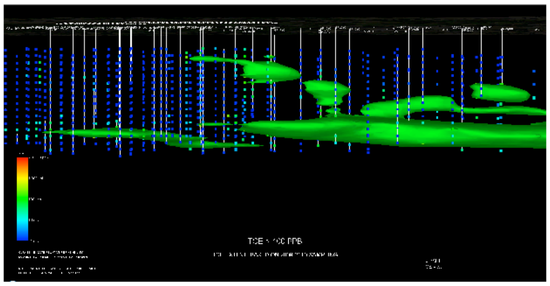
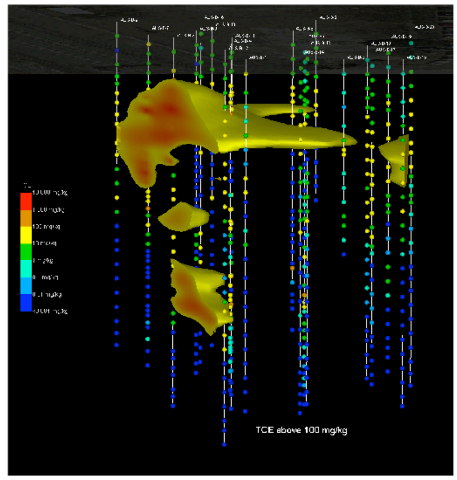
Detailed Structure in Large, Dilute Plumes

Developing Actionable Intel From the Sub-Surface





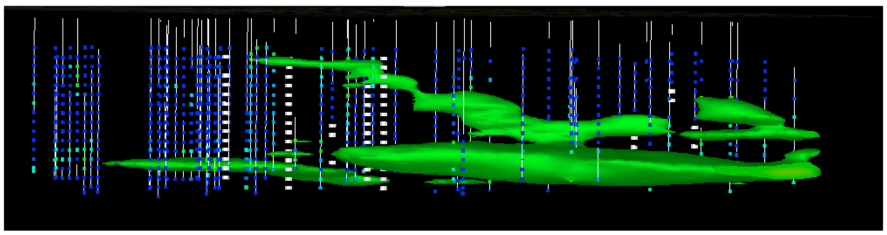
Fred C. Payne, Ph.D. FRTR Webcast – May 1 2013

Outline

- Higher Resolution Characterization ➪ Conceptual Model Adjustments
  - Overview of conceptual changes
  - Solving the Missing Mass Problem
  - Assimilative Capacities of Lower-Permeability Zones
- Tools and Strategies
- Case Studies
  - Mapping Transport at a Glacial Outwash Site
  - Directed Groundwater Recirculation in an Alluvial Fan Aquifer
  - Enhanced-Gradient Reagent Injection and Directed Groundwater Recirculation at Reese AFB

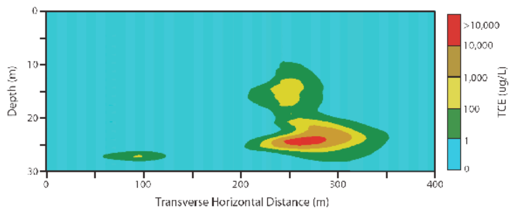
A New Conceptual Foundation
Decreasing dependence on simplifying assumptions

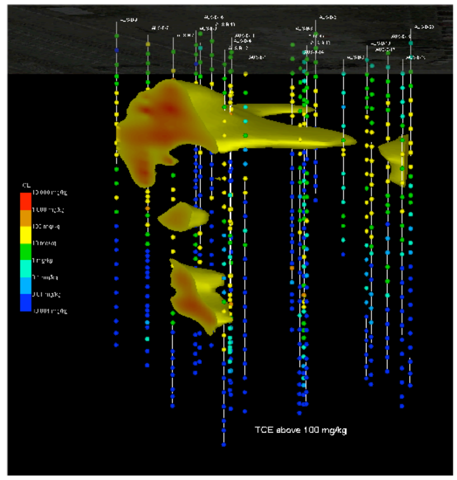
• Homogeneous	• Heterogeneous
• Isotropic	• Anisotropic
• Gaussian	• LogNormal
• Steady-State	• Perpetual Transient State



Re-Casting the Site Hydrogeology Framework

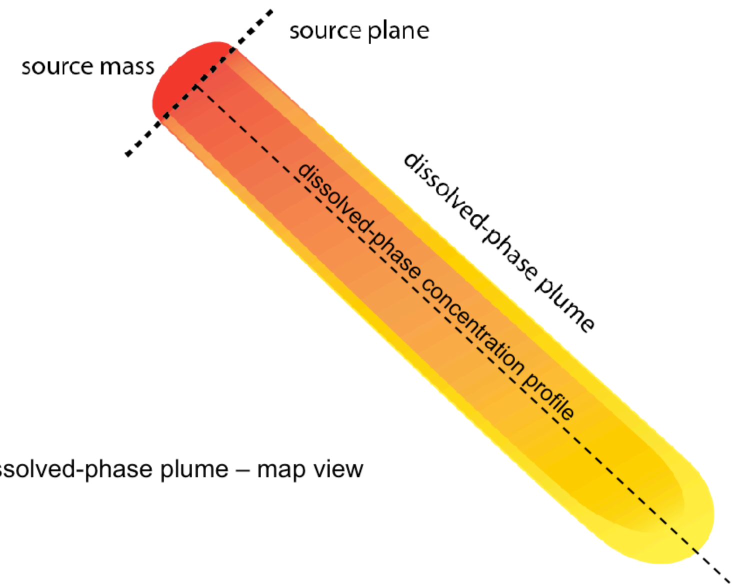
- Contaminant mass transport is often concentrated in a small portion of the aquifer cross-section
- Contaminant may enter storage along the transport pathways
- Remedies can be designed to take advantage of this distribution pattern



