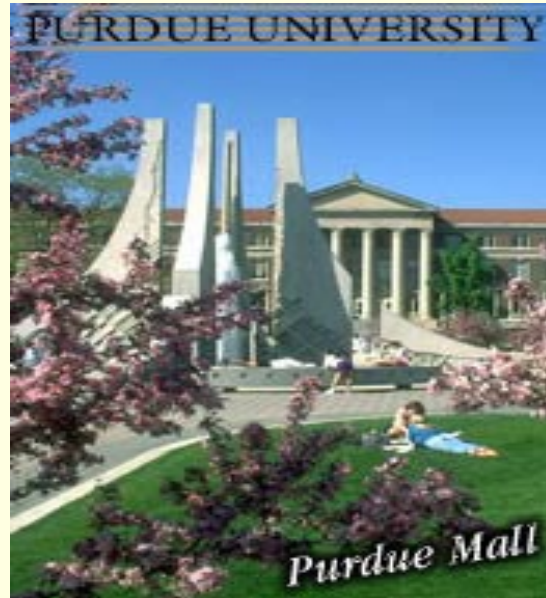


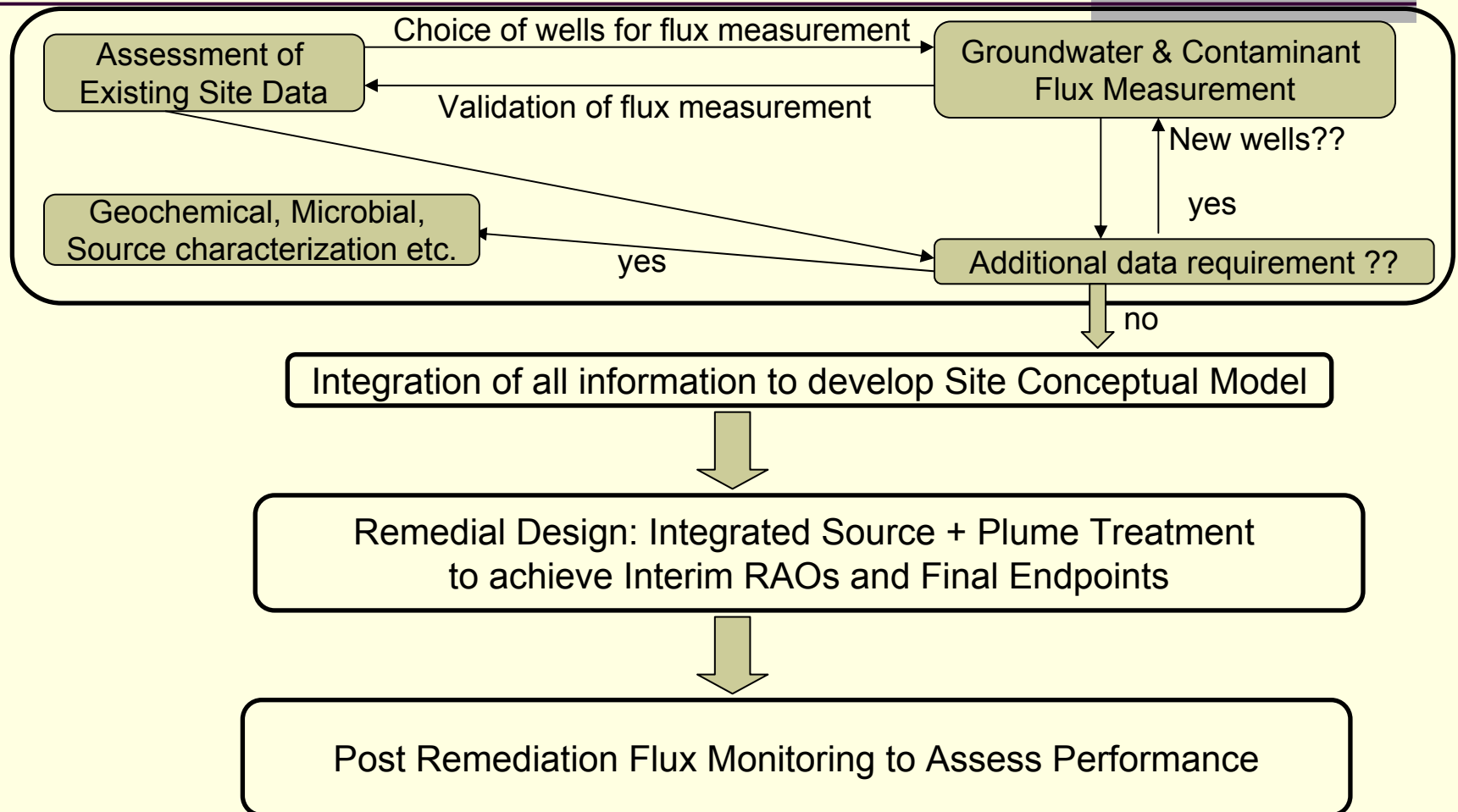
Flux-based DNAPL Site Assessment and Remedial Design: A Midwestern US Case Study



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Flux-Based Site Assessment and Management (FB-SAM)



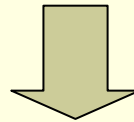
Objectives of the Study

Implement FB-SAM at a “real world” corporate site in the Midwestern US

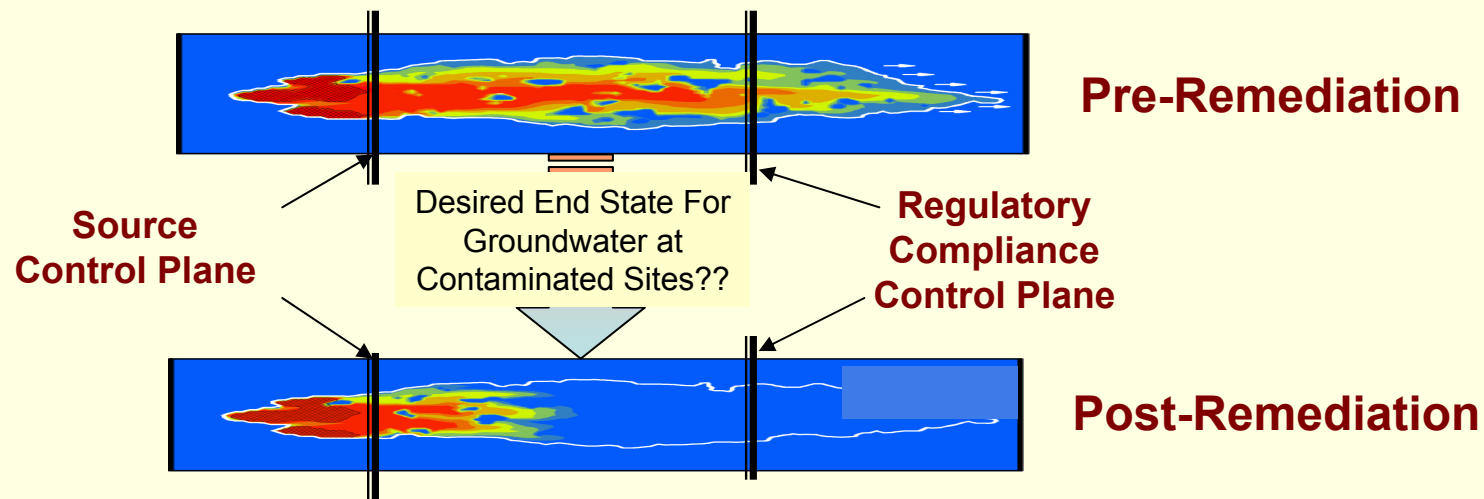
- (1) Field demonstration of PFM technique
- (2) Validation with traditional flux estimation techniques
- (3) Source and plume characterization using PFM and groundwater monitoring information
- (4) Design of remediation system
- (5) Proposal of additional studies to enhance data quality and improve remedial decisions

What do we need to know?

