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# Mass Flux Field Measurement Techniques

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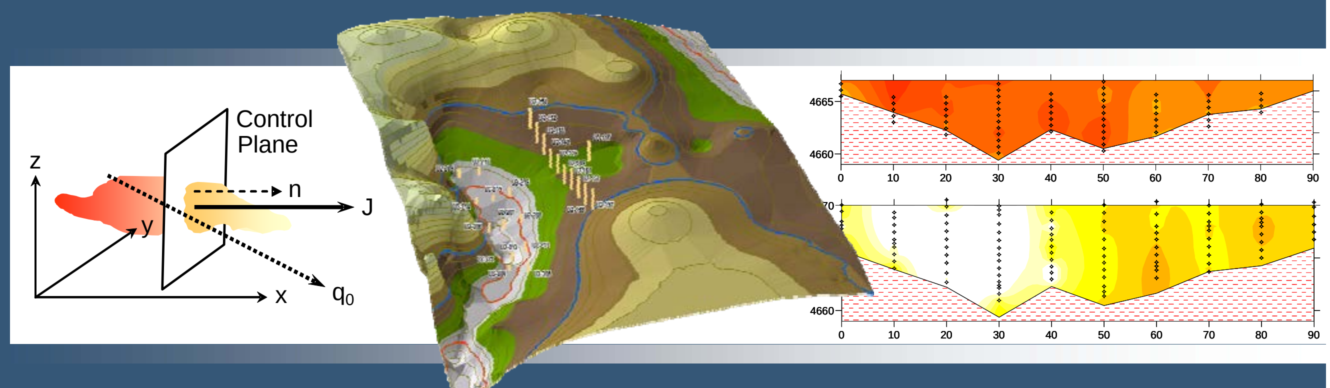


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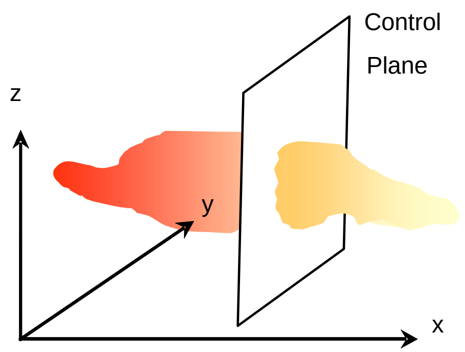
# Mass Flux Field Measurement Techniques

## *Outline*

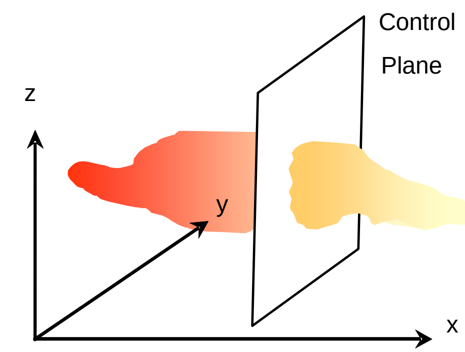
- Control Planes
- Methods
  - Traditional Methods
  - Passive Flux Meter
  - Pumping Methods
- Uncertainty
- Select Field Results



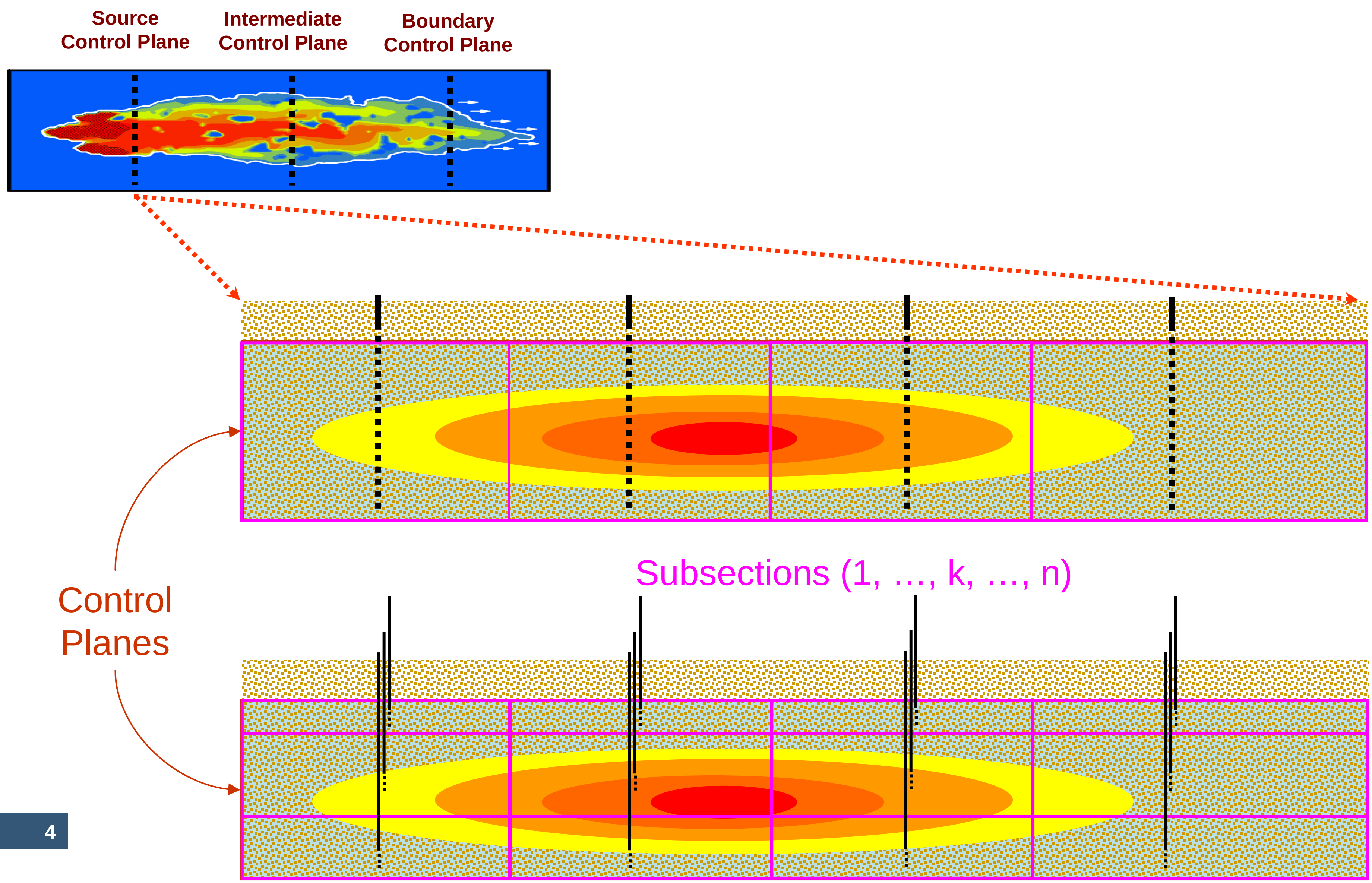
# Mass Flux Field Measurement Techniques