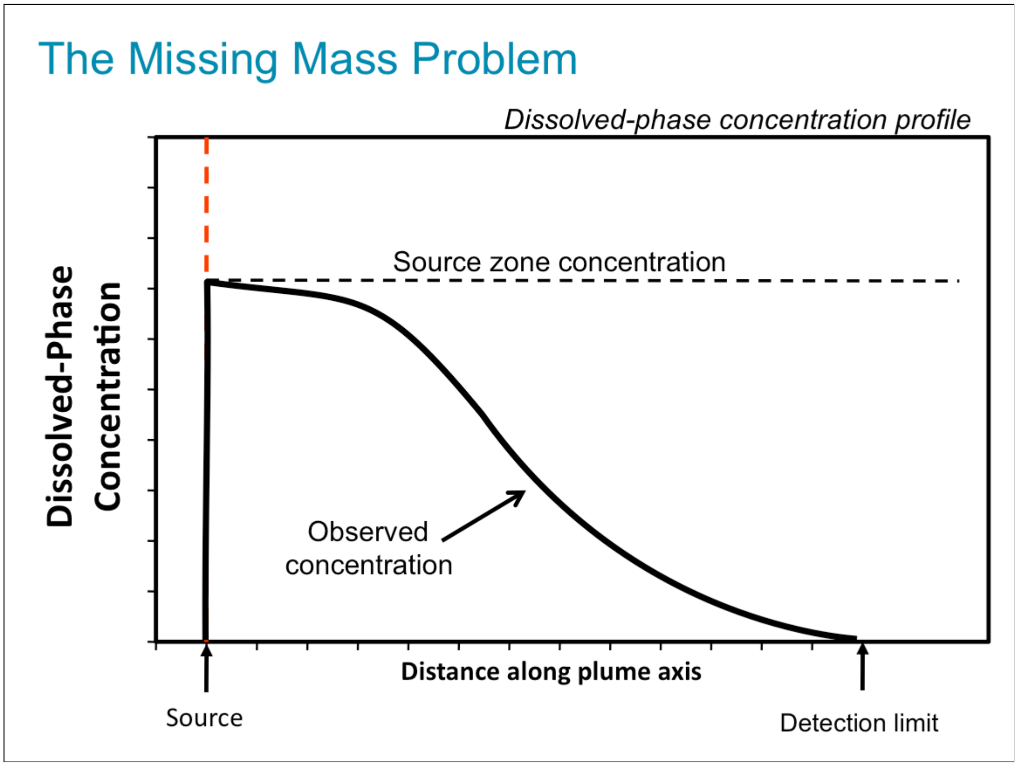


On-going DNAPL source zone characterization

The Missing Mass Problem



Dissolved-phase plume – map view

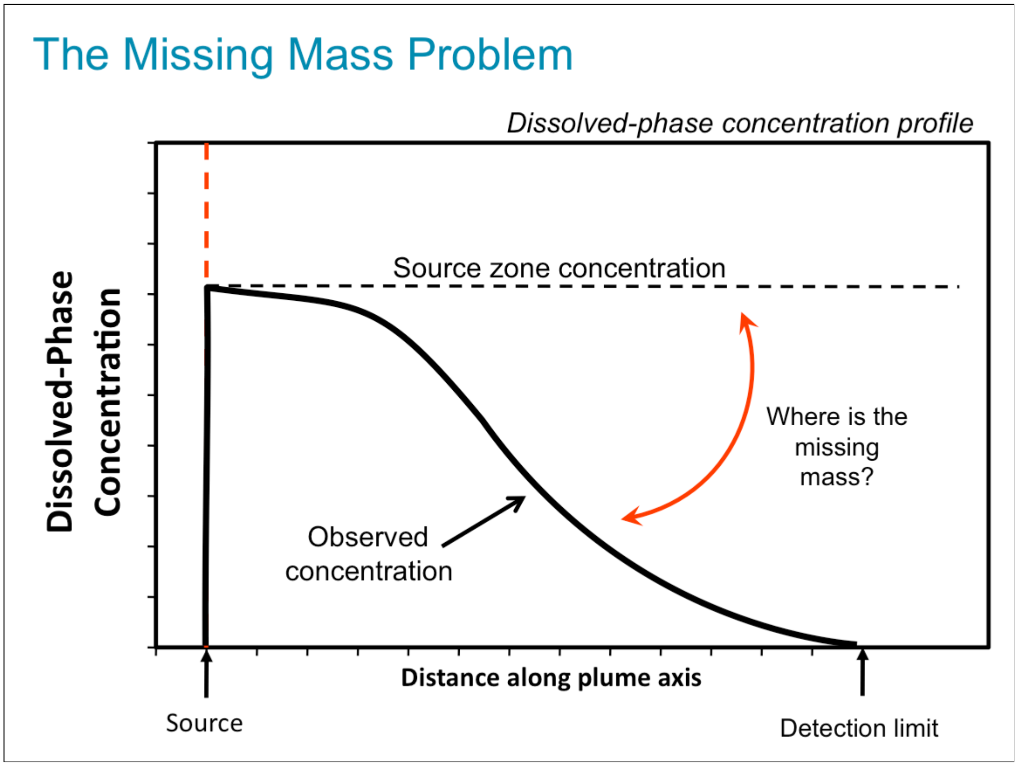


Contaminant concentrations typically decrease along the groundwater flow path.