- ❑ Source strength
- ❑ Natural Attenuation Rate
- ❑ Remediation performance metrics at down-gradient compliance boundary



Degree of Reduction of Source Strength Required : **Source Treatment**
Enhancement of Degradation Rates in the Plume: **Plume Treatment**

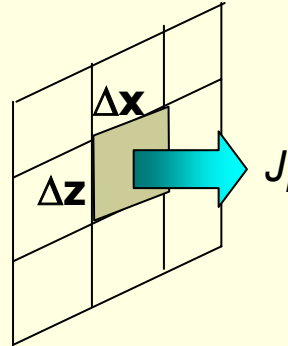


Measurement of Contaminant Mass Discharge : Conventional versus Innovative Approach

$$M_d = \sum J_i A_i = \sum (q_i C_i) A_i = \sum (Ks_{i,j}) C_i A_i$$

M_d = mass discharge (M/T)

J_i = mass flux (M/L²/T)



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

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

Conventional Approach

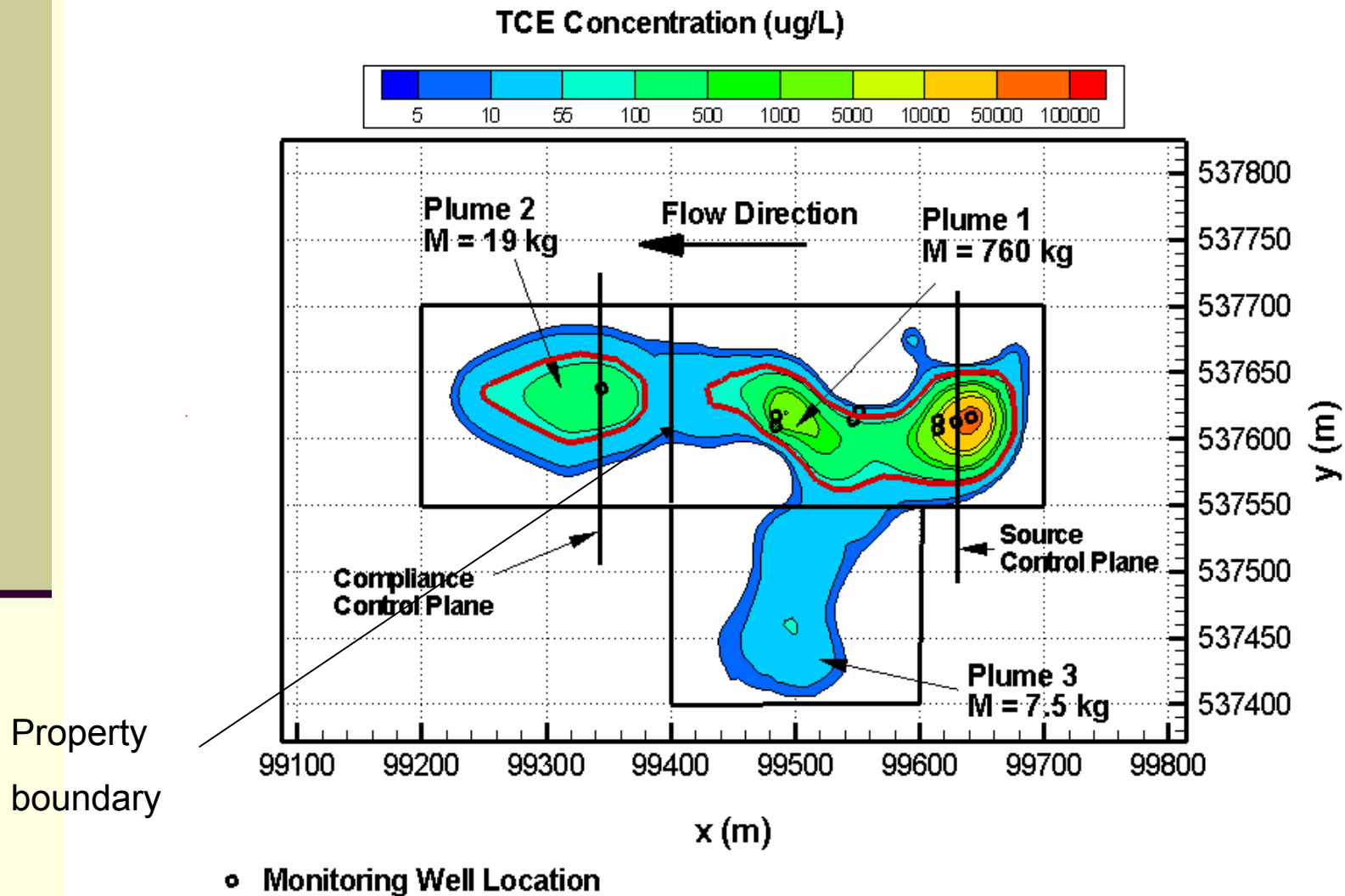
Individual measurement of Ks , j and C – significant uncertainty propagated

Innovative Approach

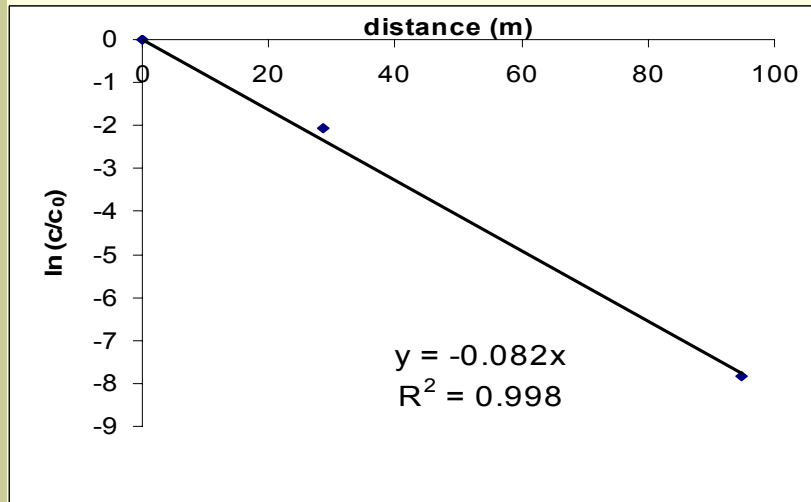
Simultaneous measurement of groundwater and contaminant fluxes

- Integral Pump Test: Active Technique
- Passive Flux Meter: Passive Technique

Planar View of TCE Plume



Natural Attenuation Rate



Centerline Approach

$$c(x) = c_0 \exp\left(\frac{v - \sqrt{v^2 + 4kD}}{2D} x\right)$$

$$k = 1.45 \text{ yr}^{-1}$$

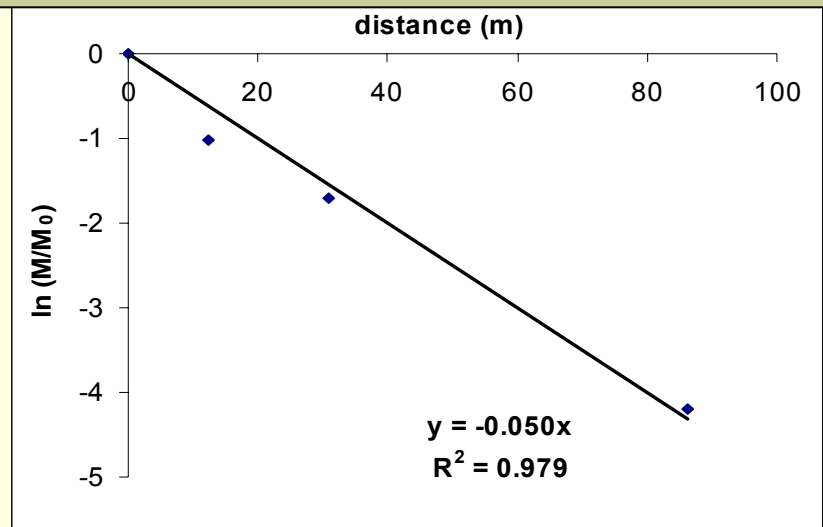
Wells selected should be along the plume centerline

Mass Flux Approach

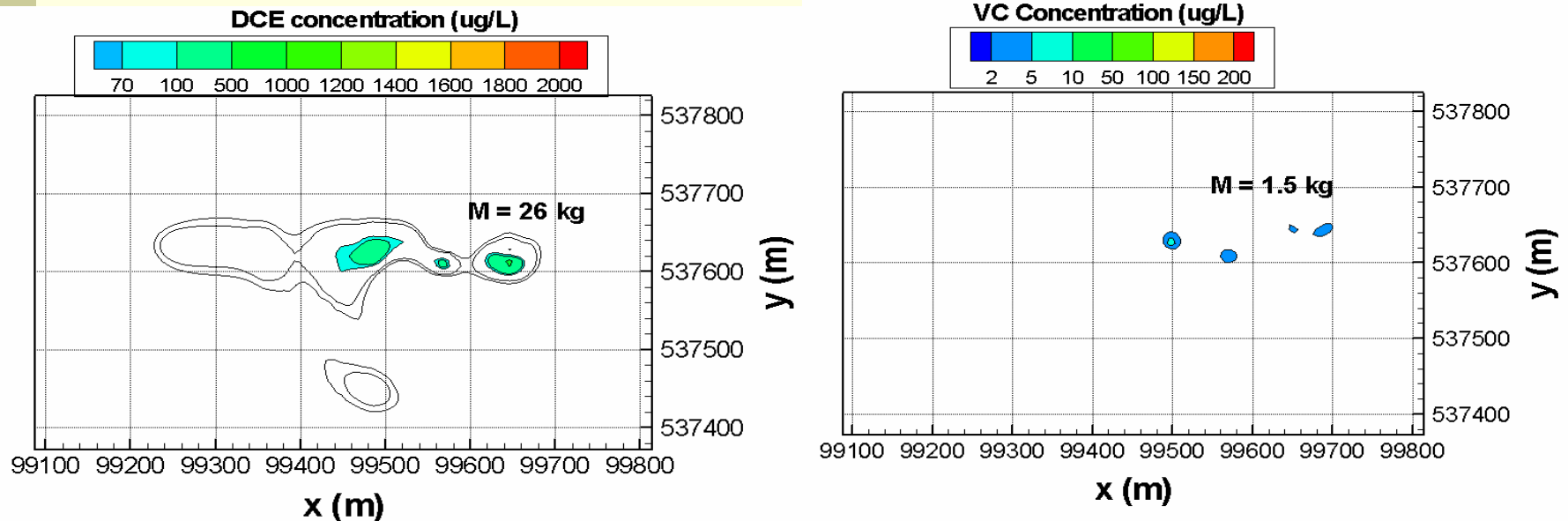
$$M_{CP(2)} = M_{CP(1)} \exp\left(-\frac{\lambda x}{v}\right)$$

$$\lambda = 1.44 \text{ yr}^{-1}$$

λ is not affected by dilution due to recharge and dispersion due to spatial integration inherent to the mass flux approach