## Control Planes (CPs)

- **How many CPs?**
  - Purpose (Source or plume characterization)
  - Existing monitoring network
  - Budget
- **CP location(s), orientation and length?**
  - Purpose (Source or plume characterization)
  - Prior characterization (groundwater flow direction, source and plume delineation)
- **Well spacing within CP(s)?**
  - Transect Length
  - Flow and contaminant heterogeneity
  - Budget
  - Mass flux measurement methods



# Control Planes, Cont'd



# Contaminant Fluxes &
# Mass Discharge at Control Planes

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

$$J_k = C_k q_k$$

$$q_k = Ki$$

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

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

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

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

$C_k$ = Concentration [$ML^{-3}$]

$A_k$ = Area of element k [$L^2$]

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

$i$ = Hydraulic gradient [-]



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

# Traditional Methods

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

**Concentration**

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

**Groundwater Flux**

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

**Hydraulic Conductivity**

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

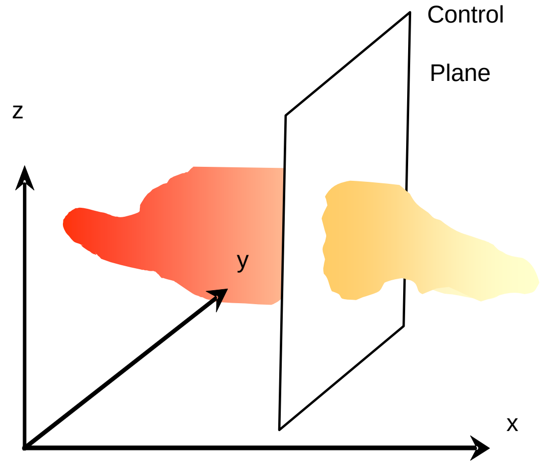
**Hydraulic Gradient**

- Head measurements

# Traditional Methods

## What's different?

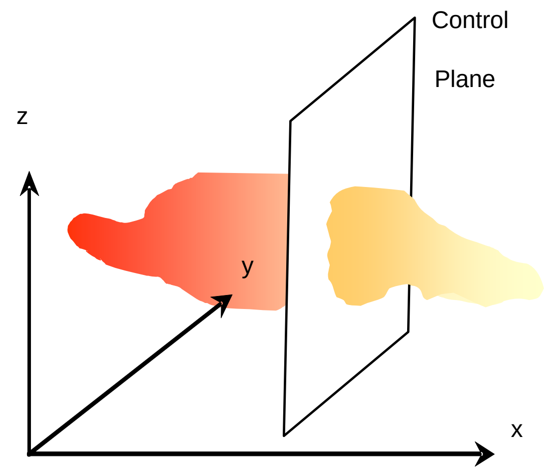
- Sampling location (i.e., focus on one or more control planes)
- Explicit combination of C, K, & *i* to estimate J and $M_D$



# Traditional Methods

## Where has it been used?

- Semprini et al., 1995; TCE degradation
- Borden et al., 1997; MTBE/BTEX degradation
- ITRC, 1998; Chlorinated solvent degradation
- Wilson et al., 2000; MTBE degradation
- Einarson and MacKay, 2001; MTBE and DCE source strength
- Kao and Wang, 2001; BTEX degradation
- Guilbeault et al., 2005; DNAPL source strength
- Barbaro and Neupane, 2006; PCE degradation



# Summary of Traditional Approach

- Advantages:
  - Generates spatial information on J & $M_D$
  - Methods exist to estimate uncertainty
  - Small waste volumes produced
  - Conventional