In the now-abandoned advection-dispersion model, the decrease in concentration was attributed to dilution via random-walk plume spreading. High-resolution observations of injected tracers, as well as contaminant plumes, show that dispersive spreading of plumes does not occur and first-principles analysis suggests we should not expect that type of random spreading.

So, why do contaminant concentrations decrease along the flow path, when the cross-sectional area of the plume stays relatively constant? That observation is fully consistent with the advection-diffusion model, initially proposed by Guilham, Sudicky, Cherry and Frind (1984) and bolstered by the observations of Doner and Sale.

Concentrations decline due to mass lost to storage along the groundwater flow path, along with some amount of destruction.



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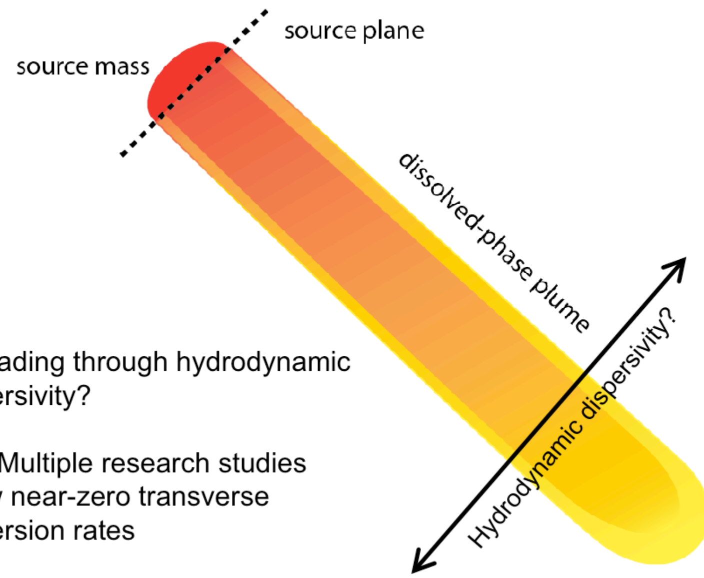
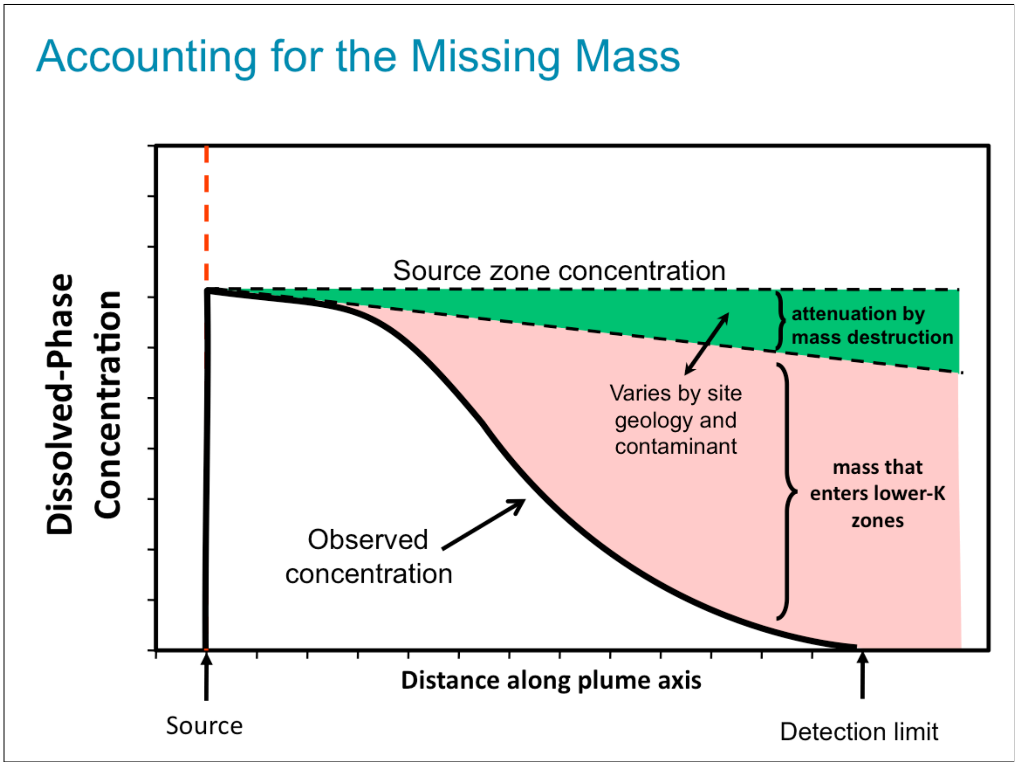
The Missing Mass Problem



Spreading through hydrodynamic dispersivity?

No. Multiple research studies show near-zero transverse dispersion rates



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Concentrations decline due to mass lost to storage along the groundwater flow path, along with some amount of destruction.

