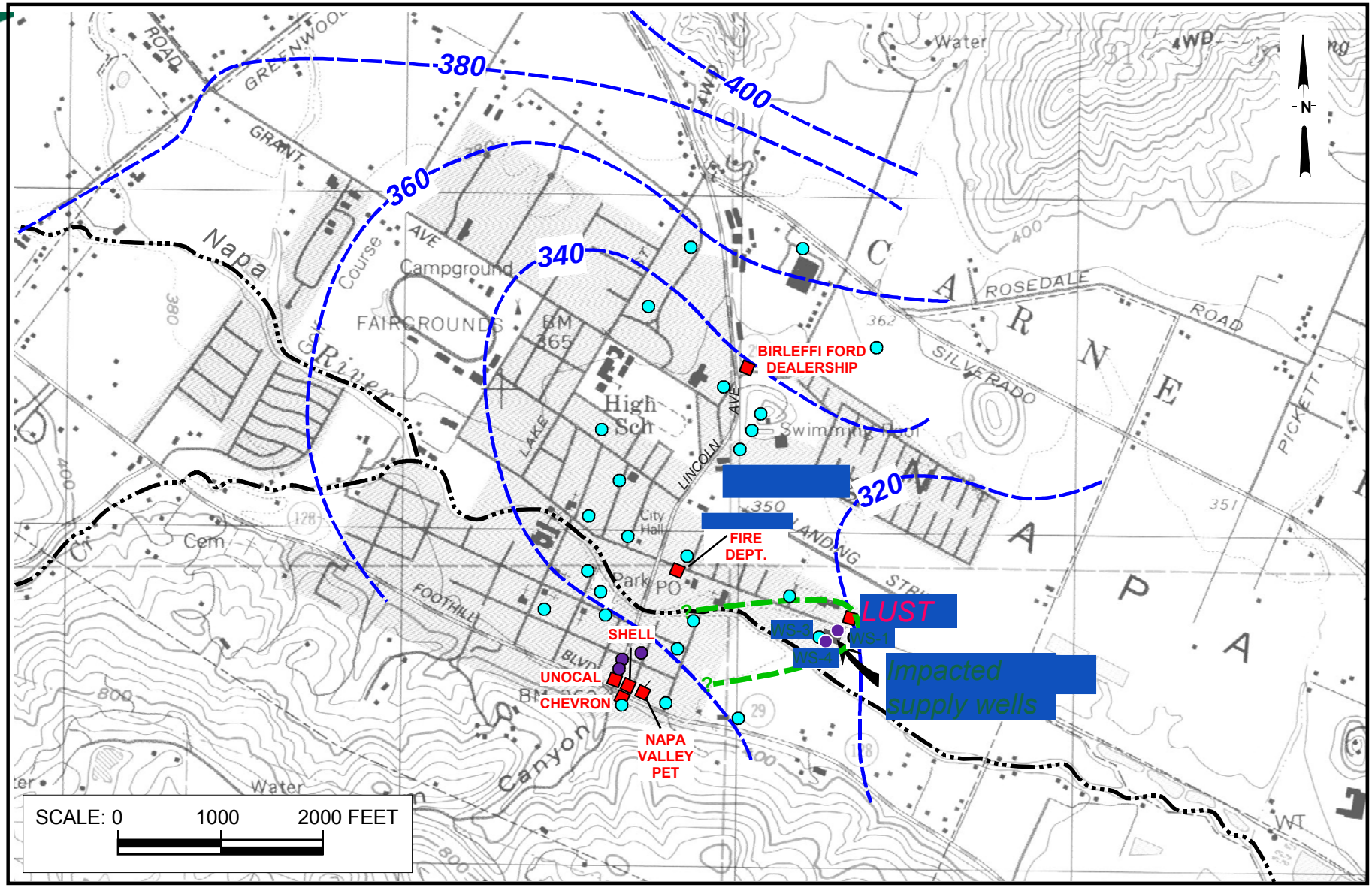
510-663-4172
murray.einarson@amec.com

SERDP/ESTCP Mass Flux Workshop
Washington, DC
December 2010

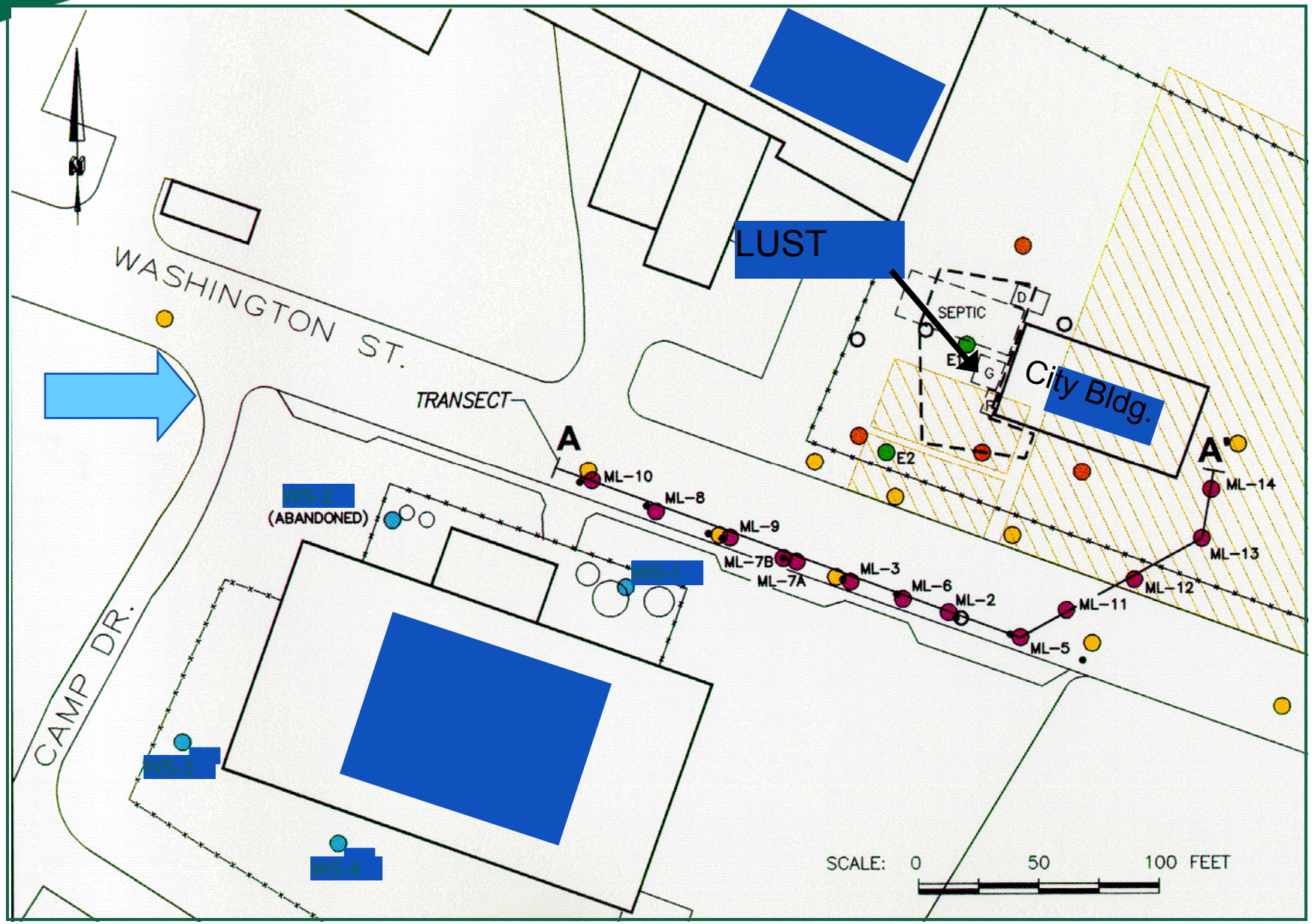
Case Study

Investigation of an Impacted Water Supply Wellfield in Northern California (2000)