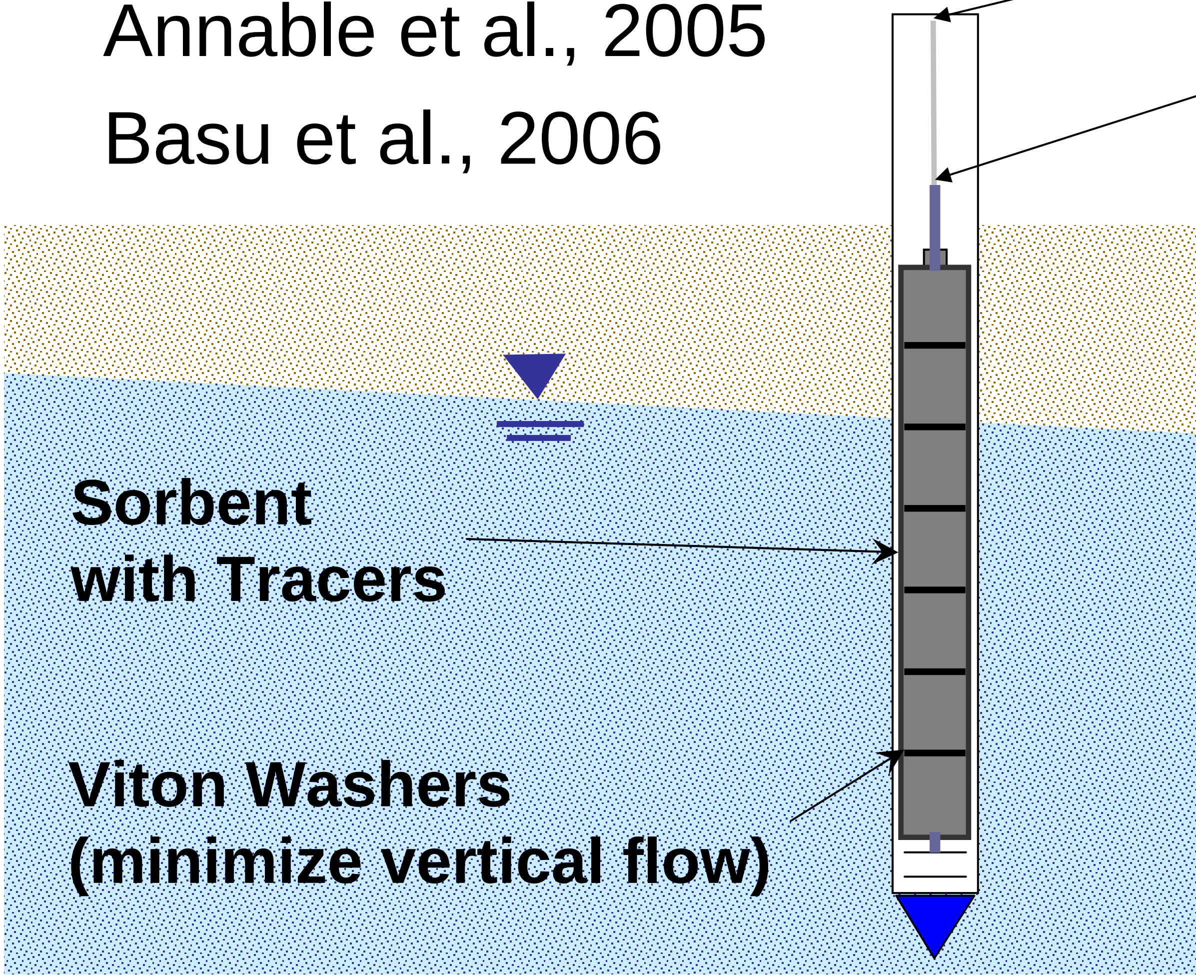
- Disadvantages:
  - Requires independent estimation of q
  - Contaminant measures are instantaneous
  - Interrogates small volumes of aquifer
  - Data must be spatially integrated to obtain $M_D$