Missing Mass Problem Solved

- Multiple field research studies: the mass isn't spreading laterally
- Importance of aqueous-phase diffusion overlooked – now known as a significant mechanism in mass transport
- Near-permanent sequestration may occur in lower-K zones
- Slow-rate reactive processes may be very significant in lower-K zones
- Emerging understanding of the assimilative capacities of natural aquifers

Cape Cod Tracer Studies

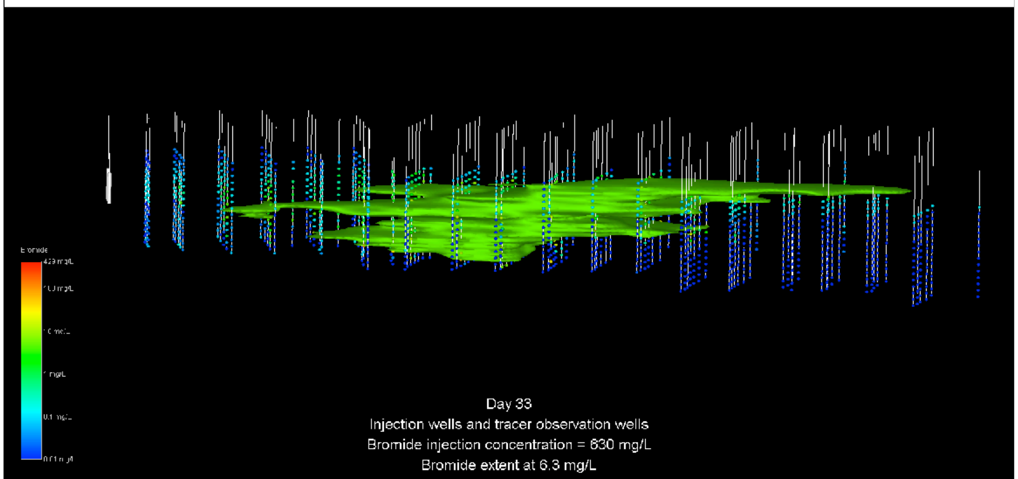
- LeBlanc, et al., 1991
- Garabedian and LeBlanc, 1991
- Hess, et al., 1992

- 3 tracer injection wells
- 656 multi-level samplers over 200-m flow path
- Garabedian and LeBlanc, 1991
- Transverse horizontal dispersivity = 1.8 cm
- Transverse vertical dispersivity = 1.5 mm

Cape Cod Tracer Studies

•A broad spectrum of transport velocities

•*Near-zero transverse dispersivities*



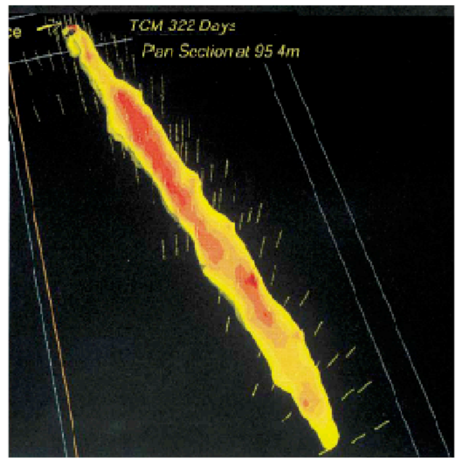
Near-zero transverse dispersivity

12

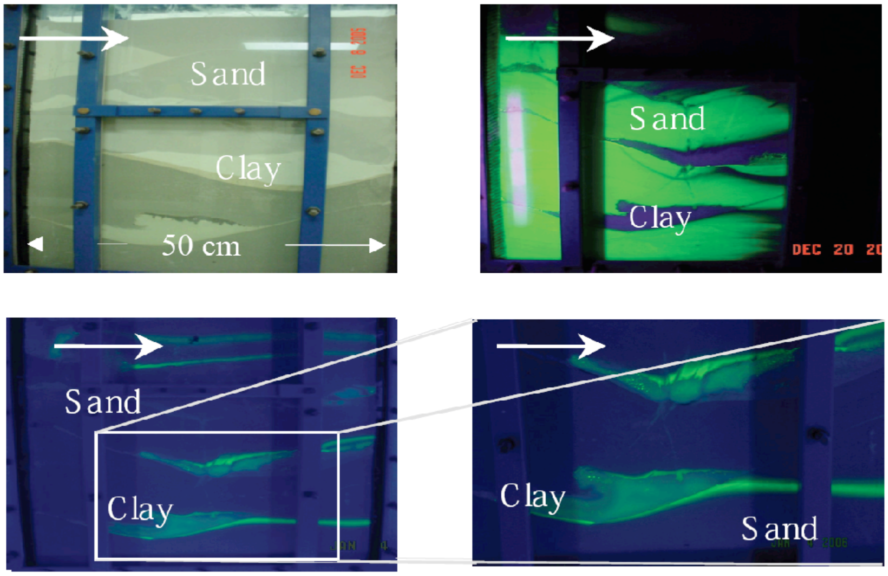
Field research repeatedly confirms that transverse dispersivity is near-zero