REGIONAL GROUNDWATER CONTOURS (WINTER 1985)



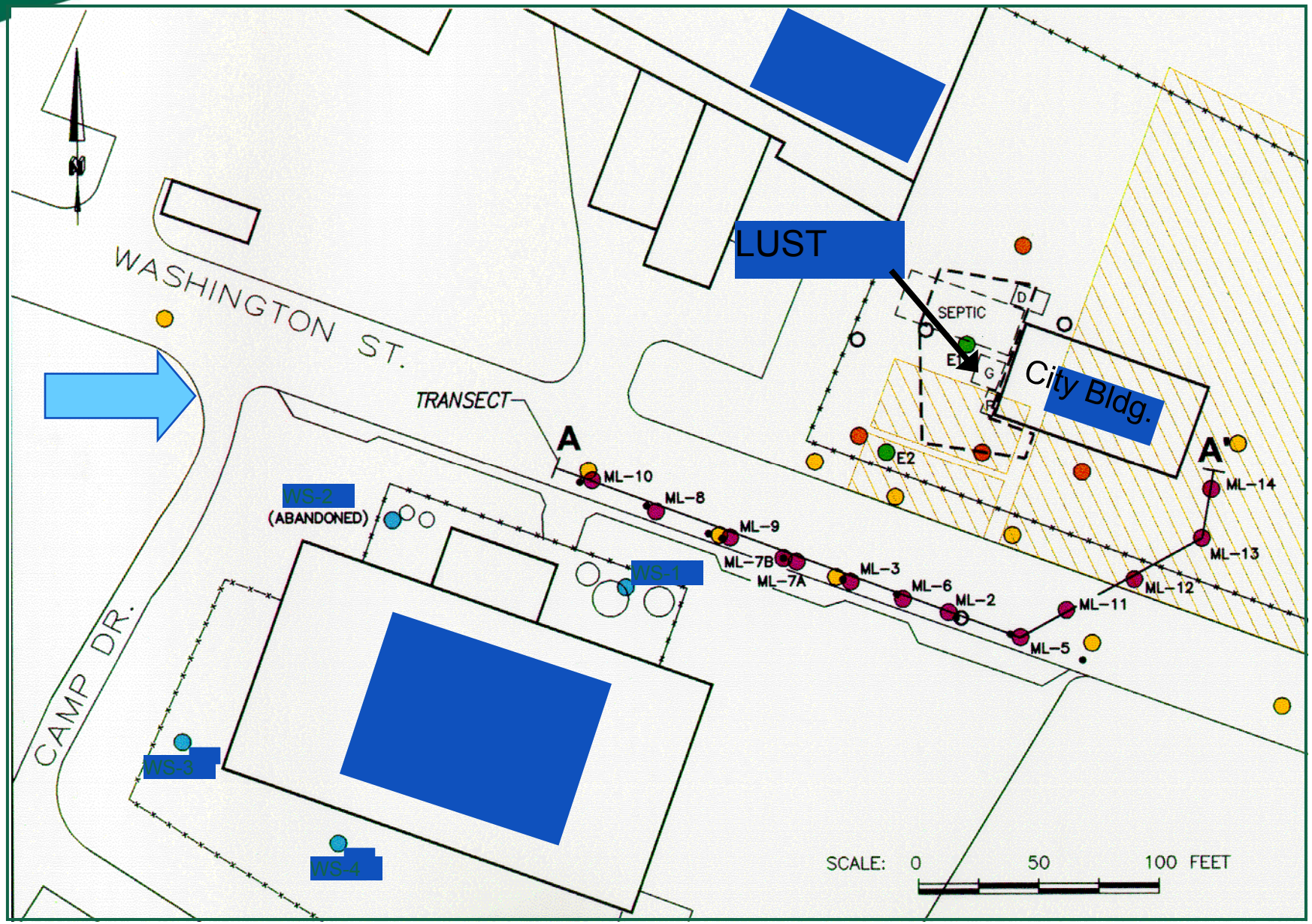
Site Plan


WASHINGTON ST.
CAMP DR.
N
LUST
City Bldg.
SEPTIC
D
E1
G
F
E2
TRANSECT
A
A'
ML-10
ML-8
ML-9
ML-7B
ML-7A
ML-3
ML-6
ML-2
ML-5
ML-11
ML-12
ML-13
ML-14
WS-2
(ABANDONED)
WS-1
WS-3
WS-4
SCALE: 0 50 100 FEET