# Passive Flux Meters

Hatfield et al., 2004

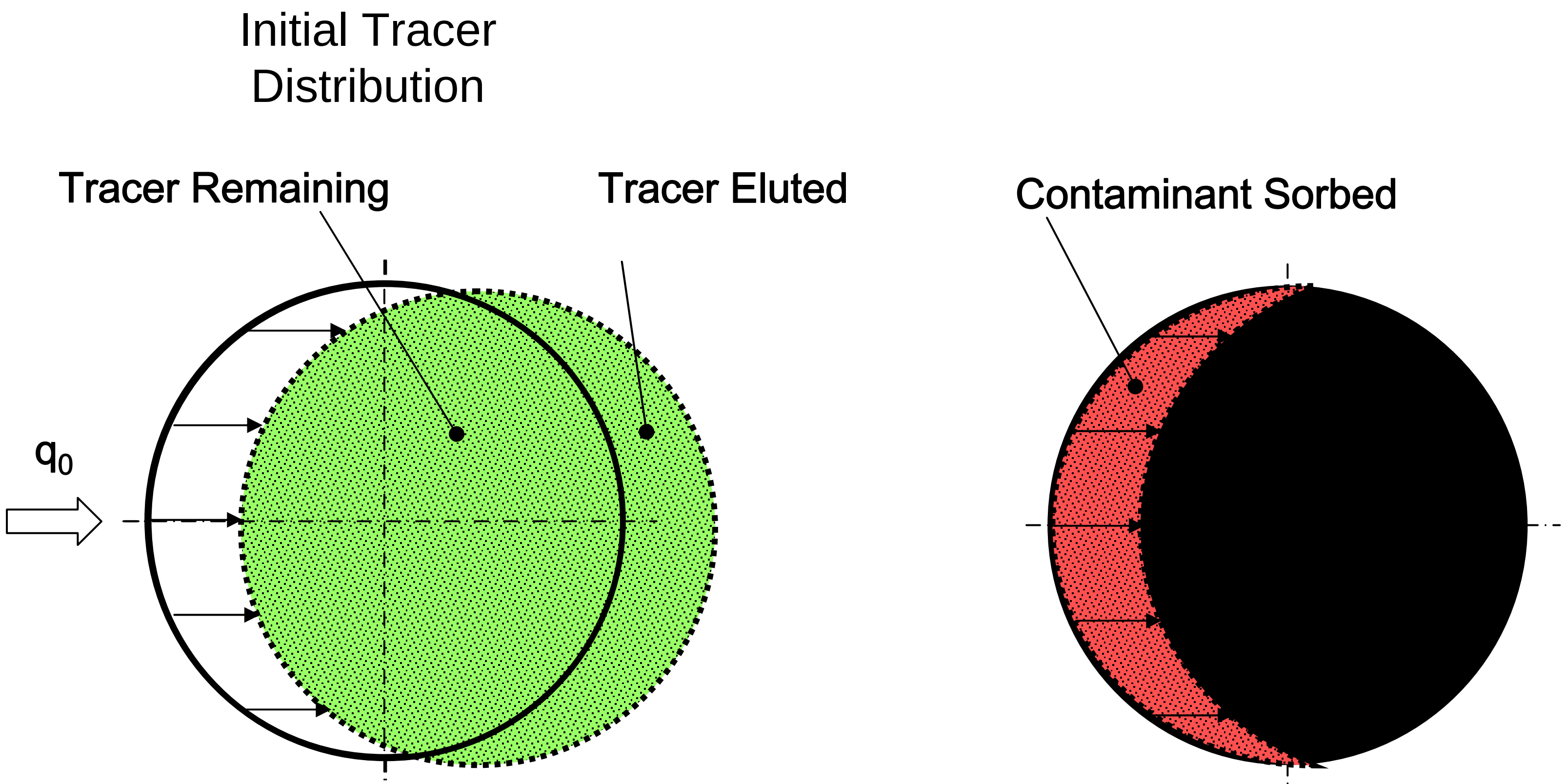
Annable et al., 2005

Basu et al., 2006

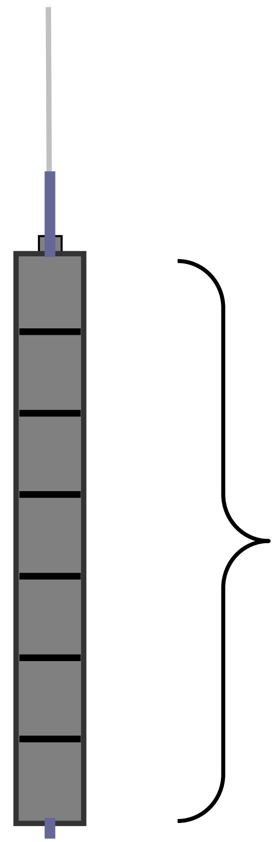



Activated Carbon with Tracers

# PFM – Horizontal Cross Section



# Passive Flux Meters

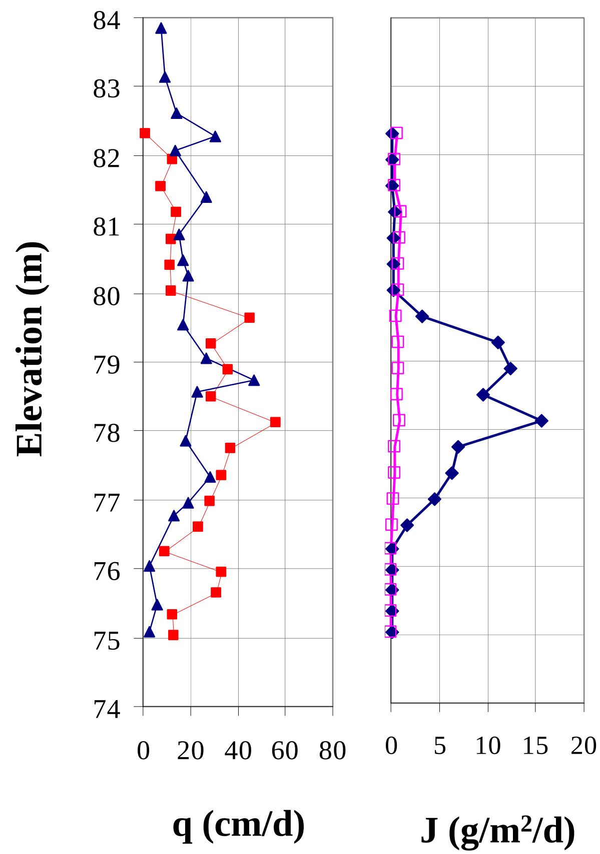


q = f(depth)

J = f(depth)

*Example Profile from*

*Ft. Lewis (well LC-211)*




~30 Field-site deployments to date

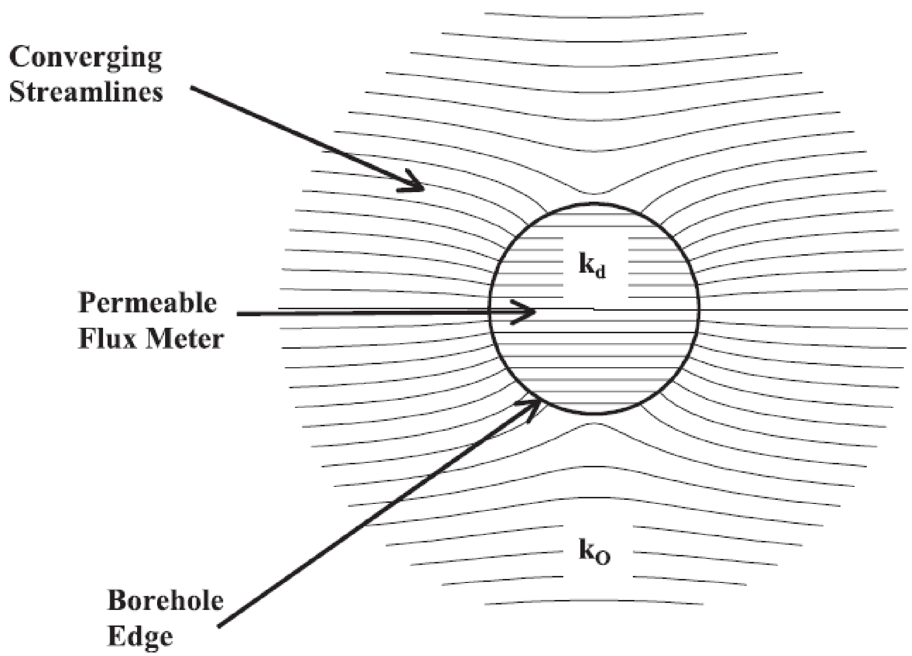
# PFM Resident Tracers

Sorbent (granular activated carbon) is saturated with multiple tracers prior to deployment

| Tracer | $K_d$ (cc/mg) | $R_d$ |
|---|---|---|
| Methanol | 0.0035 | 4.3 |
| Ethanol | 0.0165 | 17.6 |
| Isopropyl alcohol | 0.115 | 110 |
| 2,4-dimethyl-3-propanol (Internal Tracer) | >1 | >1000 |

$R_d = 1 + \frac{\rho}{\theta} K_d$ , Water content (θ) = 0.55 and bulk density ($\rho$) ~ 520 mg/cc

# Flow Lines Through PFM




$\alpha > 1$

Convergence ($\alpha > 1$)
Divergence ($\alpha < 1$)

$$q_D = \alpha q_0$$

$q_D$ = Groundwater flux in well bore

$q_0$ = Groundwater flux in formation

$\alpha$= Convergence factor

*All three are functions of depth*

Depending on well construction:

$$\alpha = f(k_0, k_1, k_2, k_3, r_1, r_2, r_3)$$

Klammer et al., *WRR*, 2007

Goal: Construct well so that $\alpha \sim 1$

# Summary of PFMs

- Advantages:
  - Concurrent estimates of q(z) & J(z)
  - Methods exist to estimate uncertainty
  - Generates local estimates of horizontal aquifer conductivity
  - Small waste volumes are produced
  - Passive