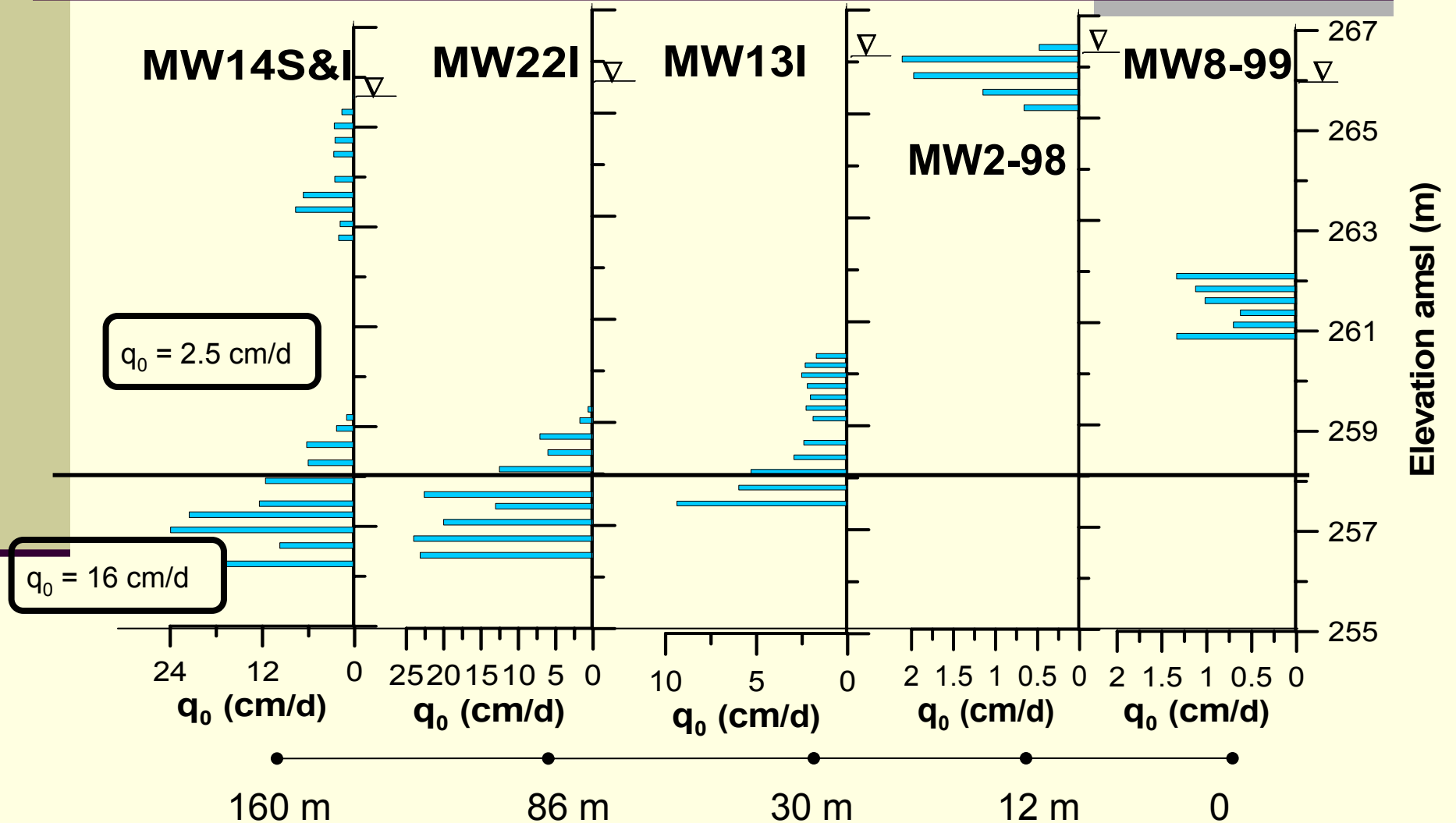


Planar view of DCE & VC plumes

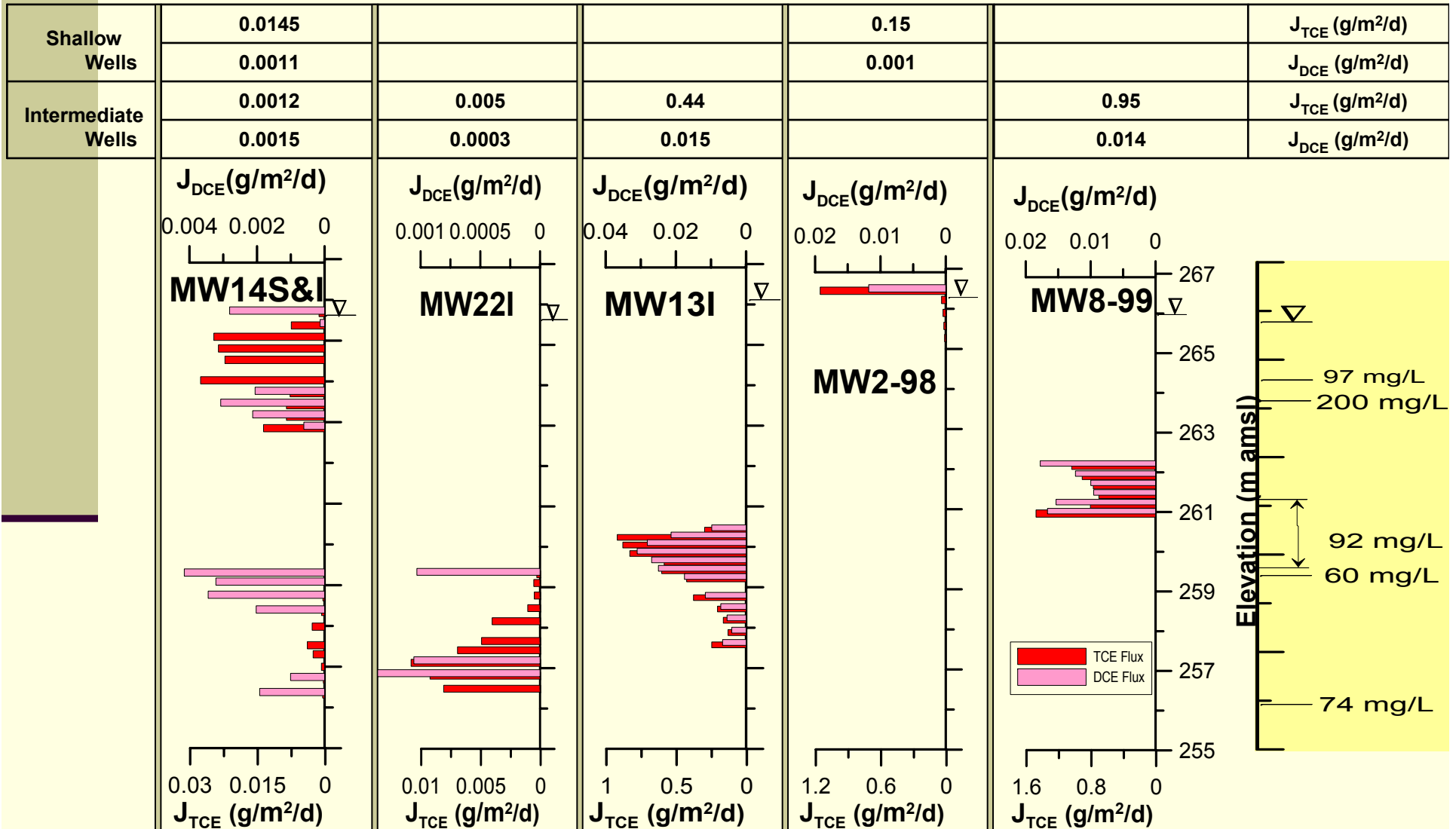


- DCE & VC Mass < 5% of TCE mass → DCE and VC degrading via alternate (aerobic ??) pathways
- Greater reductive dechlorination near source due to presence of electron acceptors
- Better geochemical characterization needed

Groundwater Fluxes along Plume Centerline (convergence factor $\alpha = 1.5$).



Contaminant Fluxes along Plume Centerline (convergence factor $\alpha = 1.5$).