5P931

AIR LIQUIDE

Site Plan


WASHINGTON ST.
CAMP DR.
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E1
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TRANSECT
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ML-8
ML-9
ML-7B
ML-7A
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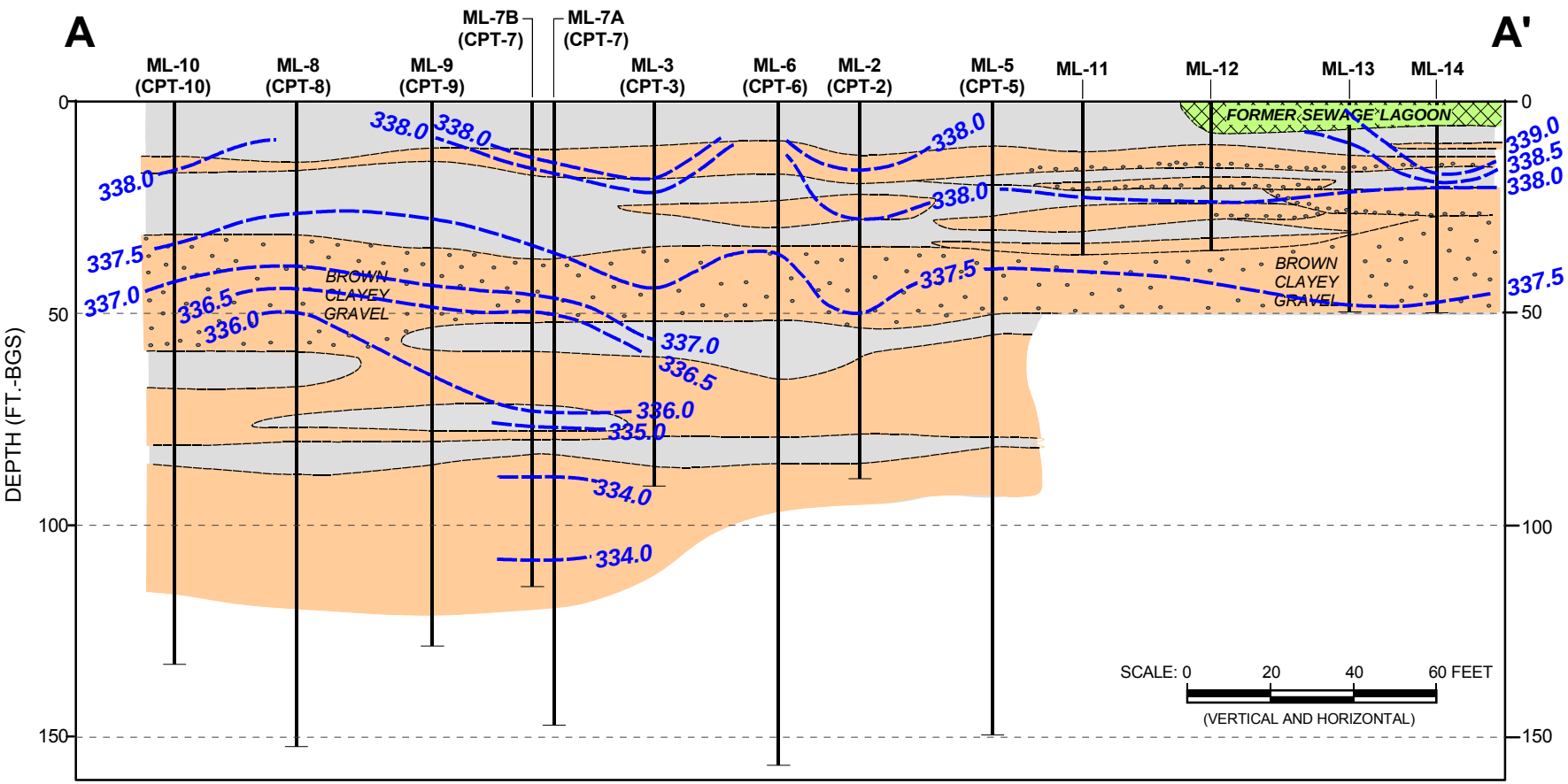
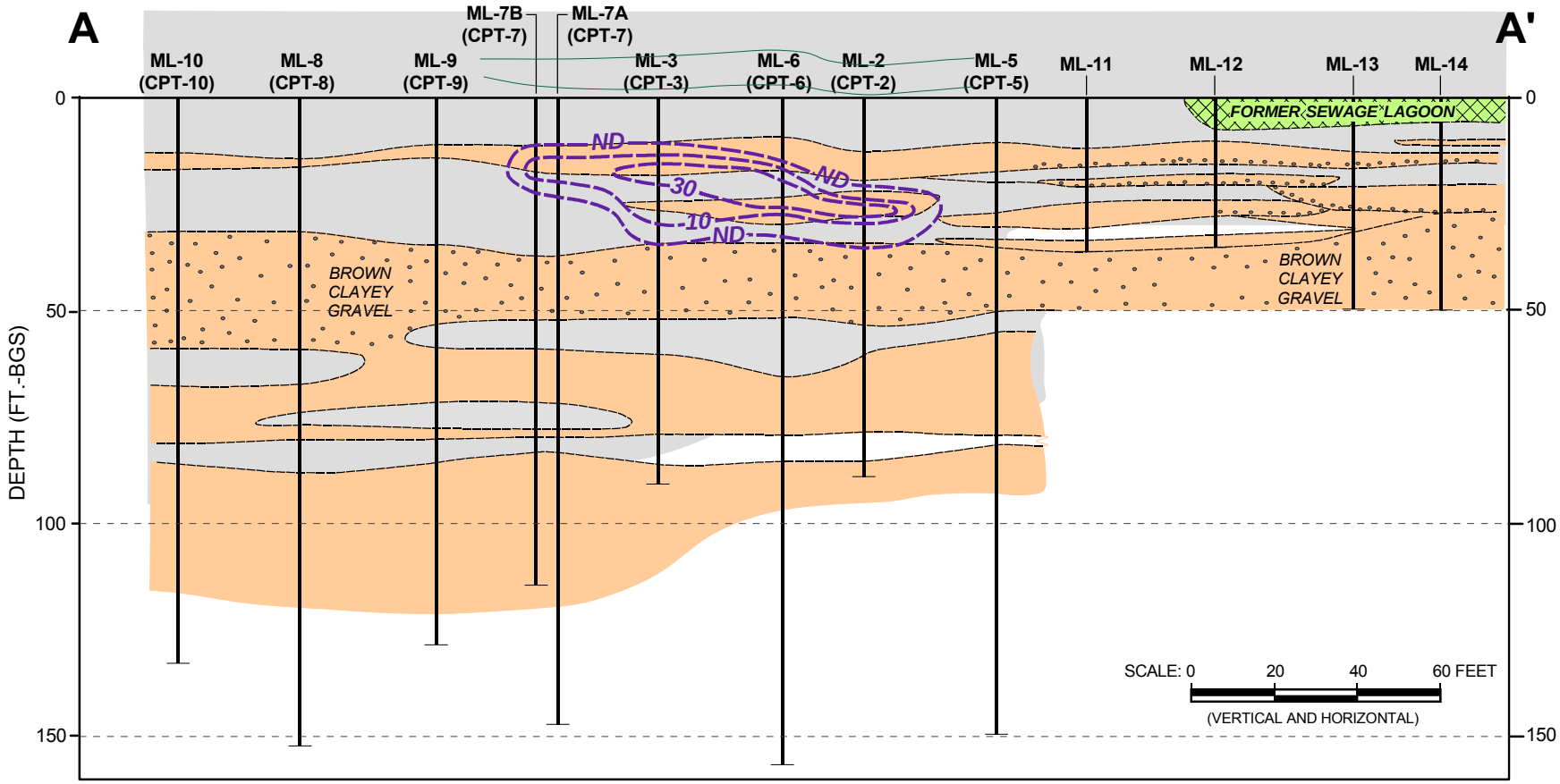
ML-6
ML-2
ML-5
ML-11
ML-12
ML-13
ML-14
WS-2
(ABANDONED)
WS-1
WS-3
WS-4
SCALE: 0 50 100 FEET