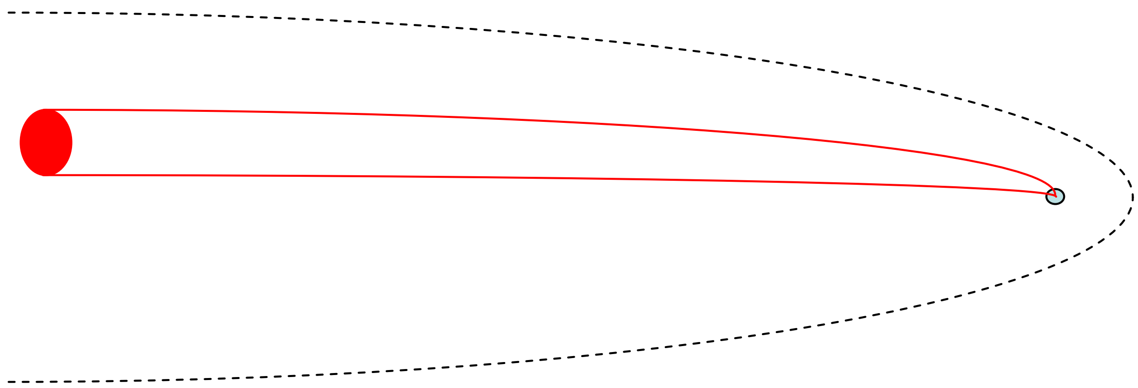
- Disadvantages:
  - Interrogates small volumes of aquifer
  - Data must be spatially integrated to obtain mass discharge
  - Uses resident tracers to estimate groundwater flux
  - Does not function in all wells
  - Proprietary method/Non-routine chemical analysis

# Pumping Methods for Determining Mass Flux and Discharge

- Long-term pumping records
- Short-term integral pump tests (IPT)
  - Sequential approach
  - Concurrent variable flow rate approach
- Short-term tandem circulation well tests

# Long-Term Pumping Records

(Holder et al., 1998; Einarson and MacKay, 2001; Brusseau et al., 2007)



$M_D = Q*C$

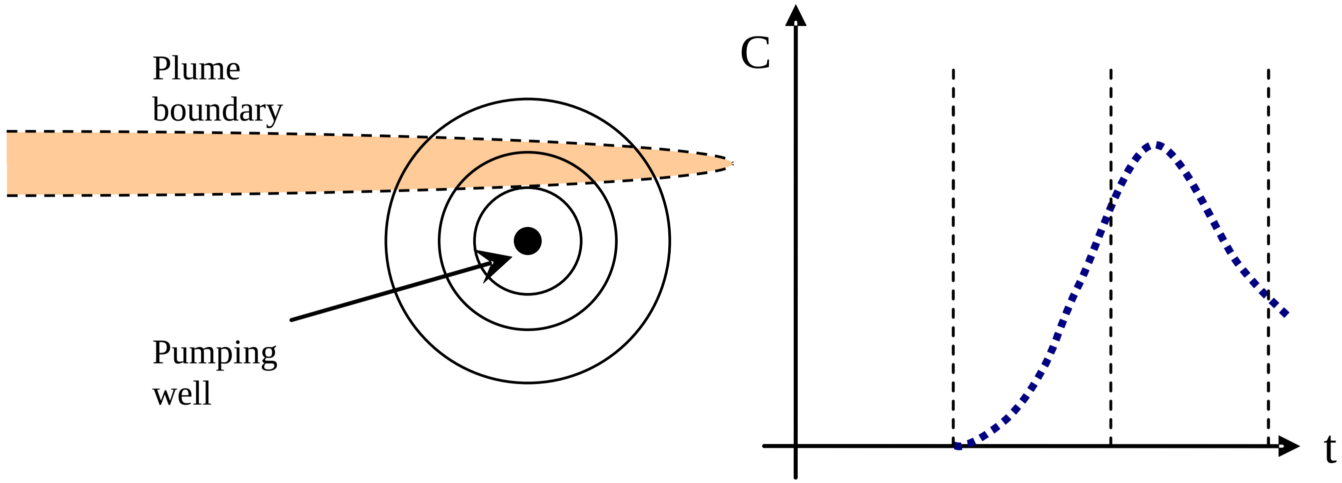
- Robust estimate of $M_D$ (within capture zone of the well)
- Flux estimate is less certain (requires estimate of capture zone dimension)
- No information on spatial distribution
- Requires steady-state, no (a)biotic losses

# Pumping Methods, Cont'd

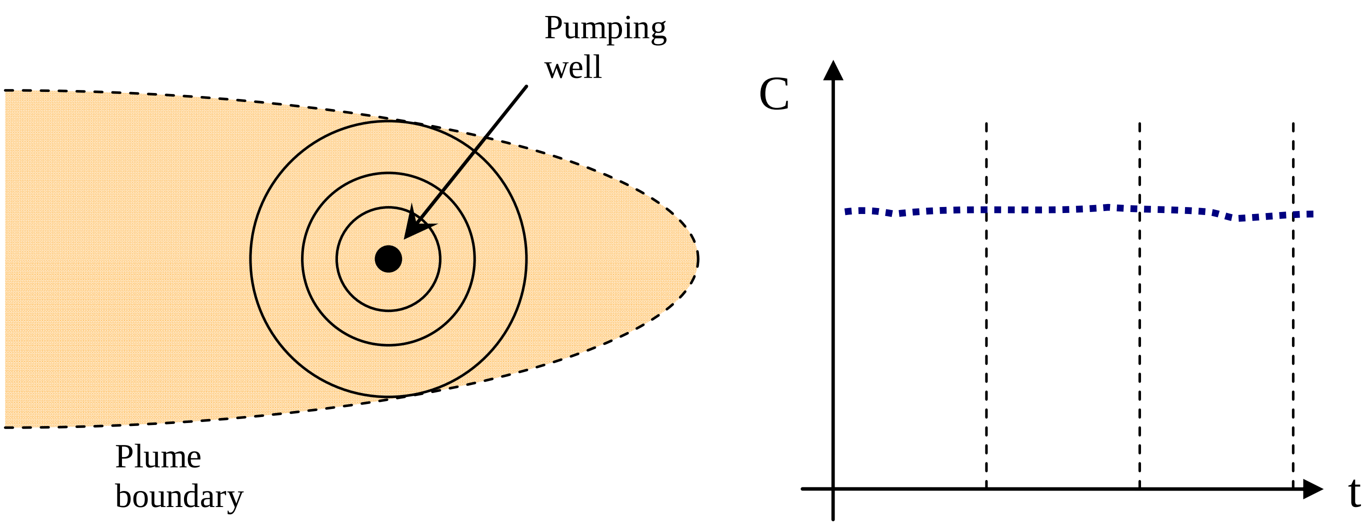
## Integral Pump Tests, Original Concept

- J = q*C
- Sequential pumping from multiple wells
- Short-term transient test
- C obtained from analytical/numerical interpretation of CT series (assumptions about contaminant distribution required)
- q obtained from traditional means
- 55 field applications according to Bayer-Raich et al., 2004.