Validation

Average Groundwater Flux: 2.5 cm/d and 16 cm/d (PFM)
2.4 cm/d (Consultant Report)¹

Flux-averaged Contaminant Concentrations $C_F = \sum J / \sum q$

Well ID	TCE(mg/L)		DCE(mg/L)	
	PFM	Groundwater Monitoring ²	PFM	Groundwater Monitoring ²
MW8-99	93	92	1.3	ND
MW13I	12	16	0.4	0.3
MW22I	0.037	0.011	0.002	0.005
MW14I	0.01	1.2	0.013	0.086
MW2-98	11	8	0.09	0.097
MW13S	?	8	?	0.14
MW22S	?	0.055	?	0.23
MW14S	0.47	0.05	0.037	0.005

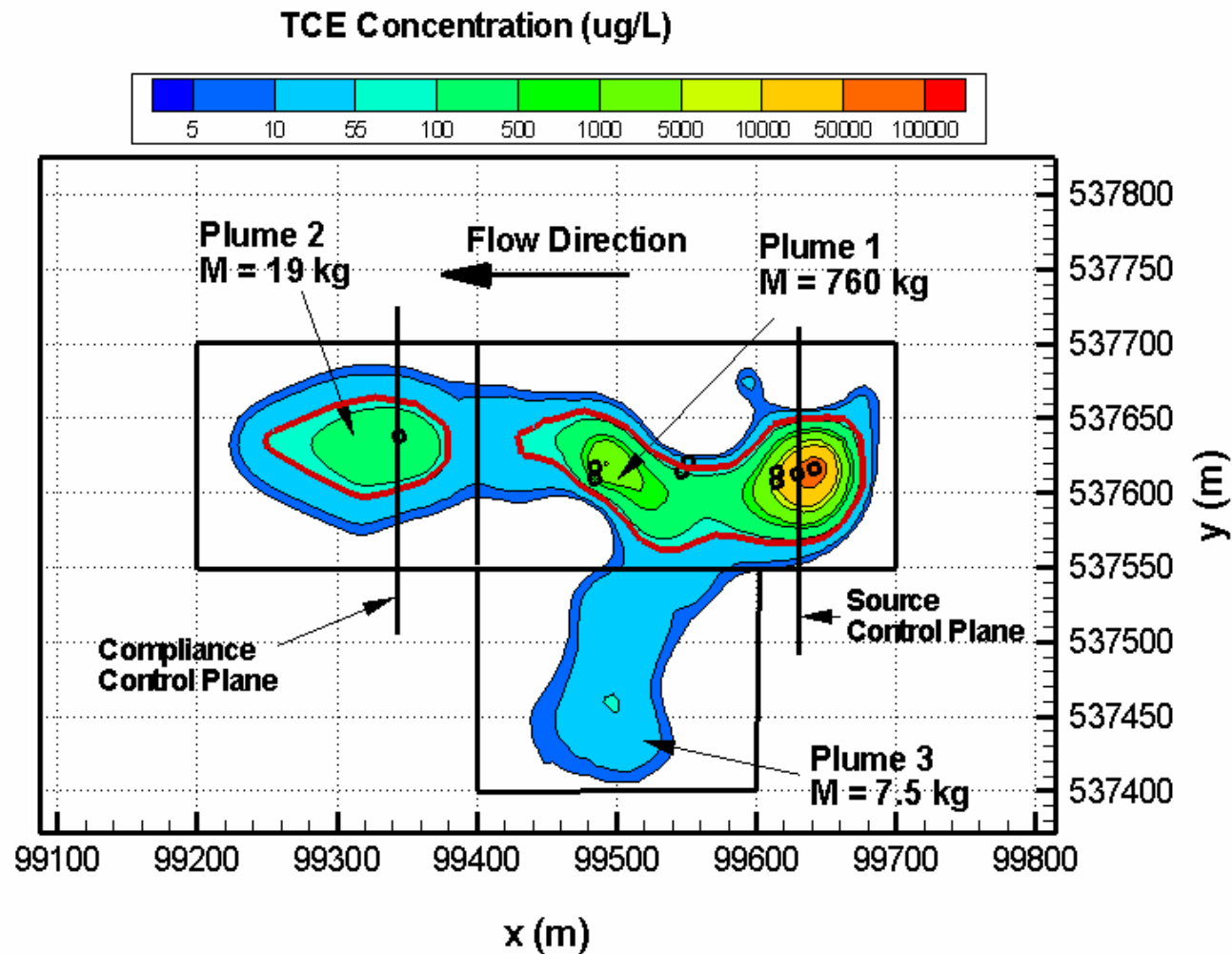
¹ Porosity of 0.3 was assumed

² Groundwater monitoring data is from 2002 while PFM measurements were done in 2004

Key Findings.....

- Two regions of low (~ 2.5 cm/d) and high (~ 16 cm/d) groundwater flux observed – important for site assessment & remedial design
- Enhanced ability to detect lower contaminant concentrations
- Contaminant flux show distinct depth pattern: important for site assessment & remedial design
- Relative magnitude of TCE and DCE fluxes provide evidence of degradation

Estimation of Source Strength

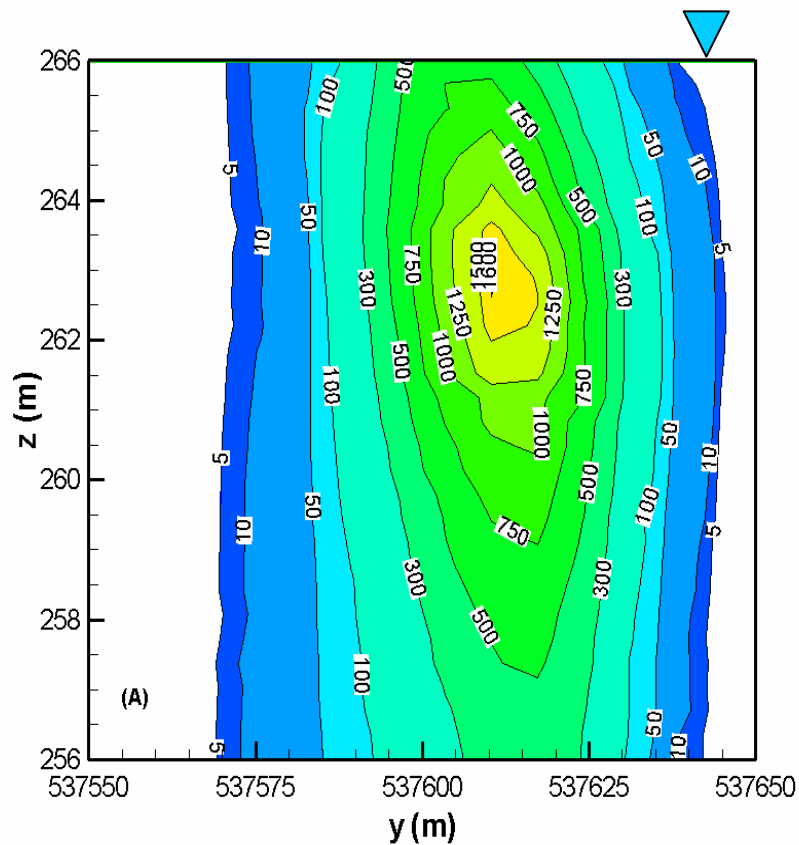


- Monitoring Well Location

Comparison of Flux Contours

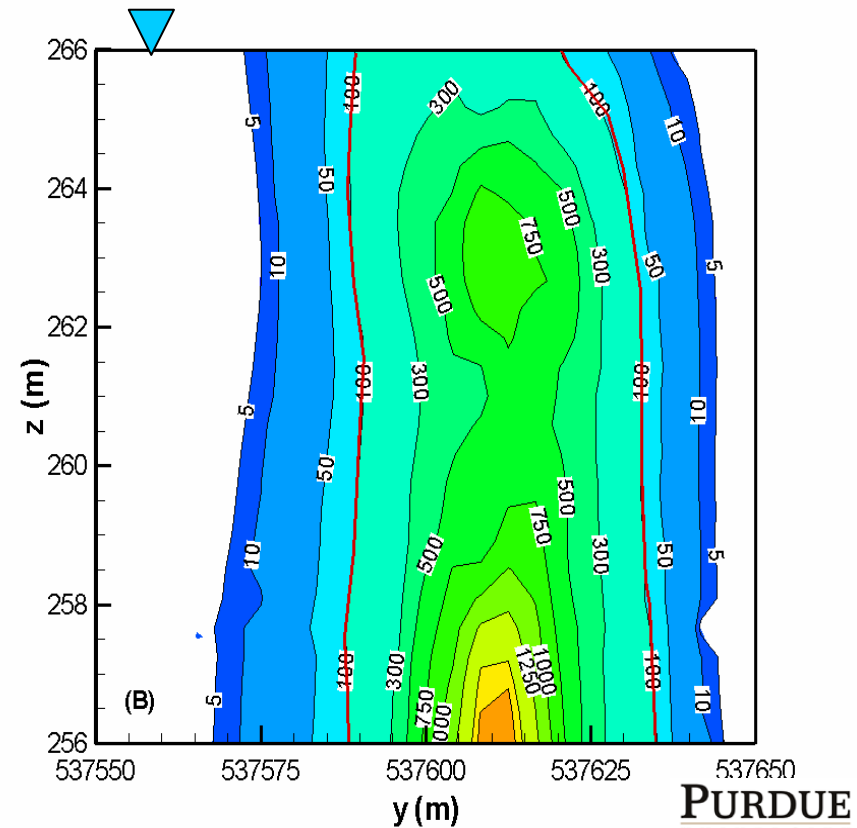
$$J_i (\text{mg}/\text{m}^2/\text{d}) = q_{\text{avg}} C_i$$