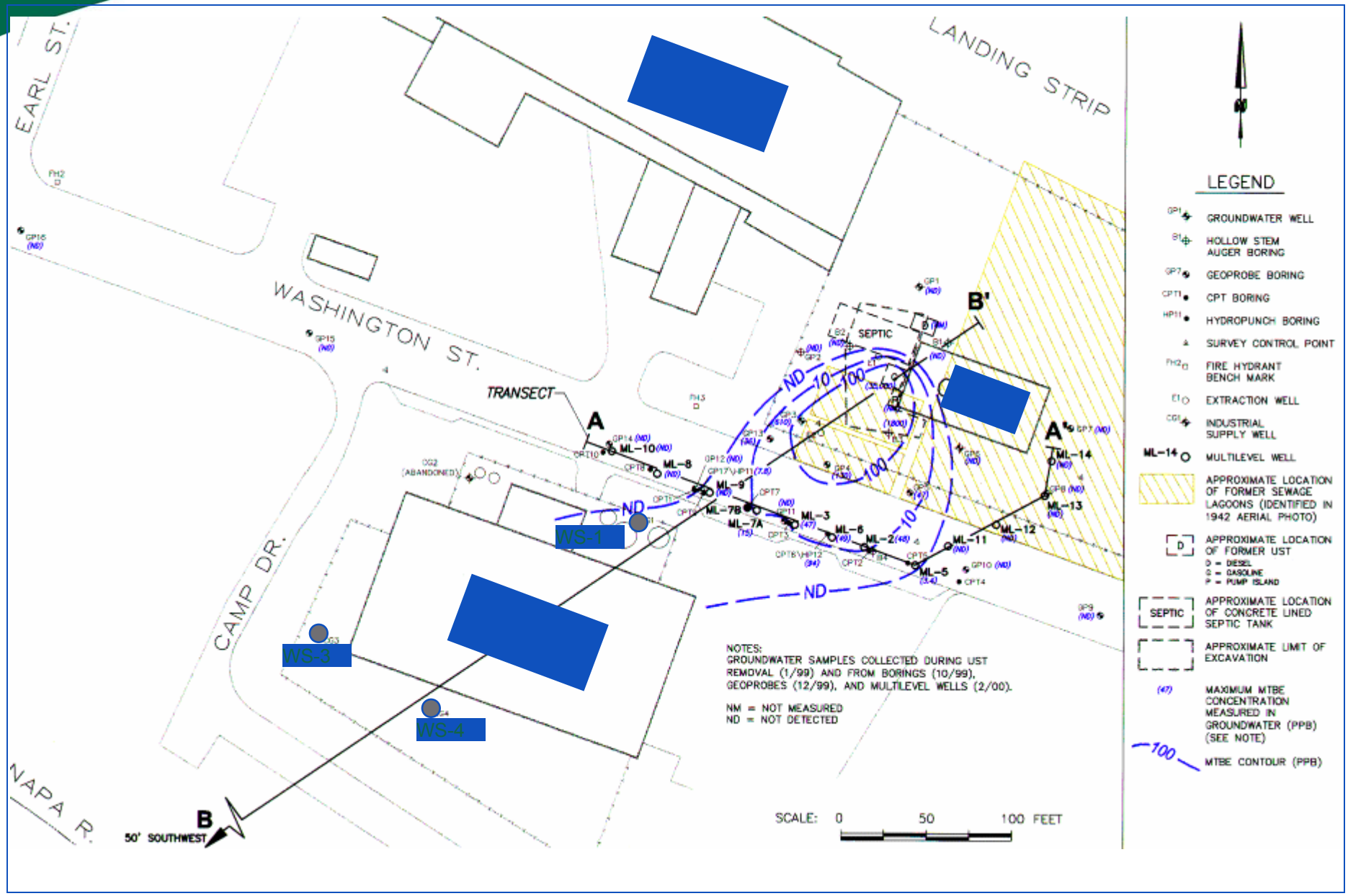
Contours of Hydraulic Head

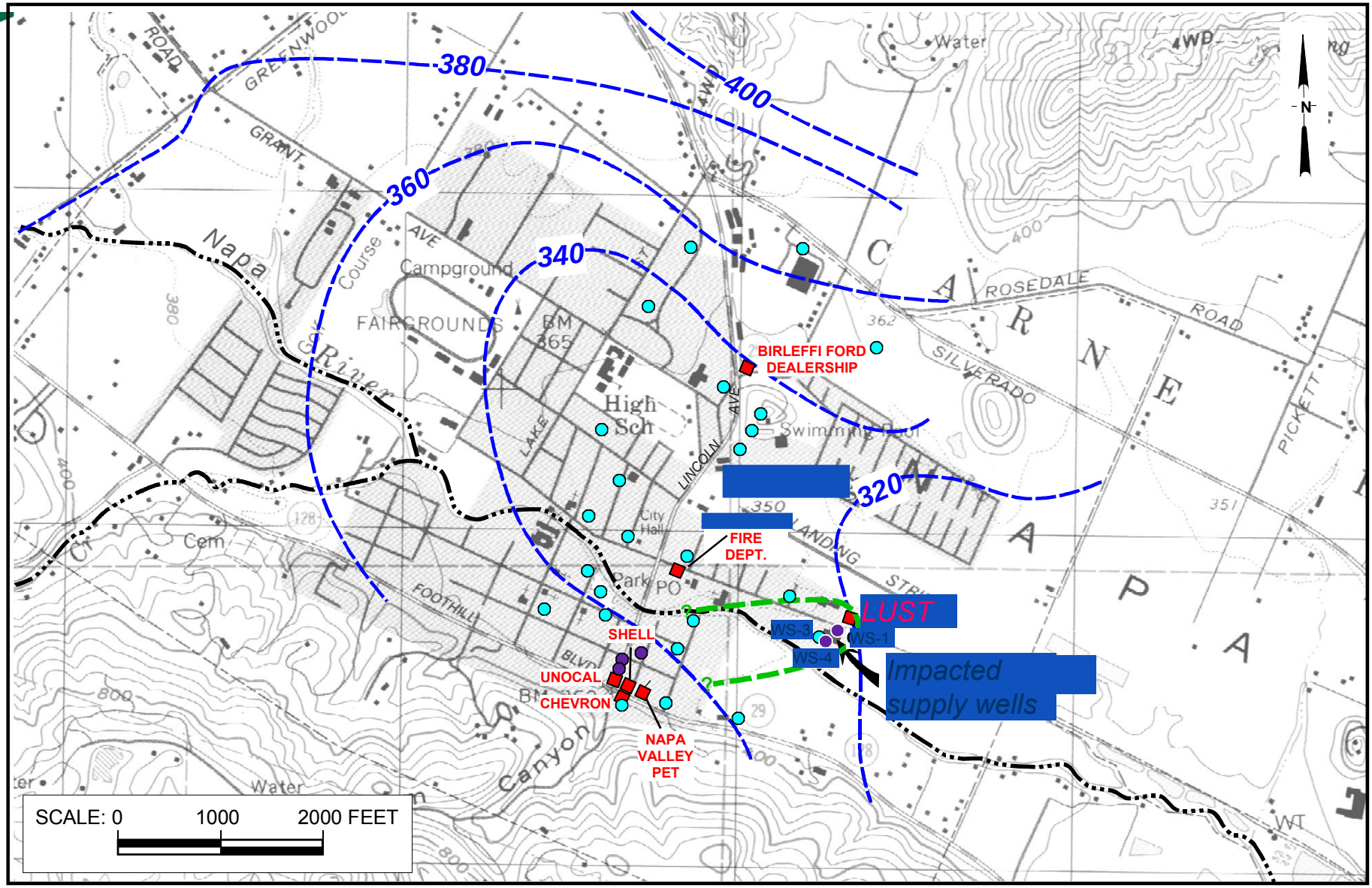


Contours of MTBE concentrations measured in multi-level wells

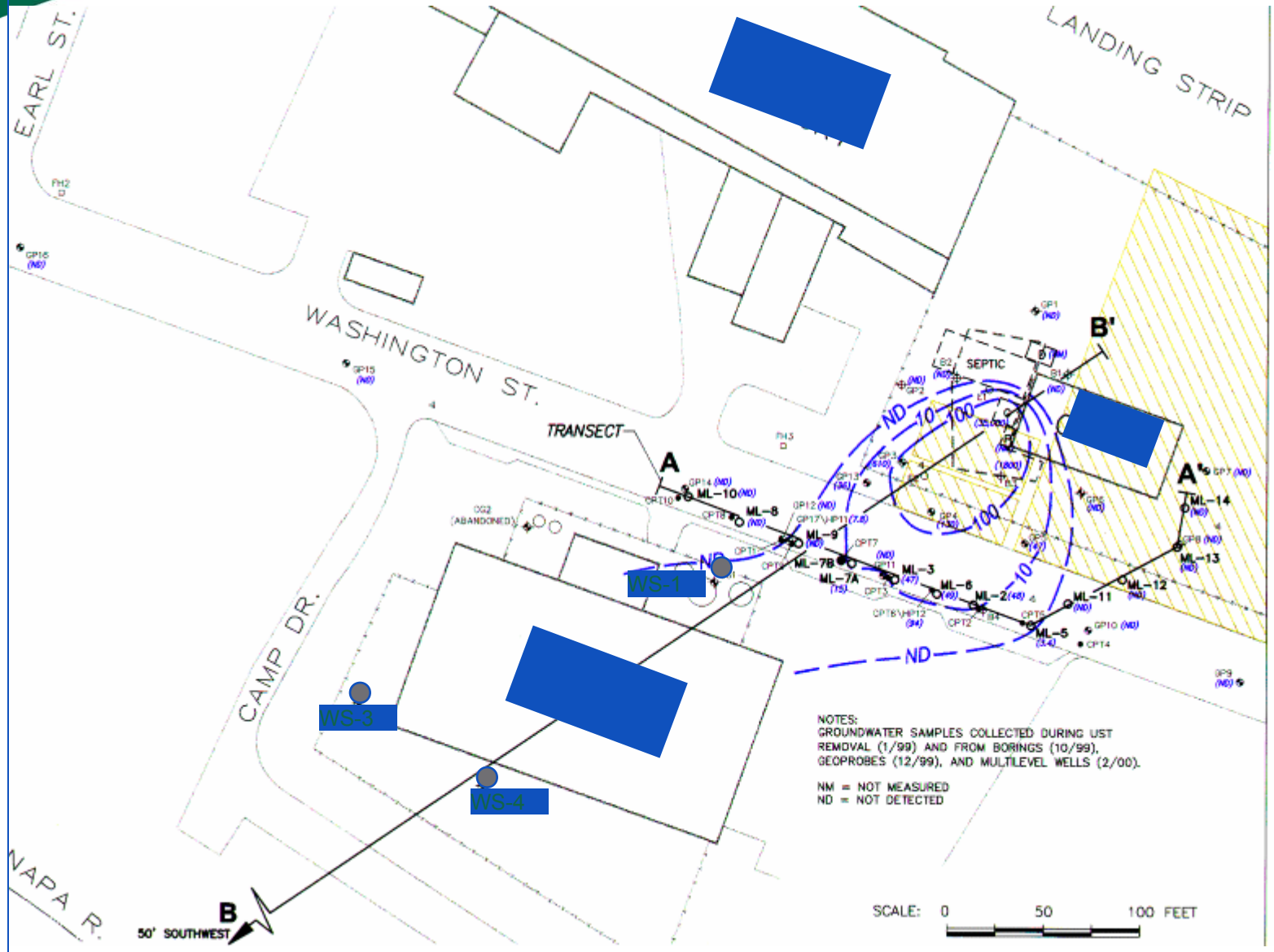


AREAL PROJECTION OF MTBE PLUME

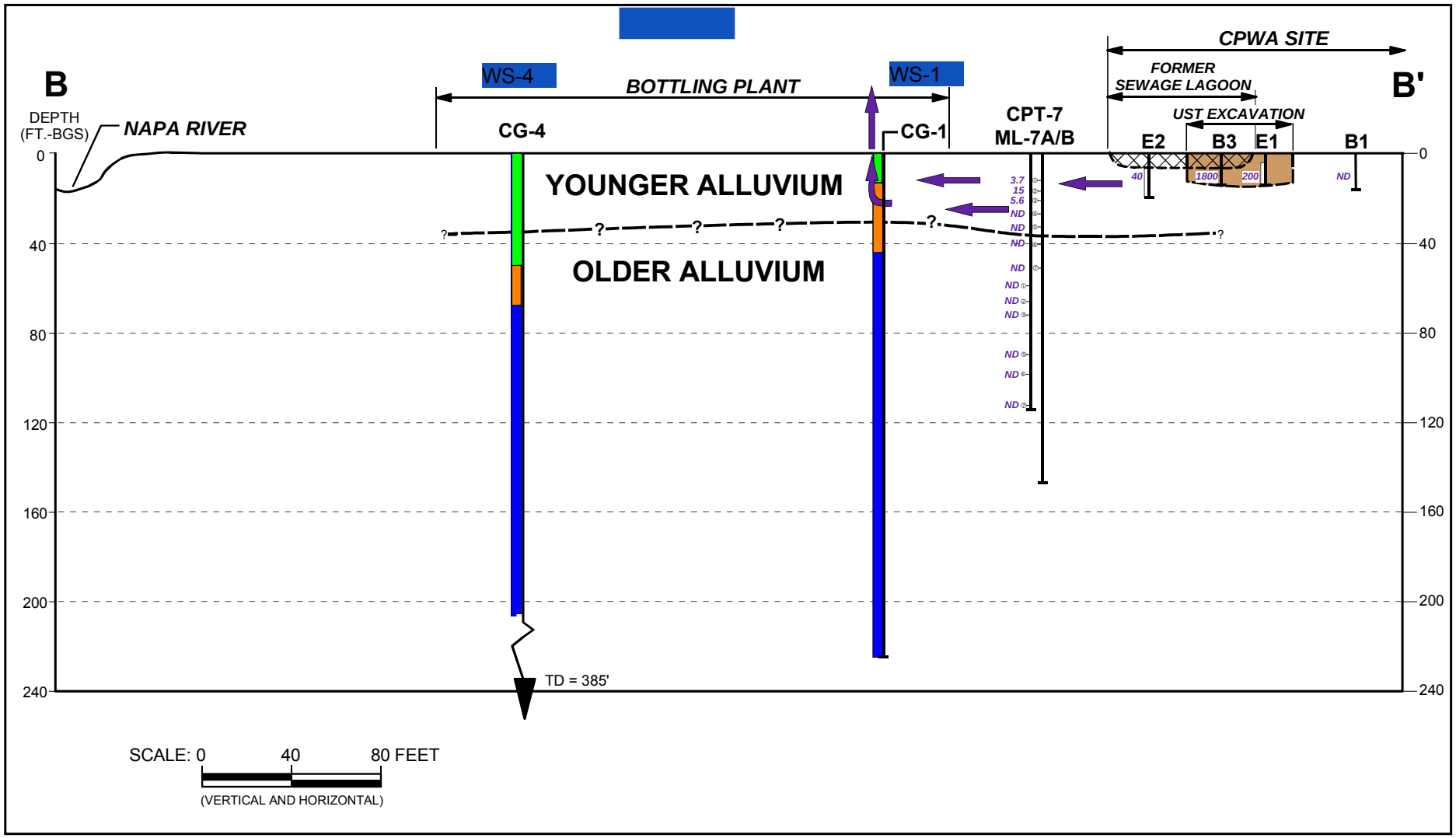



380
400
360
340
320
BIRLEFFI FORD DEALERSHIP
FIRE DEPT.
LUST
SHELL
UNOCAL
CHEVRON
NAPA VALLEY PET
WS-1
WS-3
WS-4
Impacted supply wells
Napa River
Campground
FAIRGROUNDS
High Sch
City Hall
Park
PO
Swimming Pool
Water
Cem
Canyon
ROSEDALE ROAD
SILVERADO
LINCOLN AVE
LANDING
FOOTHILL BLVD
GRANT
GREENWOOD ROAD
LAKE
PICKETT
N
SCALE: 0 1000 2000 FEET