# Interpretation of CT series




**Capture zone scale is "large" compared to the contamination scale**




**Capture zone scale is "small" compared to the contamination scale**

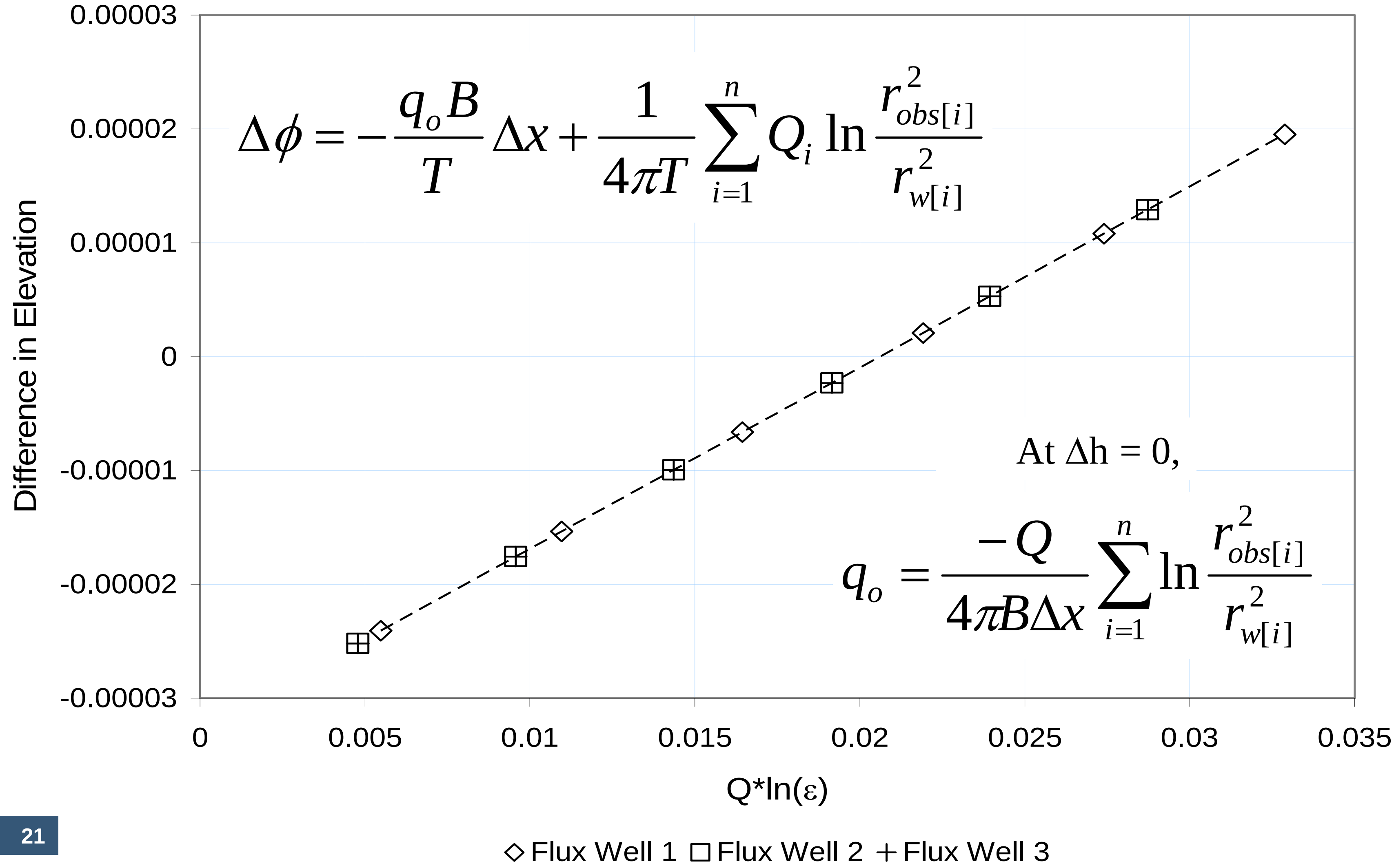
Adapted from Bockelmann et al. (2003)

# Pumping Methods, Cont'd

## Integral Pump Tests, Concurrent variable flow rate approach

- $J = q*C$
- Concurrent pumping from multiple wells
- Short-term transient test
- q obtained from pumping test hydraulic information
- To date, C taken as average of CT series