Source Strength
= 235 g/day



$$J_i = q_i C_i$$

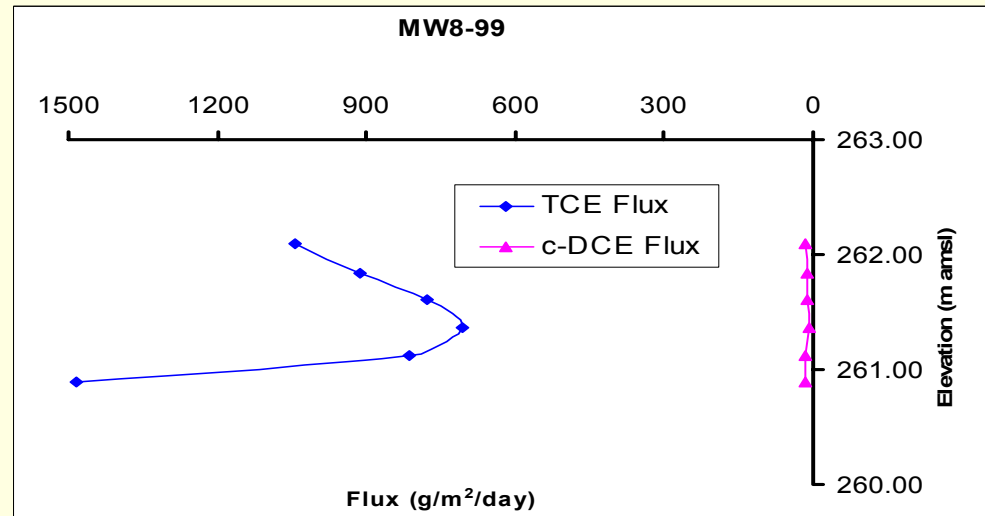
Source Strength
= 160 g/day



Natural Attenuation ?

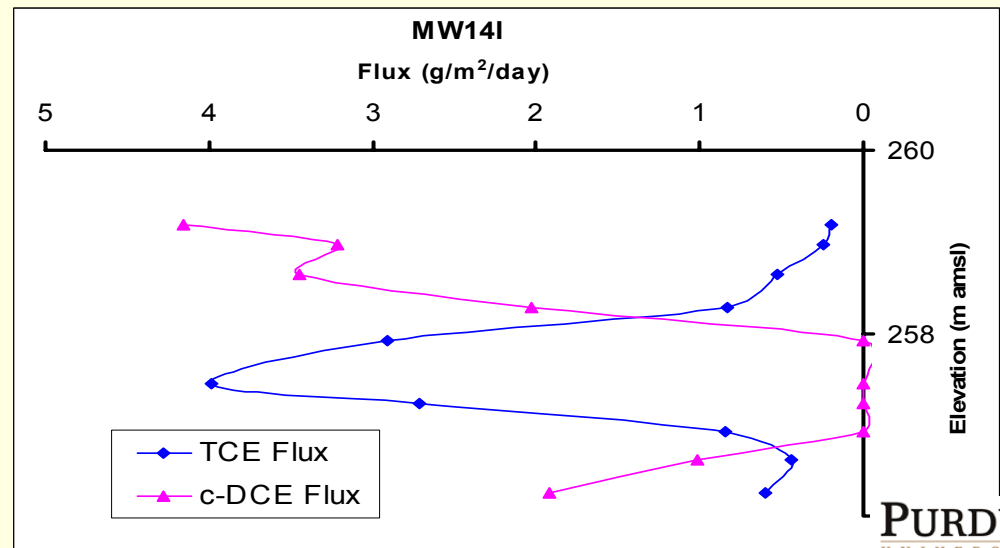
Intermediate Wells

Well ID	DCE/TCE ratio
MW8-99	0.014
MW13I	0.034
MW22I	0.054
MW14I	1.300



Shallow Wells

Well ID	DCE/TCE ratio
MW2-98	0.008
MW14S	0.079

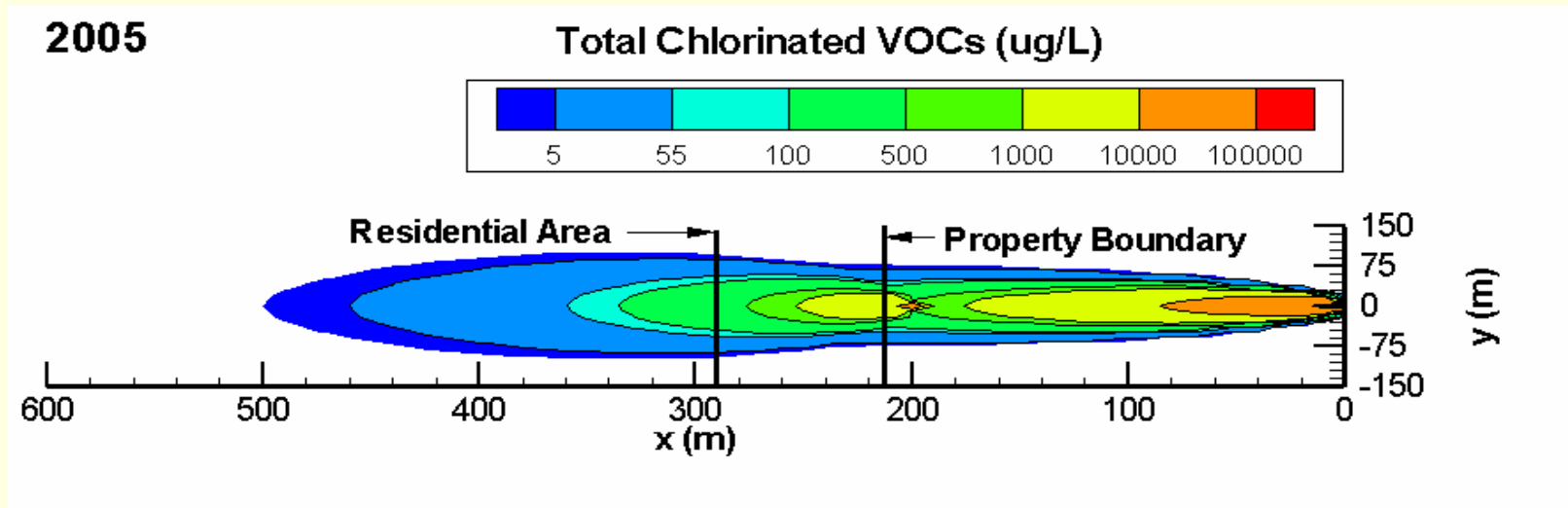


Remedial Design

How were the split plumes created?

- Spatially variable degradation rates
- Temporally displaced release scenarios
- Spatially and temporally displaced release scenarios