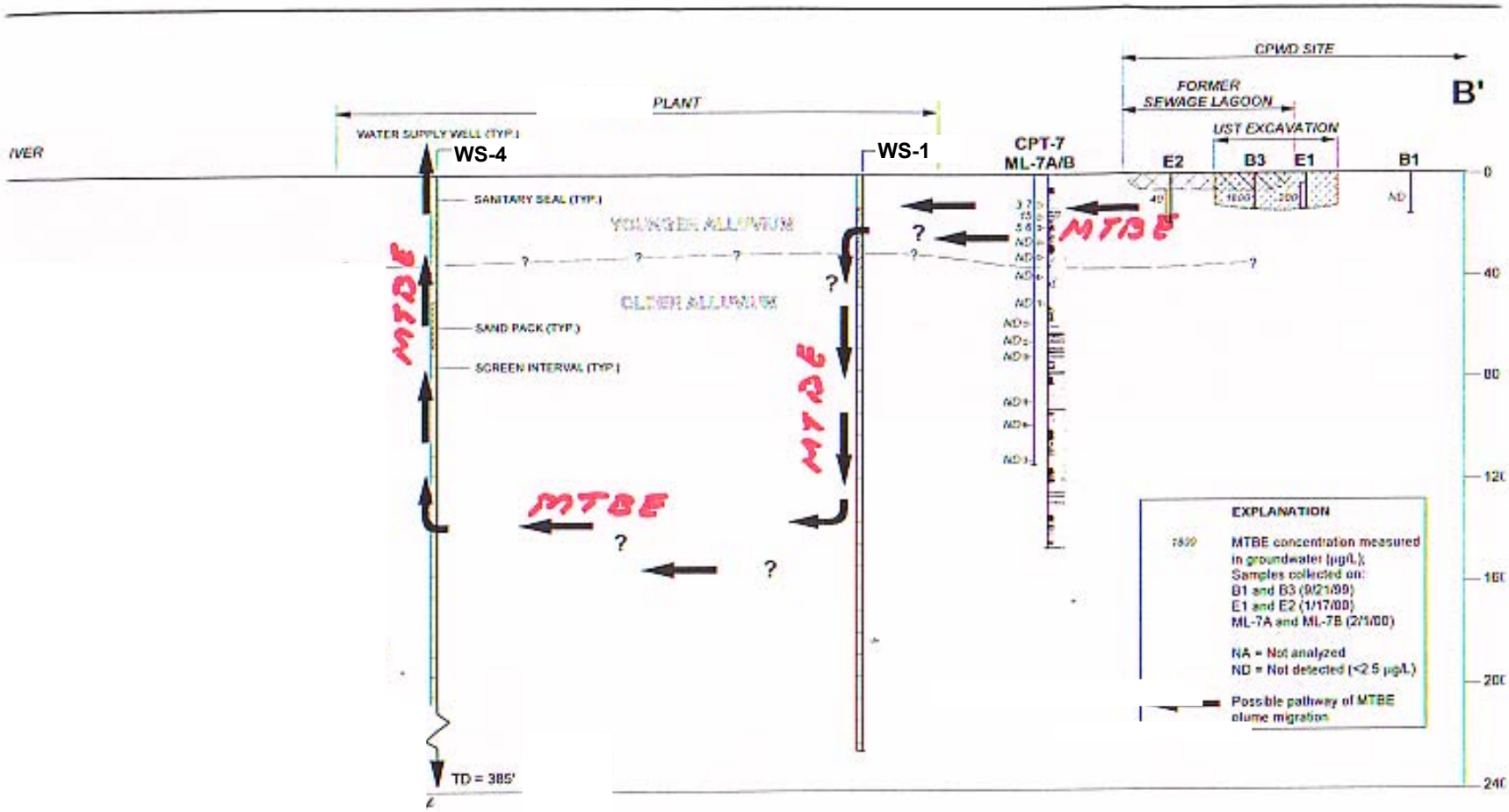
AREAL PROJECTION OF MTBE PLUME



POTENTIAL MTBE PATHWAY TO WELL WS-1 VIA A SHALLOW ANNULAR SEAL



Hypothesis: Well WS-1 conveys MTBE to greater depths when Wells WS-3 and WS-4 are pumped

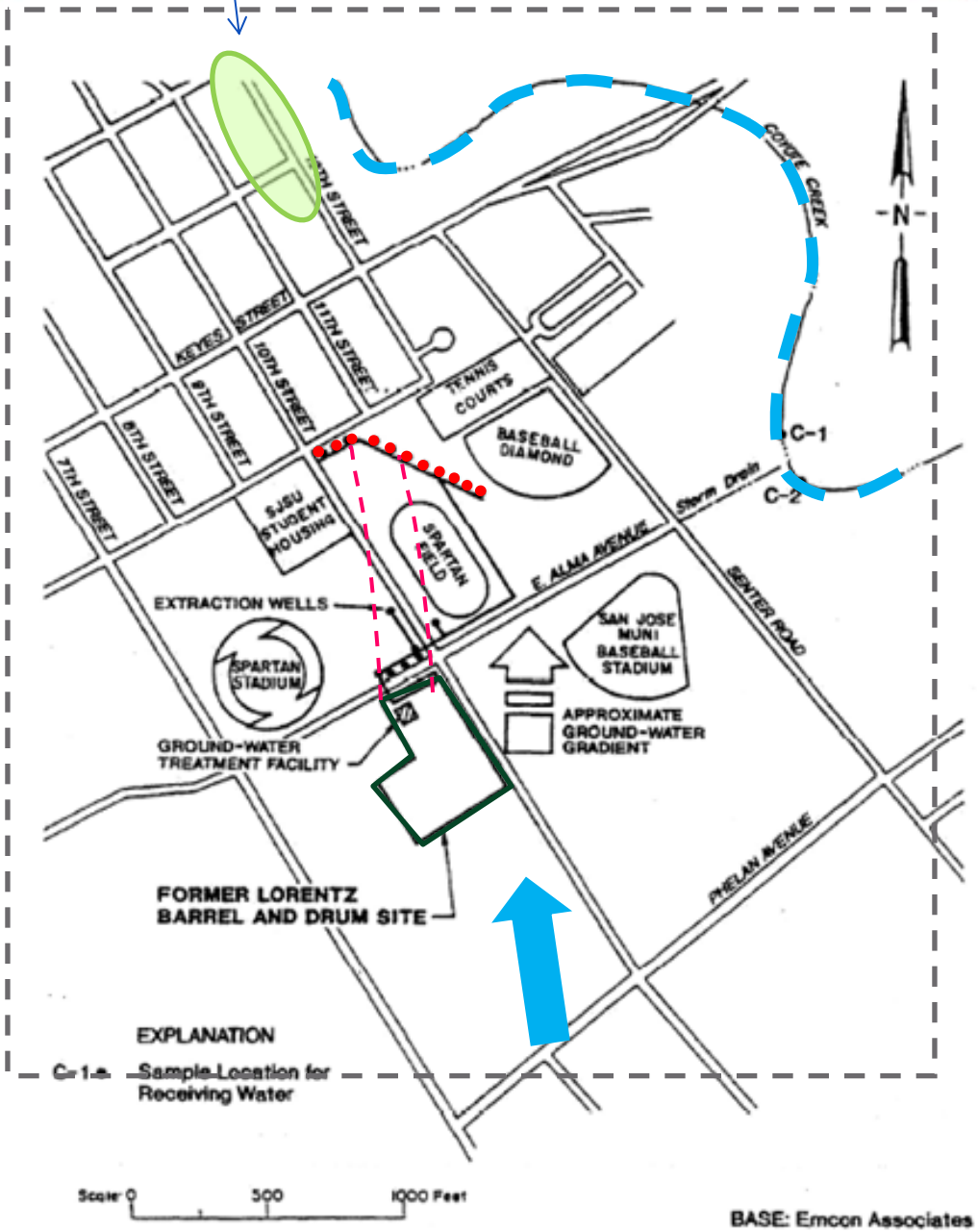


Case Study

Using pump–and-treat data to estimate historic mass discharge

California Superfund Site
2009

Approximate location of
San Jose Water Co.
12th Street Well field



$$Md = C \cdot Q$$

Q = KiA

T(gpd/ft)*	T(ft2/d)	K(ft/d)	Horizontal gradient (i)			Cross Section Area (B zone)			Q (B zone)			
			dl (map)	dh (map)	i (di/dh)	width	thickness	Area	ft3/d	gal/day	gal/year	Kgal/y
200	27	2	400	0.5	0.00125	300	15	4500	10	75	27375	27
10000	1337	89	400	0.5	0.00125	300	15	4500	501	3750	1368750	1369

Historic Extraction Rates

Extraction estimates (Kgal/y)**					
1993 to 1999	% flow in B zone	2000 to 2003	% flow in B zone	2004 to 2007	% flow in B zone
4100	14977%	2190	8000%	733	2678%
4100	300%	2190	160%	733	54%