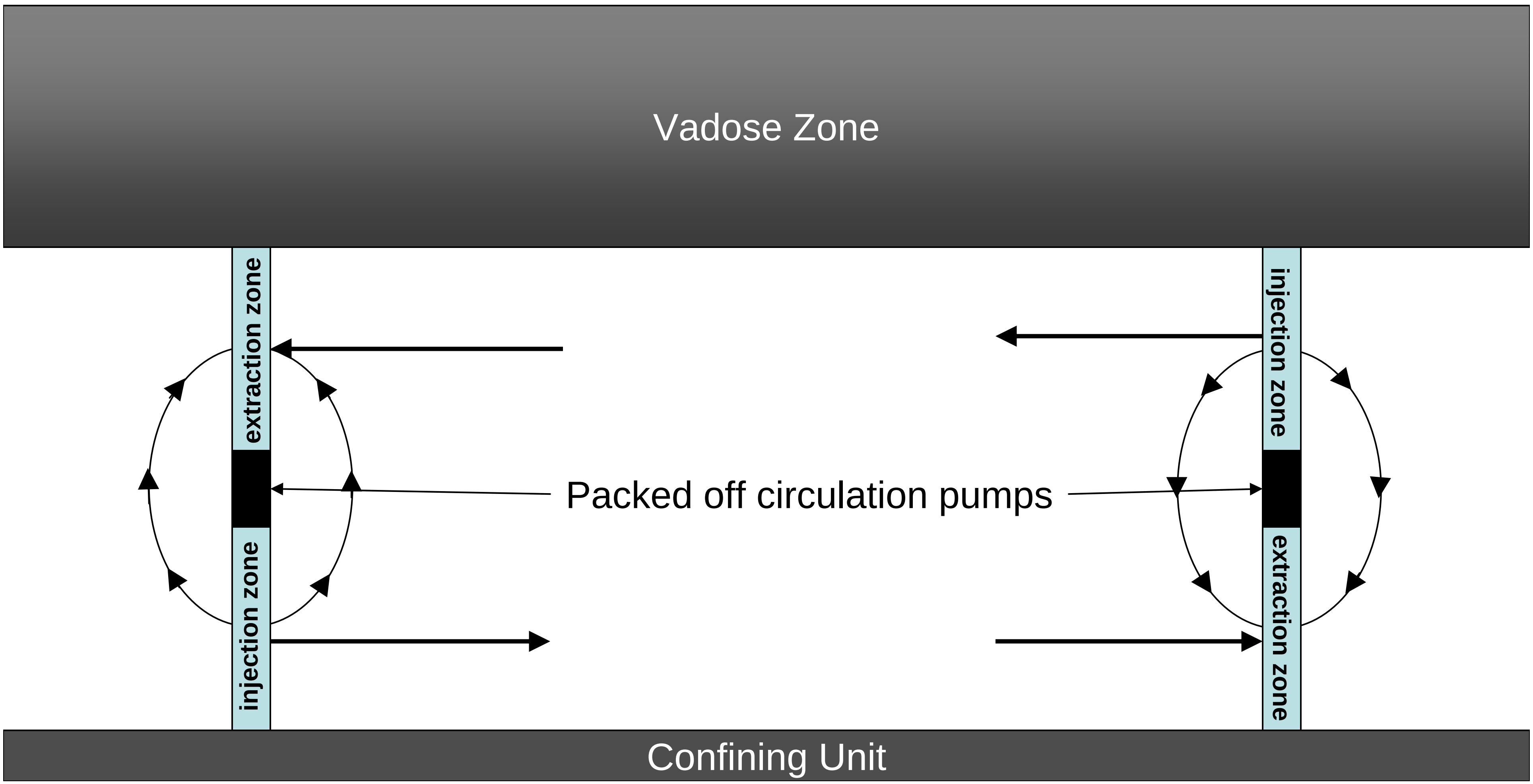
# Superposition of Uniform flow and multiple Sinks




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

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

# Tandem Circulation Wells (No wastewater produced)



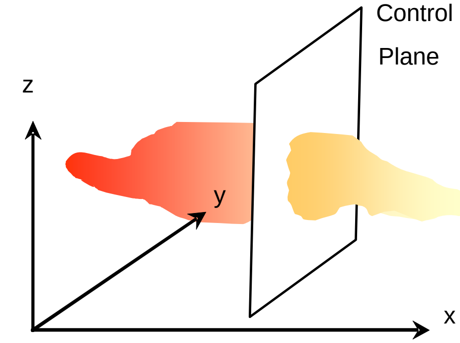
# Analysis Approach

- A circulation pattern is established.
- Head measurements are collected and subsequently used with an analytical model to estimate K, or…
- Tracers are injected, and an inverse numerical modeling approach is used to estimate K.
- q is determined using independent estimates of i.
- J is then estimated using measured concentration data.

# Summary of Pumping Methods

- Advantages:
  - Generates integrated estimate of J and $M_D$
  - Interrogates large volumes of aquifer
  - Can be used in deep aquifers

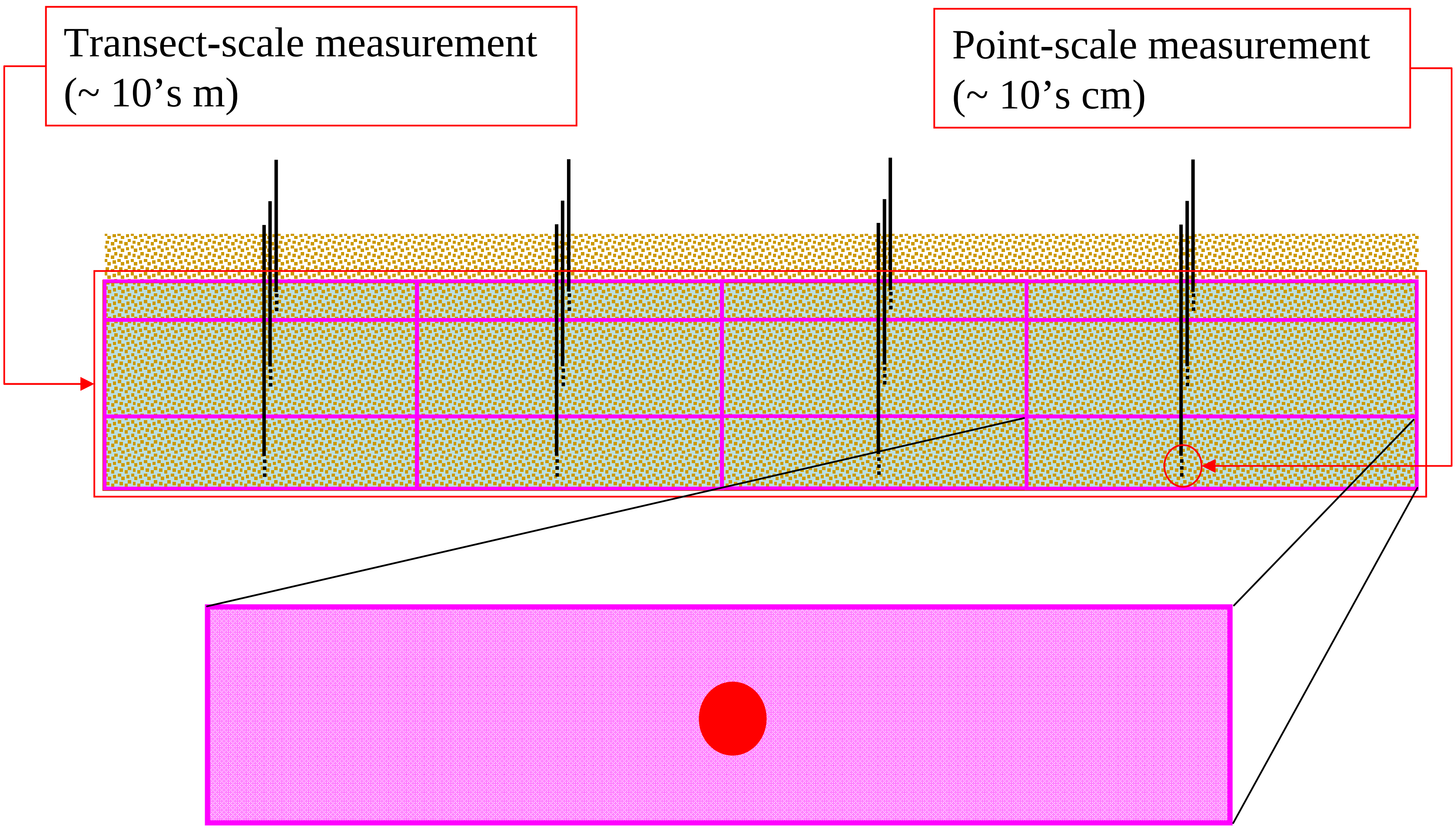
- Disadvantages:
  - Costly [equipment, labor, wastewater disposal (w/ exception of TCWs)]
  - May require independent estimation of q
  - May require assumptions that aquifer is homogeneous
  - Does not provide spatial information (difficult to quantify uncertainty)
  - Does not provide estimates of local maximum concentrations