Borden aquifer studies – Rivett, Feenstra and Cherry

Natural aquifers show near-zero transverse dispersivity

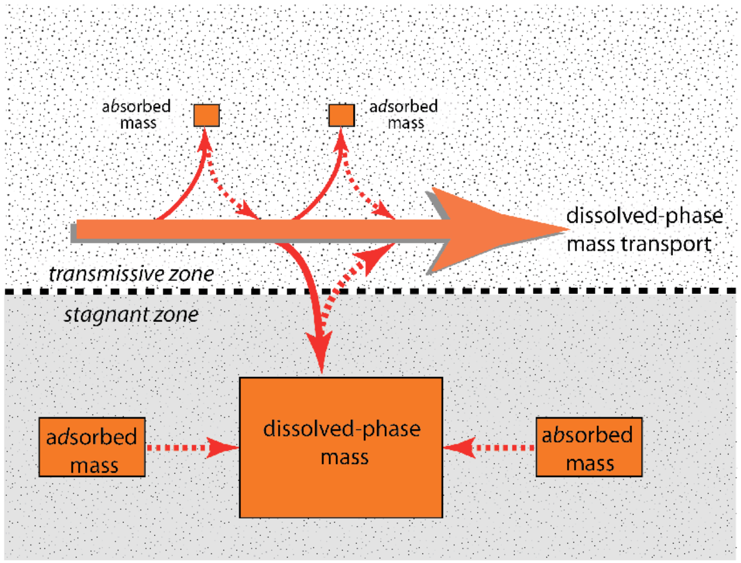


Back diffusion studies at Colorado State University

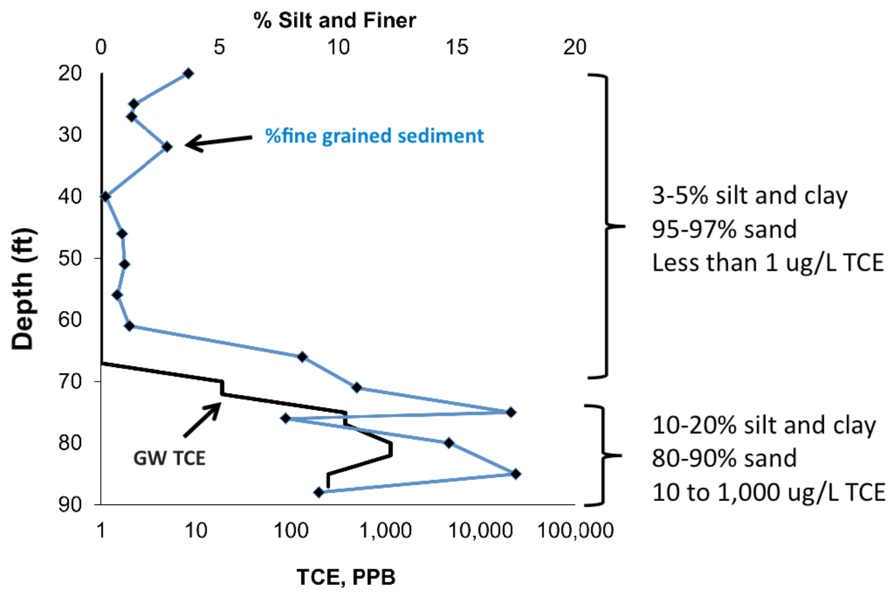


Courtesy Lee Ann Doner and Dr. Tom Sale, CSU

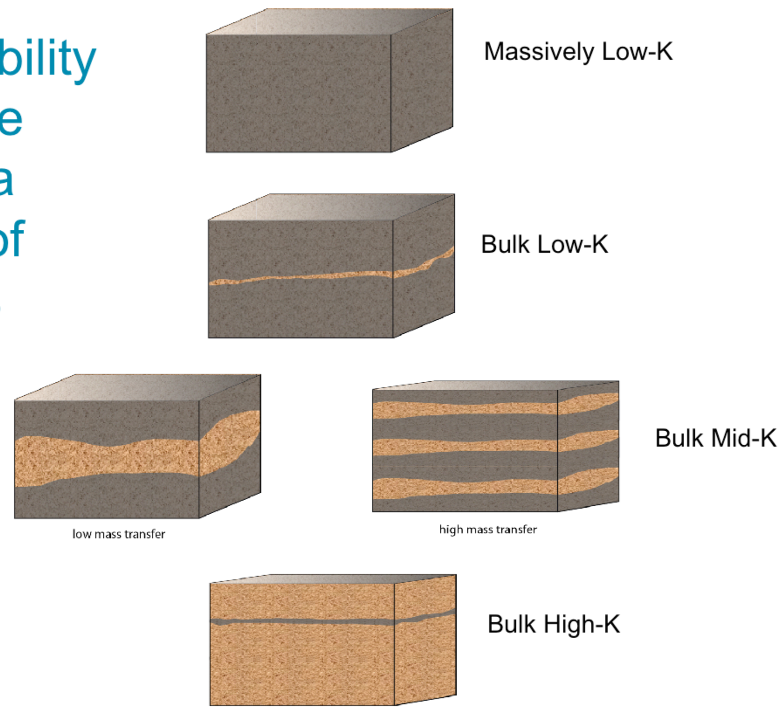
Role of Lower-Permeability Zones in Contaminant Assimilation



Late-Stage Example - Highest TCE concentrations are in lower permeability sediments



Permeability Structure Across a Range of Settings



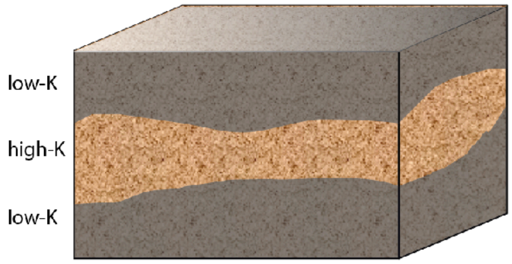
Aquifer Matrix Effects

Two aquifer blocks with equal:

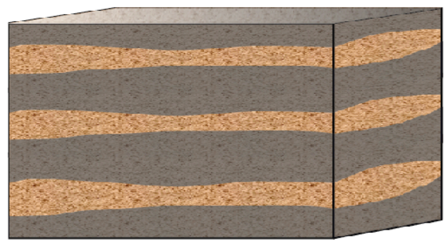
- Average hydraulic conductivity
- Transmissive pore fraction
- Groundwater transport velocity

In the high-mass-transfer geometry, the rate of diffusive migration into the low-K zones is approximately 10-fold greater than for the low-mass-transfer case.