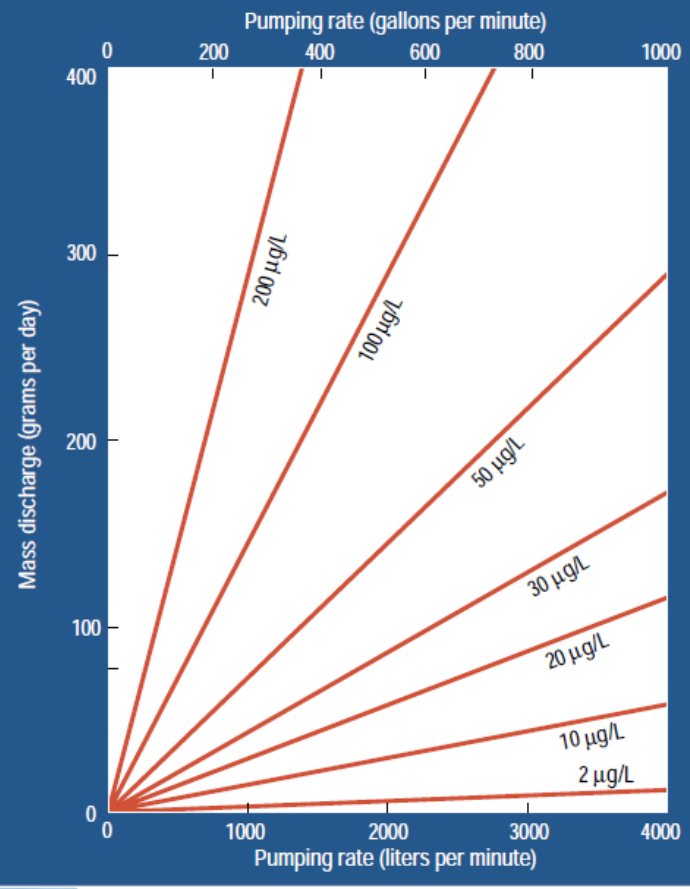
* Ebasco 1990 V. 1, Table 3-1
** Pegasus 2008 GWMR

Figure 15. Screenshot of spreadsheet used to calculate groundwater flow and historic extraction in B Zone

FIGURE 2

Solute concentration nomogram

Concentrations of a dissolved solute in a continuously pumped well can be estimated if the pumping rate and contaminant mass discharge are known. It is assumed that the contaminant plume is fully captured by the well and that no mass is lost from the plume during transport from source to well. This simple figure does not account for various complexities; for example, mass discharge from the source may fluctuate seasonally and can change over time as a result of new spills or source depletion. Mass discharge can also be affected by variations in the pumping rates of supply wells located close to the contaminant source areas.



Source: Einarson & Mackay, 2001. Predicting the Impacts of Groundwater Contamination. ES&T 35 v3 p 66A-73A

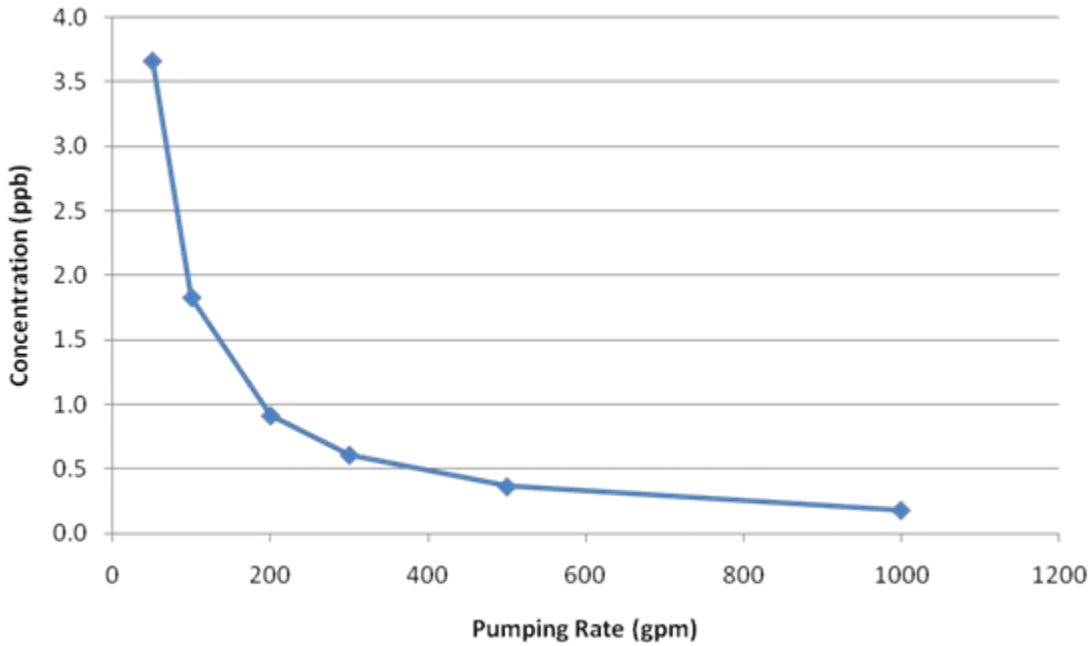
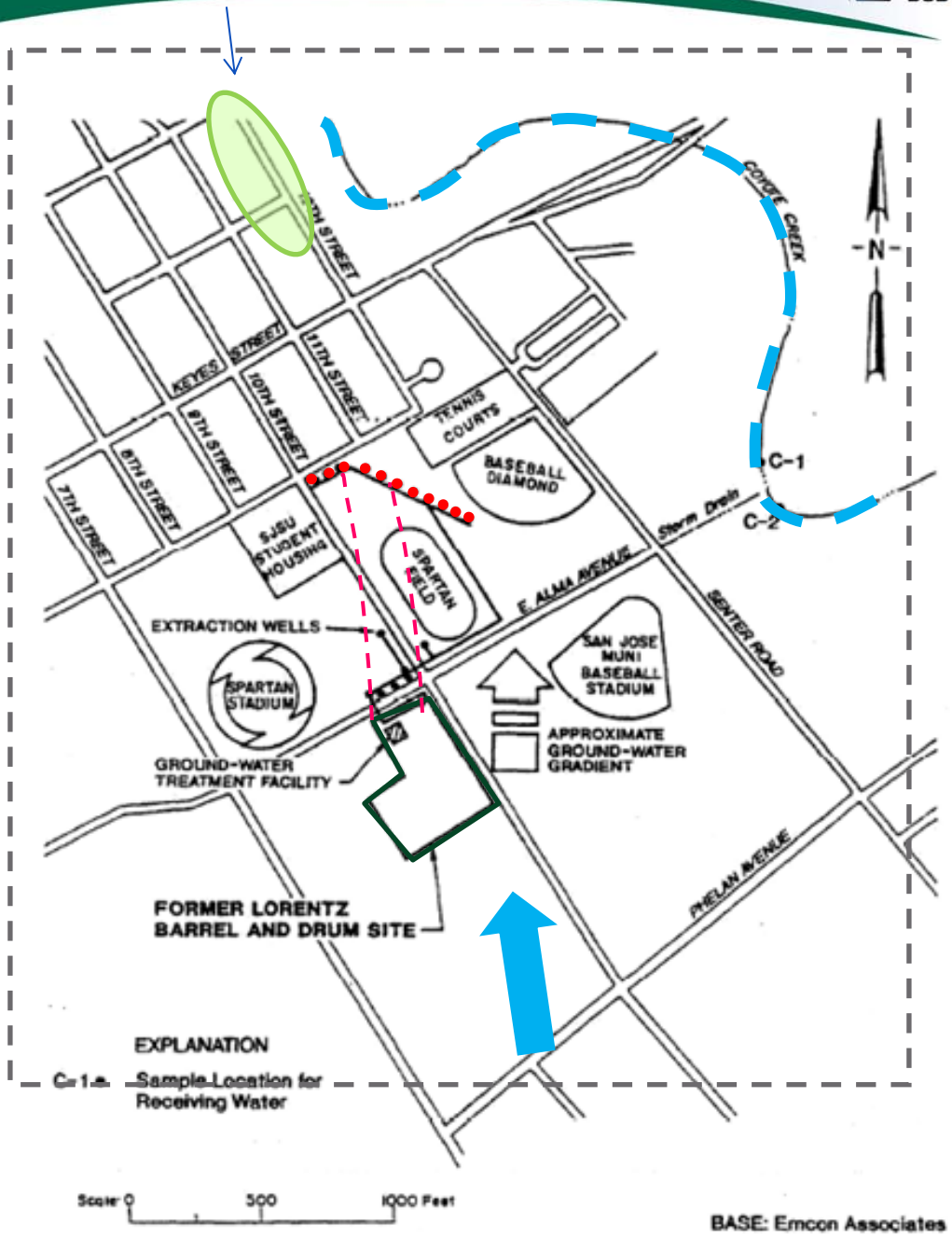