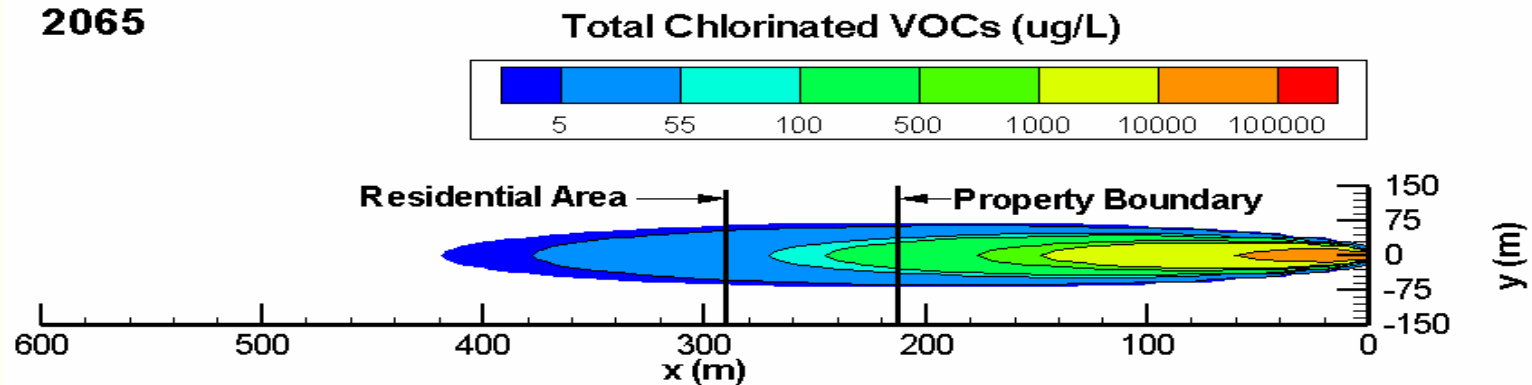
Falta et al. 2005 a & b



Remedial Design

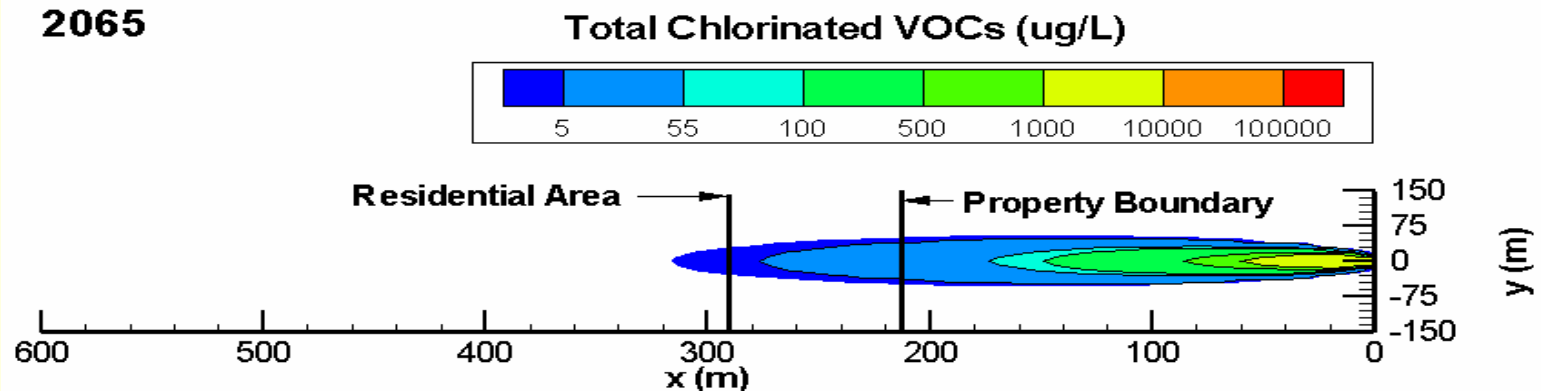
No Treatment

2065



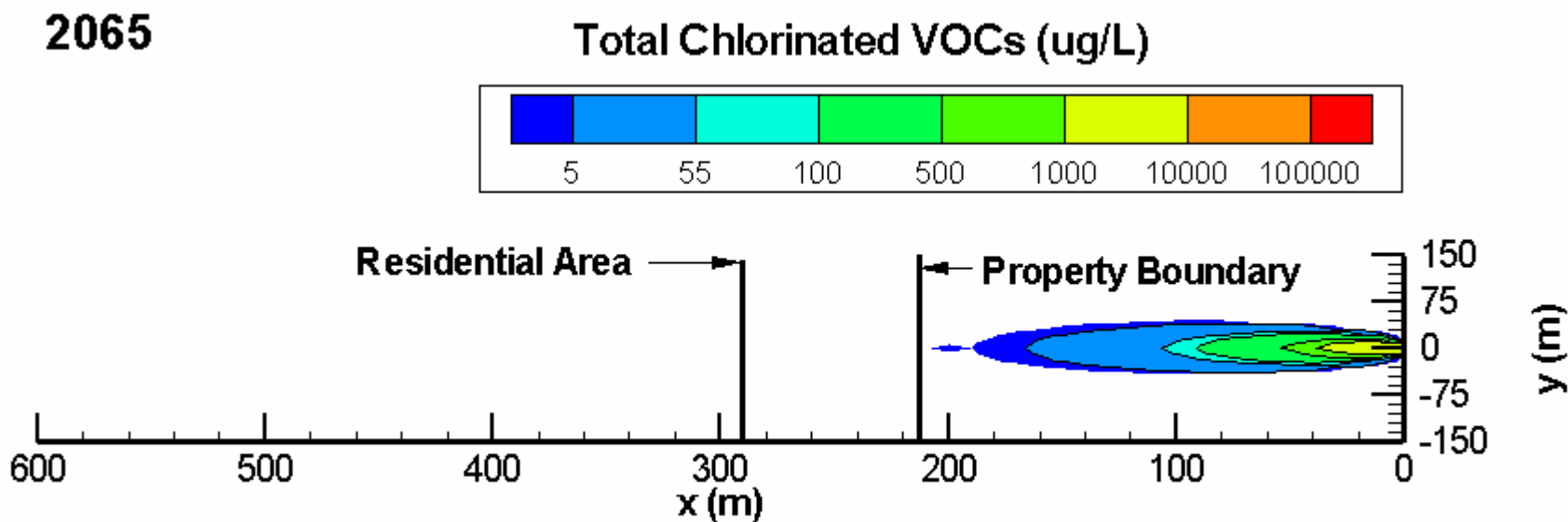
Source Treatment

2065



Remedial Design

Source Plus Plume Treatment



Summary & Recommendations

Additional Studies Proposed

- ❑ Detailed geochemical and microbial characterization of site
- ❑ Flux measurements along source control plane

Remedial Design

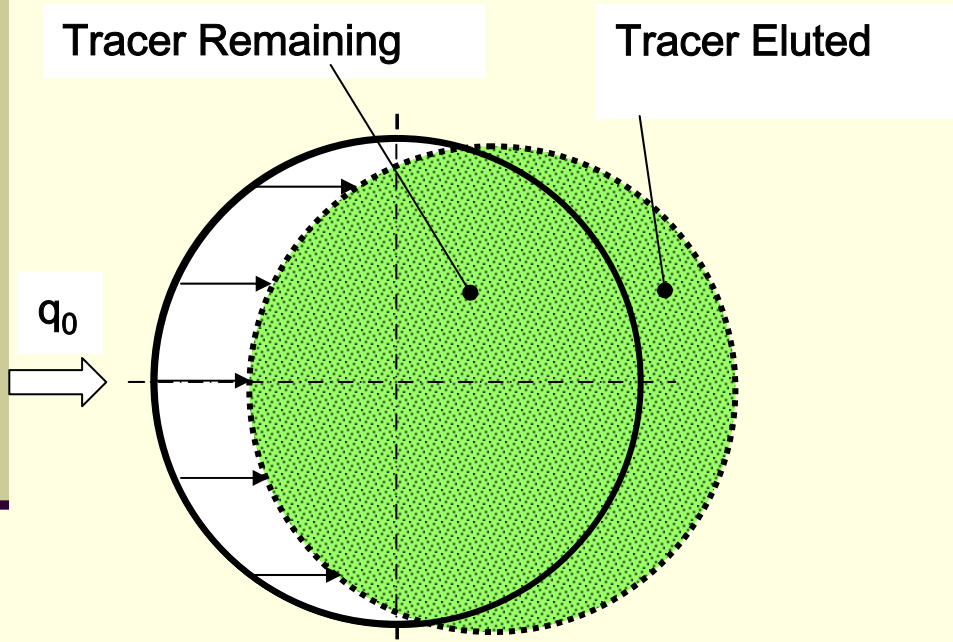
- ❑ Remedial objectives and timelines govern degree of source removal and plume treatment required
- ❑ Inverse modeling can be used for better characterization of release scenarios



Questions?

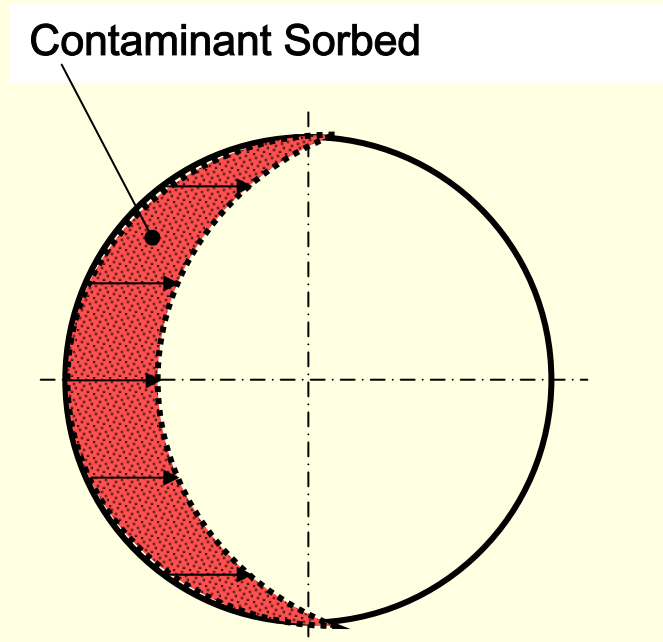
Passive Flux Meter: Groundwater & Contaminant Fluxes