- Increased exchange surface area
- Decreased diffusion path lengths



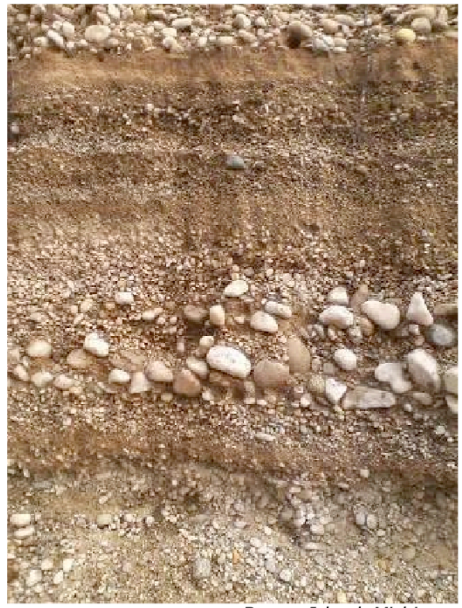
low mass transfer



high mass transfer

A Synopsis of the ‘Take-aways’

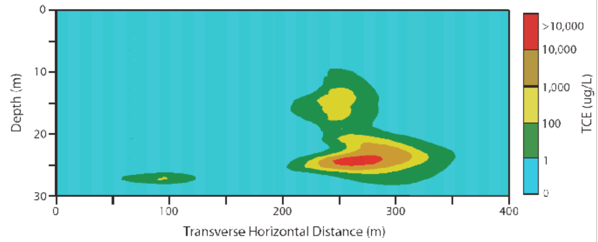
- Patterns Emerging from Intensified Site Characterization
  - Heterogeneous, anisotropic structure
  - Extreme low dispersivities
- Large-Plume Conceptual Model
  - Transport in transmissive zones
  - Storage in less-transmissive zones
  - Mass exchange rates are a critical factor
- New Opportunities Arise
  - Remedial strategies (e.g., directed groundwater recirculation)
  - Compliance (e.g., dynamic groundwater monitoring)



Beaver Island, Michigan

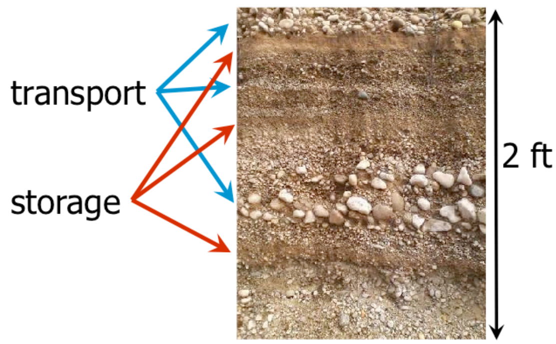
Impacts and Opportunities

- Contaminant mass transport is often concentrated in a small portion of the aquifer cross-section
- Remedies can be designed to take advantage of this distribution pattern



However,

- High-resolution sampling is also unmasking contaminant mass storage – High-C, Low-K zones
  - Mass transfer behavior controls remedy design and success
  - ***Now we can identify and target the critical zones***



We need to add some insight here

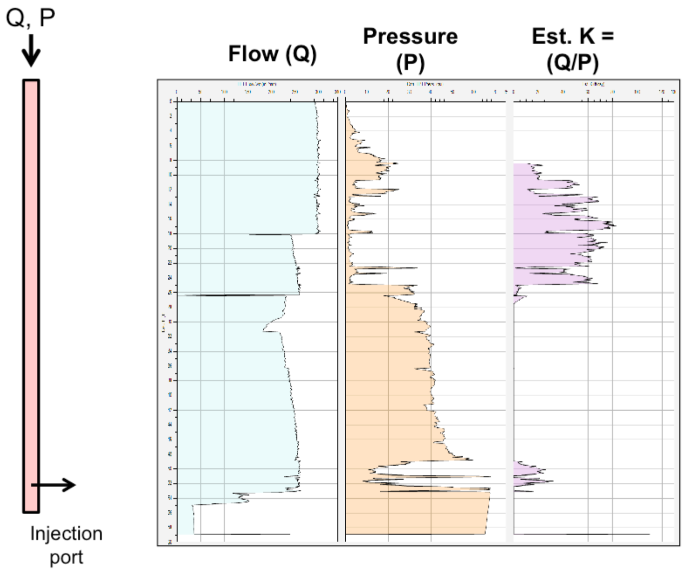
Tools and Strategies

- Separation of characterization and monitoring functions
- Re-thinking monitoring wells
- Higher-resolution characterization tools
  - Hydraulic profiling tools (HPT)
  - Vertical aquifer profiling (VAP)
  - Whole-core analysis

Re-Thinking Monitoring Wells

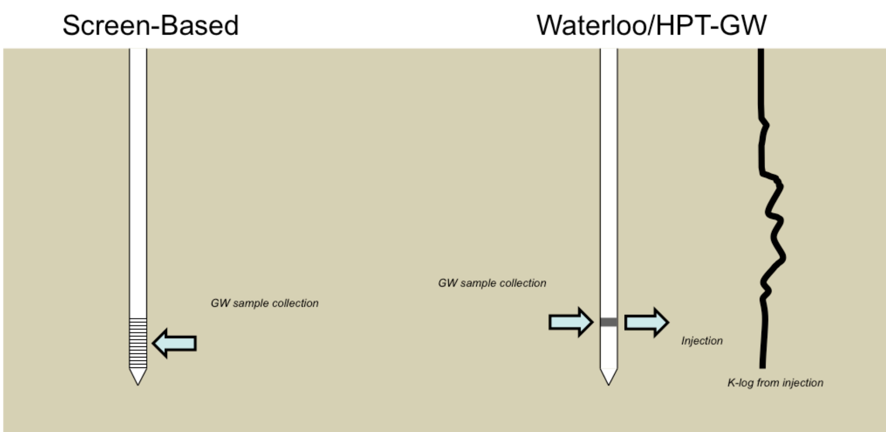
- 10-year life-cycle cost of a single monitoring well ~ $150,000 (construct, develop, monitor and report quarterly, abandon)
- Better approach – ***separate site characterization from monitoring well construction*** – characterize, then determine most effective monitoring well locations.
- Yields a significant reduction in the number of monitoring wells