# Mass Flux Measurement Uncertainty

- Measurement Uncertainty
  - (e.g., analytical precision)
- Model Uncertainty
  - (e.g., governing equations used to interpret the data)
- Interpolation Uncertainty
  - (e.g., unknown conditions between sampling points)

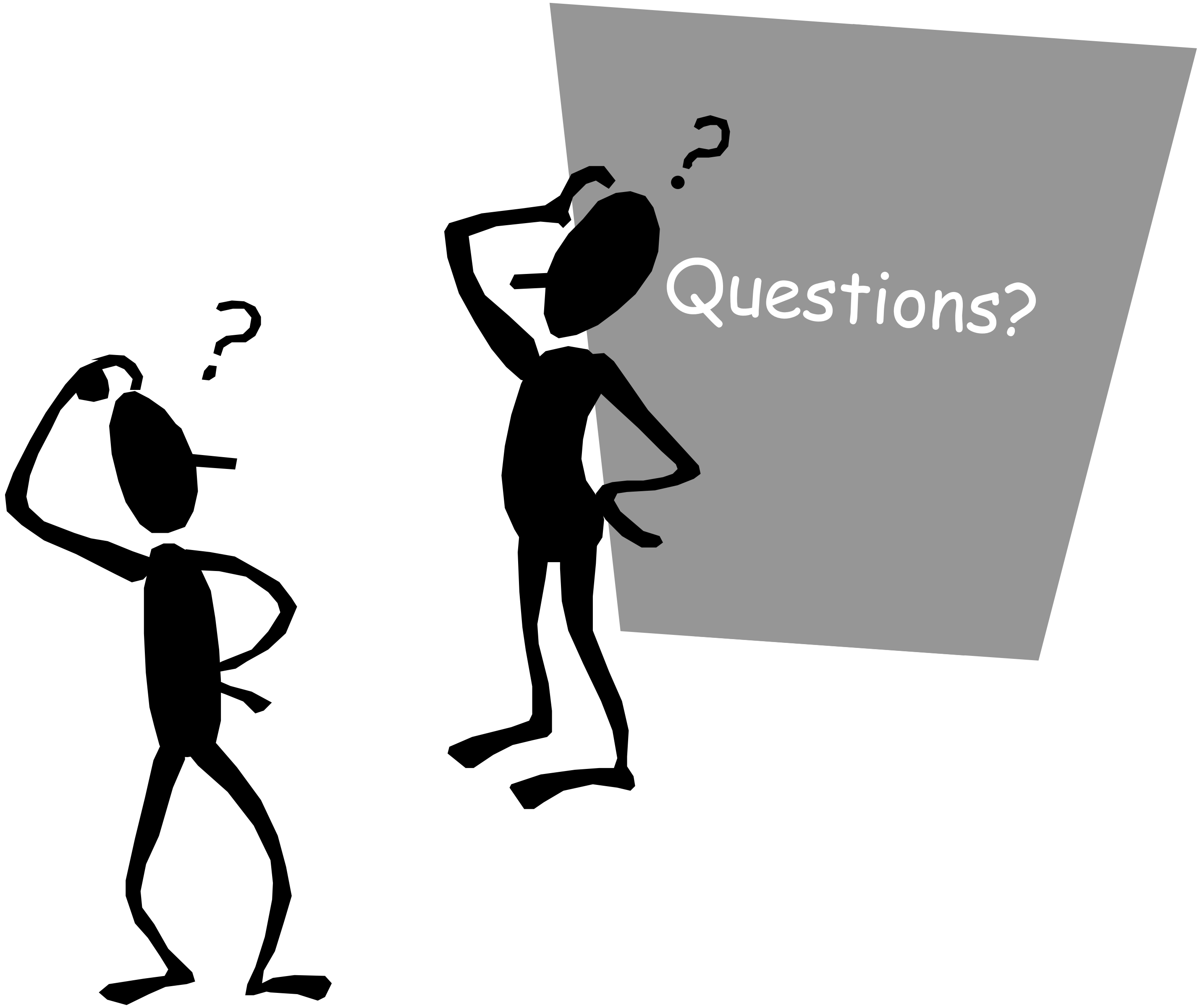
# Scale of the Measurement




Scale of device support volume relative to subsection?

# Summary

- Methods are currently available that can reliably measure both mass flux and mass discharge.
- Point measurement techniques are the best option to assess spatial distribution, but uncertainly arises from the unsampled space.
- Integrated pumping tests are less likely to miss potential hot spots compared to point measurements, but are limited in their ability to estimate spatial distributions.
- Importance of collaborative data sets; q = f(t) & J = f(t)


Questions?