Water Flux



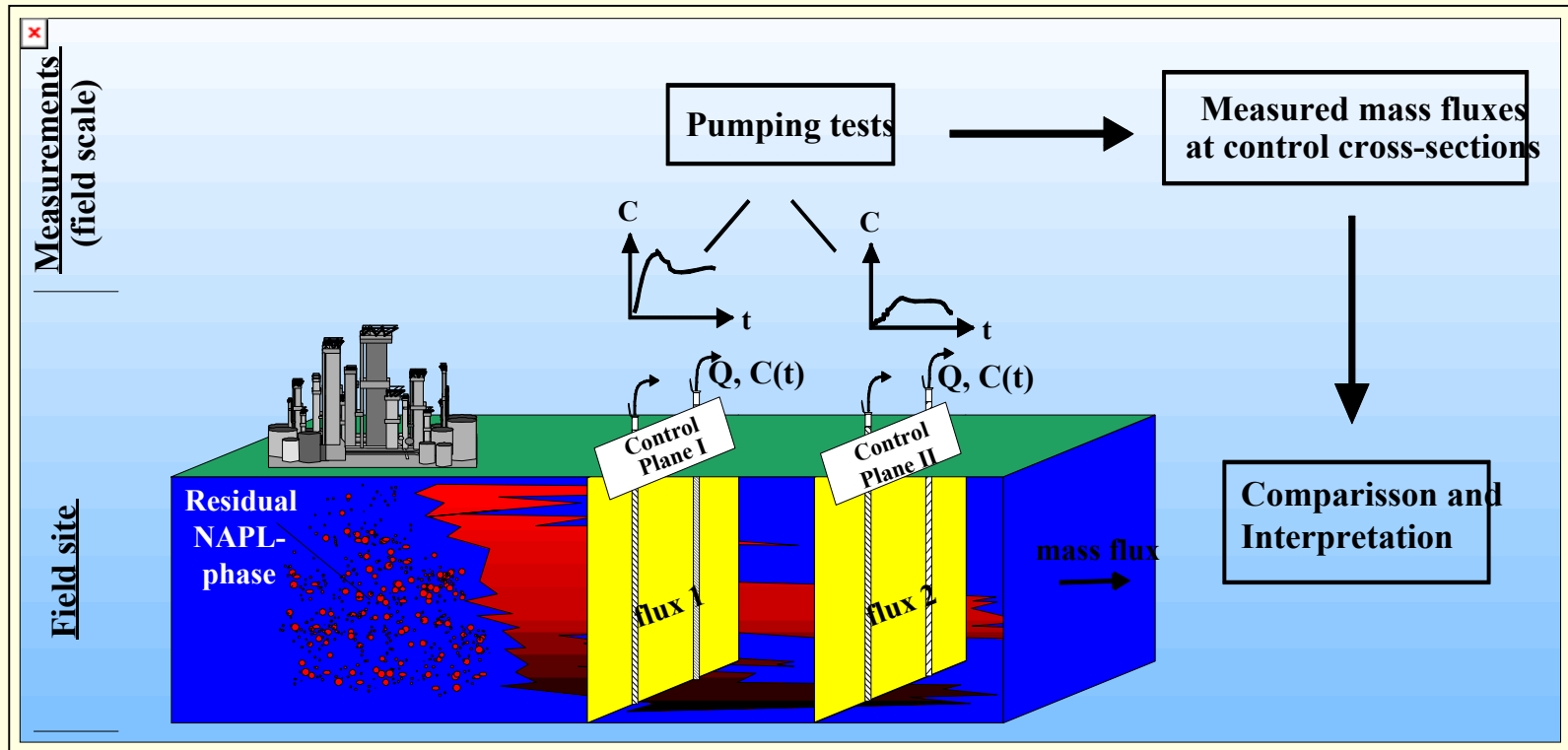
$$q_o = \frac{1.67(1 - \Omega_R)r\theta R_D}{\alpha t}$$

Contaminant Flux



$$J_c = \frac{1.67m_c}{\alpha \pi r b t}$$

Natural Attenuation Rate



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

λ = degradation rate (T^{-1}); not affected by dilution due to recharge & dispersion due to spatial integration

Summary

Assessment of Existing Site Data

- ❑ Multiple plumes
- ❑ DCE and VC degrading via oxidative pathways
- ❑ Mass Flux approach more robust for estimation of degradation rates
- ❑ $\lambda_{\text{TCE}} = 1.4 \text{ yr}^{-1}$

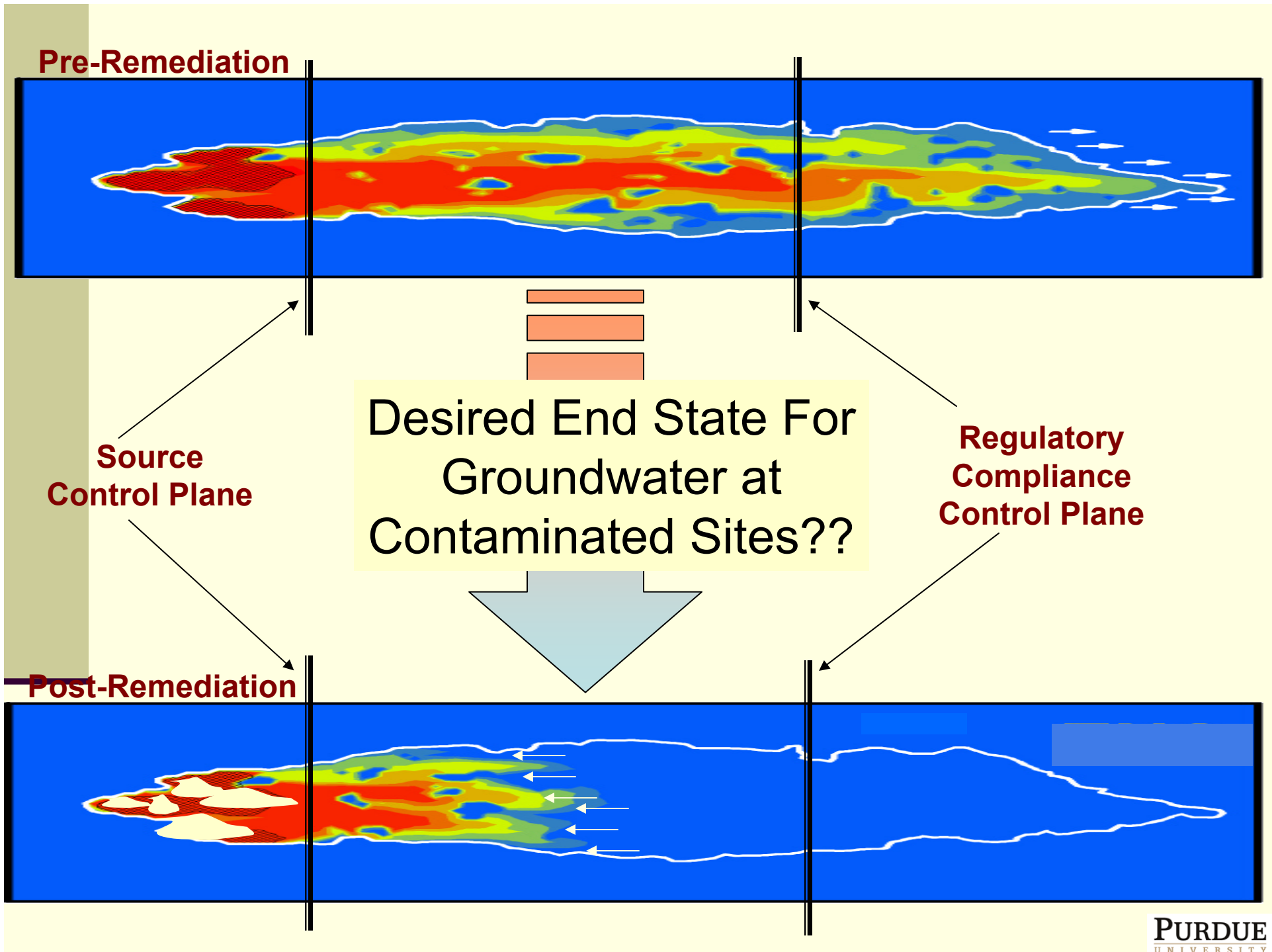
Groundwater & Contaminant Flux Measurement

- ❑ Two regions of low ($\sim 2.5 \text{ cm/d}$) and high ($\sim 16 \text{ cm/d}$) groundwater flux observed – important for site assessment & remedial design
- ❑ Contaminant flux show distinct depth pattern
- ❑ Flux distribution across source control plane important for remediation design

Estimates of Source Strength

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

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



Contaminant Mass Discharge

$$M_d = \sum J_i A_i$$

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

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

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

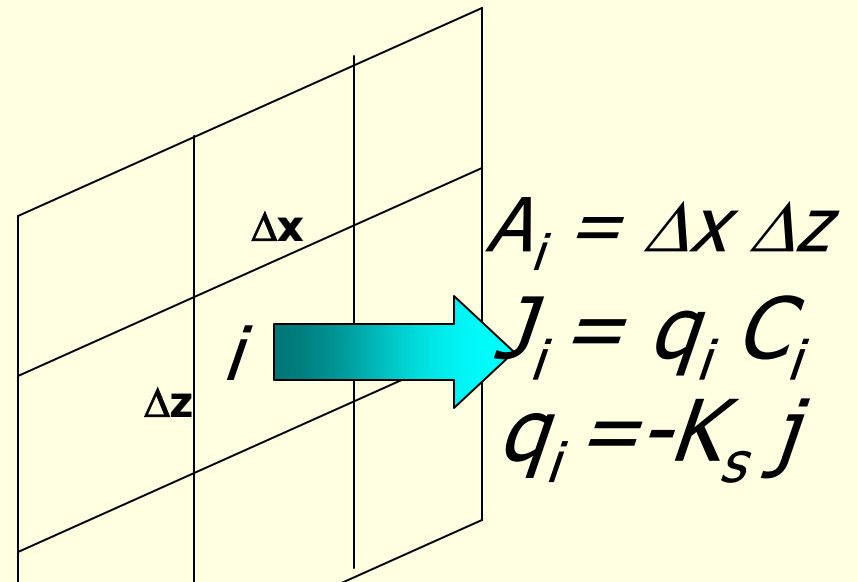
A_i = Area of element i (L^2)