Hydraulic Profiling Tool - Estimating Hydraulic Conductivity (K)



- Corrected for empirical relationship between Q/P and K measured using slug tests
- Est K represents a relative permeability for the borehole

Vertical Aquifer Profiling

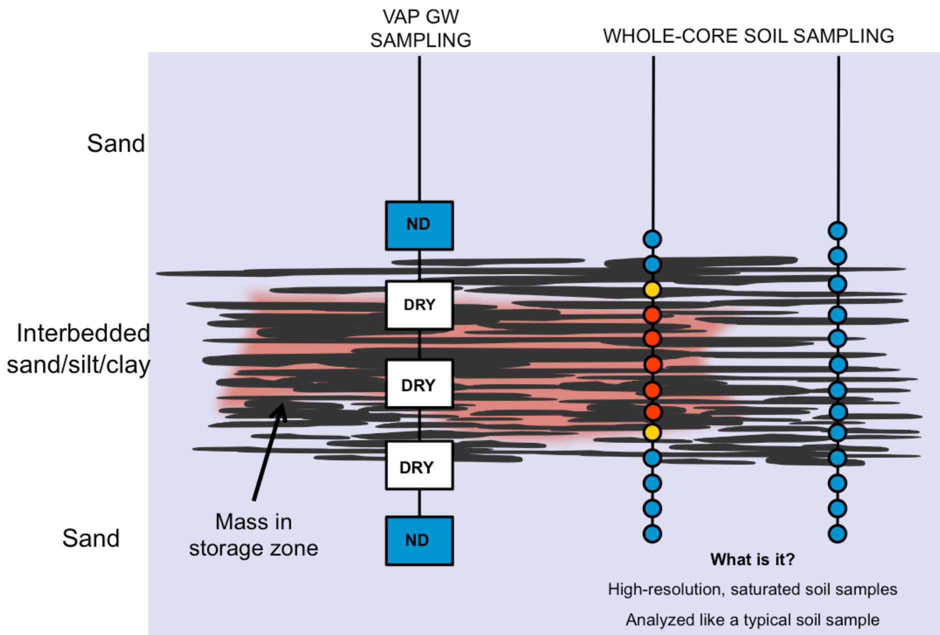


- Multiple-push
- Able to sample moderate-lower K
- Cost-effective for lower #s of samples
- No K-data integrated
- Slug-testing possible

- Single-push
- Slow/no sampling in moderate-lower K zones
- Cost-effective for higher #s of samples
- K-data integrated
- No slug testing