Figure 17. Plot of calculated VOC concentrations in water pumped from a hypothetical supply well as a function of pumping rate (assuming 1 g/day Md)

Approximate location of
San Jose Water Co.
12th Street Well field



$$Md = C \cdot Q$$

Groundwater chemical discharges now being considered in TMDL calculations

Dissolved contaminant mass loading (i.e., mass discharge) is now being considered in TMDL calculations

Florida
Department of Environmental Protection

"More Protection, Less Process"
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Florida Geological Survey - Hydrogeology Section

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Simplified Method for Estimating Ground Water Discharge to Surface Water for the purpose of Total Maximum Daily Loads (TMDL) Allocation

Virtually all of Florida is underlain by karst geology dominated, in some parts of the state, by conduits that cause ground water to flow under multi-porosity conditions fostering heavy interaction with surface waters. Quantifying this interaction has been a challenging problem to regulators involved in allocating TMDL to surface waters located in such settings. Difficulties in accurately quantifying ground water contribution to surface waters have forced those involved in implementing the TMDL program to estimate such contribution as percentages of total flow or to ignore it altogether. However, ground water contribution to surface waters has been shown by the USGS to range from as little as 10% to over 90% across the US (in some spring-fed streams it approaches 100% of base flow). Overlooking such contribution could obviously result in significant miscalculations in allocating waste loads to surface waters; thus in listing or

To address this dilemma; the Hydrogeology Section outsourced a research task, in 2004/2005, to faculty members (Drs Burnett and Chanton) of the Department of Oceanography at FSU to

Orange County
Nitrogen and Selenium Management Program (NSMP)
A five-year plan to address selenium and nitrogen issues in the Newport Bay watershed

Working Group Login

Overview | Public Involvement | NSMP Library | FAQs

- Background
- Working Group
- The Work Plan
- Program Timeline

Overview

Background

Selenium and Nitrogen Background
Selenium is a naturally occurring element that is necessary for life, but it is toxic at high levels and is unusual in that the difference between essential and toxic levels is relatively small. Selenium is a bioaccumulative pollutant, meaning that it accumulates in the food chain through uptake and consumption by plants and wildlife, and can cause adverse effects on fish and birds. Addressing bioaccumulative pollutants to protect fish and birds is complex, because pollutant levels in water or soil don't necessarily reflect what is happening in the ecosystem. Selenium occurs in many forms in the environment, and can convert between different forms depending on chemical and biological conditions. Also, some forms of selenium are more harmful than others. Similar to selenium, nitrogen is an essential nutrient, but it can cause harmful algal blooms when nitrogen levels are excessive. Excessive algal blooms decrease dissolved oxygen in surface waters (referred to as eutrophication) and can result in fish kills.

The Problem with Selenium and Nitrogen in the Newport Bay watershed
In the Newport Bay watershed, selenium derived from ancient marine sediments in local foothills accumulated over the last several thousand years in an area known as the Swamp of the Frogs. This ancient swamp, though now drained and filled, has become an almost limitless source of selenium because of the high water table in the area. Virtually any activity that mobilizes groundwater to the surface has the potential to increase selenium contamination of surface waters in the Newport Bay watershed. Activities associated with increased urbanization of the watershed result in passive and active discharges of selenium-laden groundwater into surface waters (e.g. drainage ditches, flood control channels with weep holes, and development and maintenance dewatering activities). Selenium levels in the watershed widely exceed the California Toxics Rule (CTR) criterion, but the actual impacts to fish and birds in the watershed, and the Newport Bay ecosystem in general, are unknown at this time.

During the 1980's and 1990's, large mats of algae were common in Lower and Upper Newport Bay. These extensive mats threatened beneficial uses by lowering dissolved oxygen levels and impeding recreational boating. The peak bloom of 1985-1986 resulted in a fish kill in the Newport Island area. Historically the major source of nitrogen in the watershed was runoff from commercial nurseries.

designated waterbody. One of the special studies needed under the Nutrient TMDL is an effort to better understand the extent and magnitude of groundwater as a nitrate source. In 2002, the EPA issued a Toxics TMDL for the watershed, which is now being broken

how to deal with elevated levels of selenium and nitrogen in groundwater levels to meet regulatory requirements (discussed below) when no feasible treatment options exist.

Regulatory Background

TMDLS
To address nutrient issues in the watershed, the Santa Ana Regional Water Quality Control Board adopted an amendment to the Basin Plan in 1998 in to establish a Total Maximum Daily Load (TMDL) for nutrients. A TMDL is a regulatory process that sets an allowable limit for a particular pollutant in a waterbody at a level, or load, from all sources that won't adversely impact beneficial uses of the designated waterbody. One of the special studies needed under the Nutrient TMDL is an effort to better understand the extent and magnitude of groundwater as a nitrate source. In 2002, the EPA issued a Toxics TMDL for the watershed, which is now being broken down into 5 separate TMDLs by the State (including a TMDL for selenium), expected to be adopted in 2007.

NPDES Permits
In 1998, the Santa Ana Regional Water Quality Control Board (Regional Board) adopted a general National Pollutant Discharge Elimination System (NPDES) permit (Order No. 98-67) prescribing general waste discharge requirements for short-term (i.e. one year or less) discharges to surface waters that pose an insignificant (de minimus) threat to water quality within the Santa Ana Region. This

MEASUREMENT AND USE OF MASS DISCHARGE AND MASS FLUX AT CONTAMINATED SITES

Start	End	Topic
8:30 AM	8:50 AM	Welcome & Introduction *(Dr. Hans Stroo)*
8:50 AM	9:40 AM	Flux-Based Site Management and Case Studies *(Dr. Michael Annable)*
9:40 AM	9:50 AM	Questions and Open Discussion
9:50 AM	10:10 AM	Break
10:10 AM	11:00 AM	Quantifying Mass Flux and Discharge *(Dr. Charles Newell and Dr. Shahla Farhat)*
11:00 AM	11:30 AM	Case Study Review *(Mr. Alec Naugle)*
11:30 AM	11:50 AM	Case Study Review – Field Measurement of Mass Discharge *(Mr. Murray Einarson)*
11:50 AM	12:00 PM	Questions and Open Discussion
12:00 PM		Adjourn

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