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

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

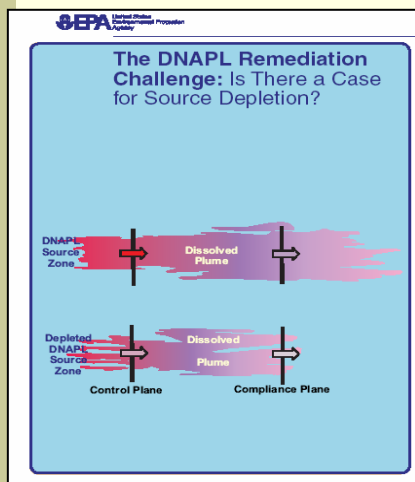
j = Hydraulic gradient (-)

Control Plane (CP)



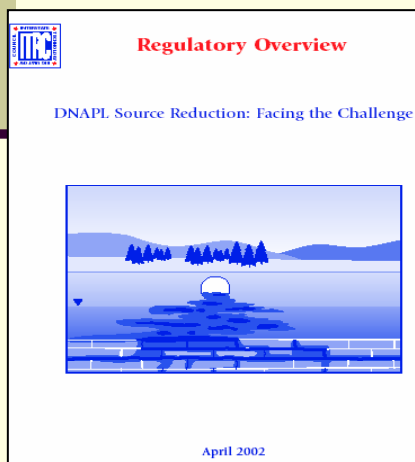
Control plane area should be just large enough to completely inscribe the dissolved plume width

EPA Expert Panel on DNAPL Remediation¹ (Dec. 2003)
&
ITRC DNAPL Source Remediation Report (April 2002)



➤ *partial mass depletion from DNAPL source zones is likely to be a viable remediation strategy at certain sites*

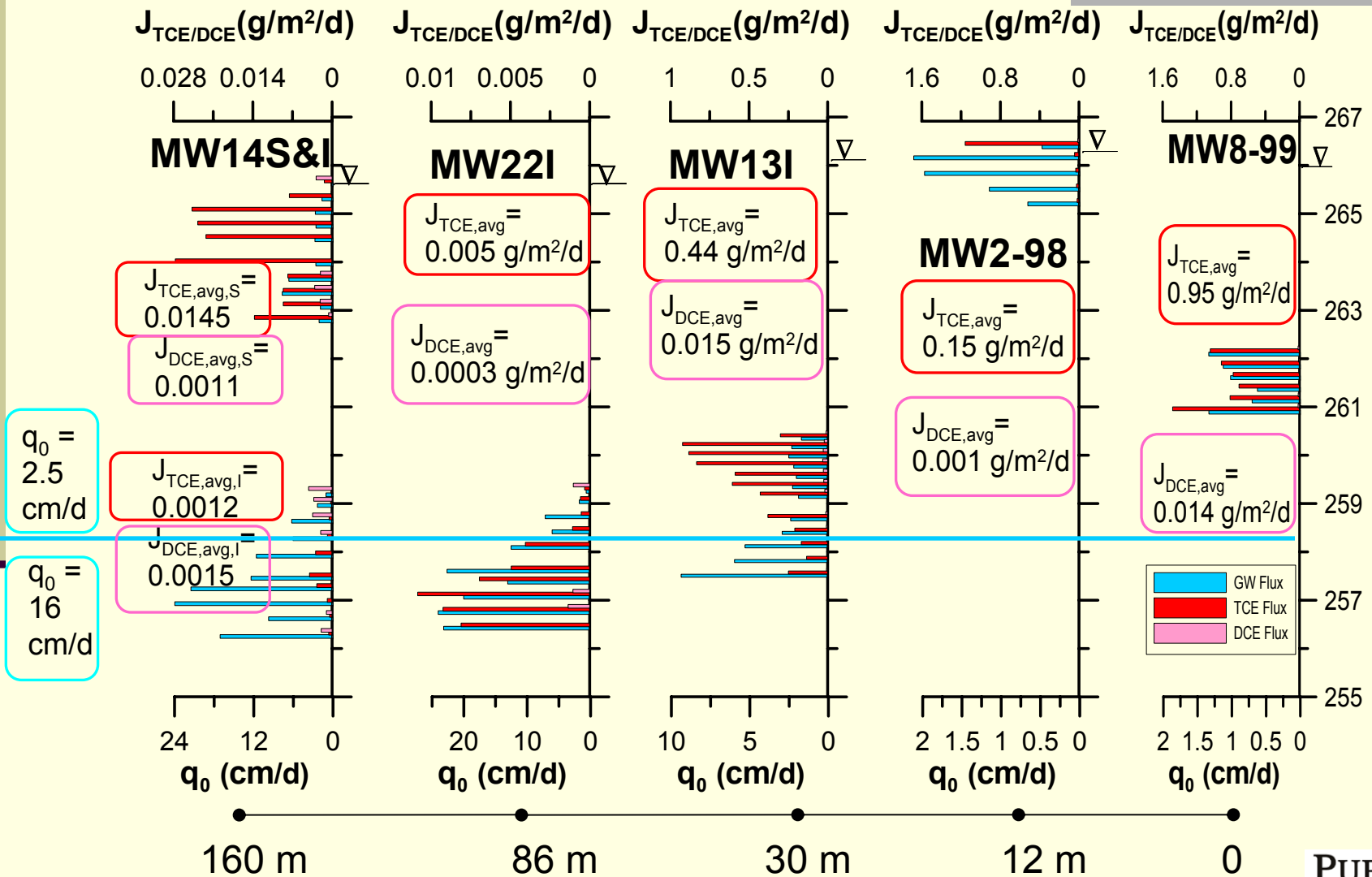
➤ *DNAPL mass depletion in the source zone reduces contaminant mass discharge*



➤ *Contaminant mass discharge should be used as an alternate performance metric to assess benefits of source depletion*

¹ Kavanaugh M. and P.S.C. Rao (Eds) 2003

Groundwater & Contaminant Fluxes along Plume Centerline (convergence factor $\alpha = 1.5$).



Input parameters

Parameter	Unit	Value	
		Plume 1	Plume 2
Initial Source Mass, M_0	kg	40,000	6000
Initial Source Flux, C_0	mg/L	1000	
Darcy Flux, V_d	cm/day	2.5	
Source Dimensions	m	10 m (width) x 5 m (depth)	10 m (width) x 10 m (depth)
Porosity	dimensionless	0.3	
Retardation Coefficient	dimensionless	2 for all species	
Dispersivities	m	$\alpha_x = 15, \alpha_y = 1.2, \alpha_z = 0.14$	$\alpha_x = 8, \alpha_y = 5, \alpha_z = 1.$
Yield Coefficient	dimensionless	$y_{DCE/TCE} = 0.737, y_{DCE/VC} = 0.64499$	
Decay Rates	yr ⁻¹	$\lambda_{TCE} = 0.8,$ $\lambda_{DCE} = 25, \lambda_{VC}$ $= 160$	$\lambda_{TCE} = 1., \lambda_{DCE} = 5,$ $\lambda_{VC} = 100$
Time from spill to present	years	55	25
Remediation Timeframe	years	55 to 56	-
% Source Removal		90	0

Passive Flux Meter

Field Installation and Sampling



Courtesy of Mike Annable, Univ of Florida

Field Testing at US Military Bases

	Site	Number of Times Used	Number of Wells	Linear Feet	Contaminants	Source or Plume	Primary Application
1	CFB Borden Ontario	5	30	140	PCE/TCE/MTBE	plume	Site characterization
2	LC-34, Cape Canaveral, Florida	4	3	30	TCE/byproduct	source/ plume	Site characterization
3	OU-1,Hill AFB, Utah	2	8	32	TCE	source	Remediation performance
4	Dover AFB, Delaware	1	6	60	PCE	source	Remediation performance
5	Patrick AFB, Florida	3	5	50	TCE/byproduct	source/ plume	Site characterization
6	Ft. Lewis, Washington	1	16	325	TCE	source	Remediation performance
7	LC-15, Cape Canaveral, Florida	1	10	100	TCE	plume?	Site characterization
9	Naval Weapons Facility Charleston, South Carolina	1	6	60	TCE/byproduct	plume	Remediation performance
10	Indian Head, Maryland		6	60	Perchlorate	plume	Site characterization
11	Port Hueneme, California	1	14	50	MTBE	plume	Site characterization

Additional Field Testing at Commercial Sites

11	Sages Drycleaner		5	50	PCE/byproducts	plume	Remediation performance
13	Manufacturing site Anderson, Indiana		8	80	TCE/byproducts	source/ plume	Site characterization
14	Manufacturing Site, Chicago, Illinois	2			TCE	plume	Site characterization
15	Dry cleaner Crawfordsville, Indiana	2	2	20	PCE/byproduct	source/ plume	Site characterization
16	Industrial site Cape Canaveral		10	100	TCE/byproducts	Plume	Site characterization