Depths: 100+ ft reachable with direct-push GeoProbe 8040 rigs

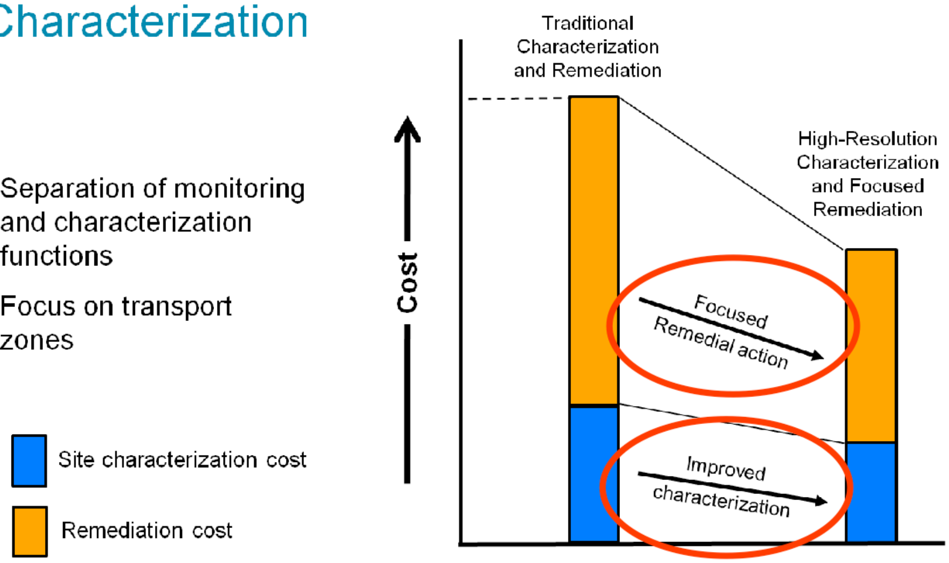
Whole-Core Sampling



Next Generation Site Characterization

Separation of monitoring and characterization functions

Focus on transport zones



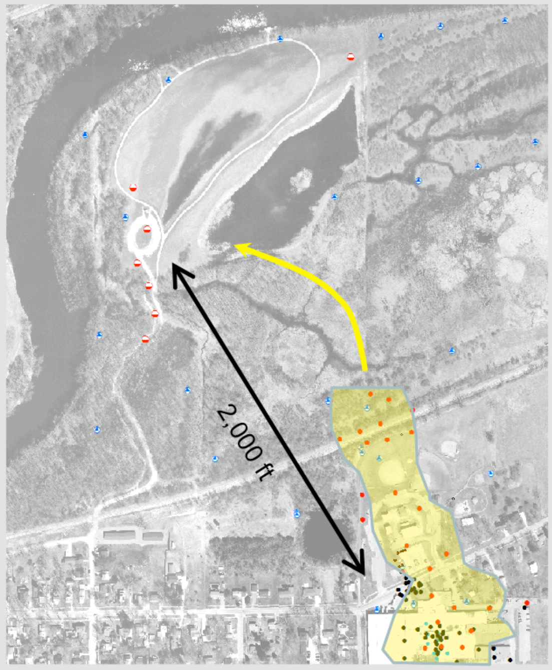
Case Studies

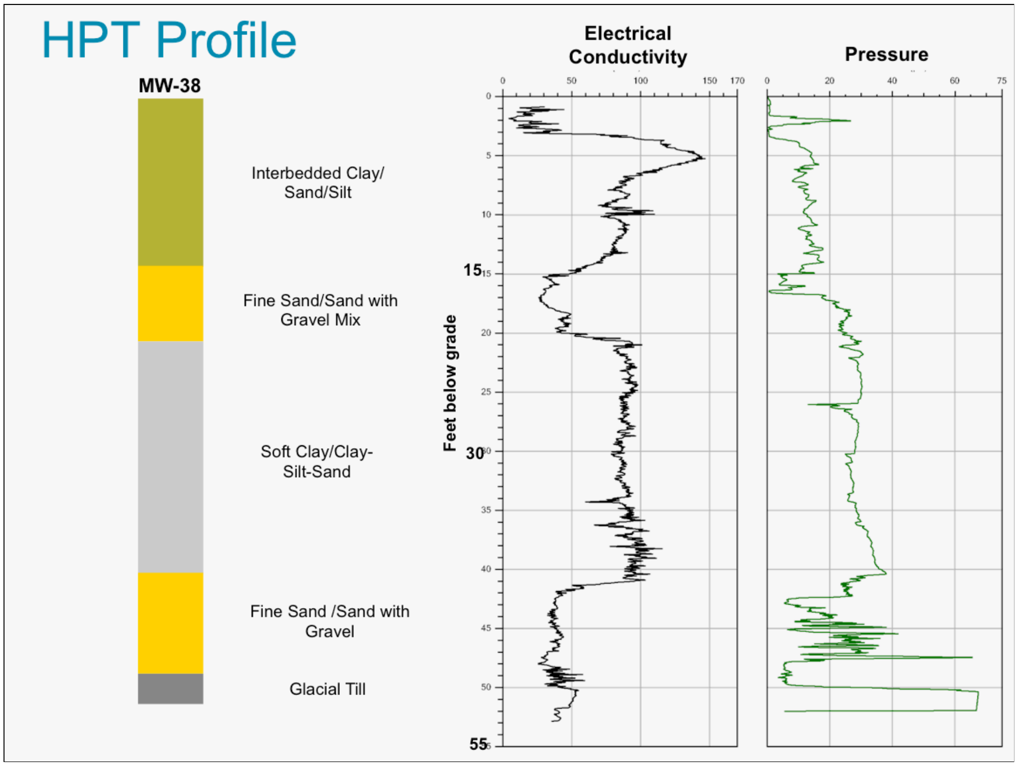
1. Mapping mass transport in glacial outwash
2. Directed groundwater recirculation in an alluvial fan aquifer
3. Enhanced-gradient flushing and directed groundwater recirculation in the Ogallala Aquifer

Case 1

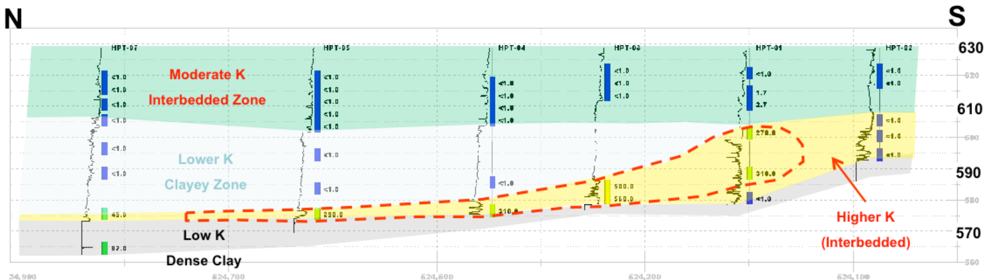
Mapping contaminant transport

- TCE in glacial outwash
- Relative mass flux mapping

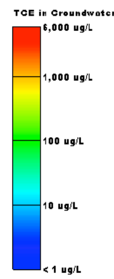


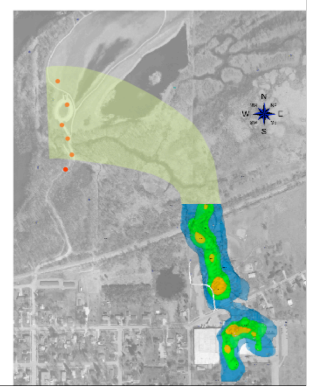

HPT Profile
MW-38
Interbedded Clay/ Sand/Silt
Fine Sand/Sand with Gravel Mix
Soft Clay/Clay- Silt-Sand
Fine Sand /Sand with Gravel
Glacial Till
Electrical Conductivity
Pressure
Feet below grade
15
30
55

HPT Long-Section

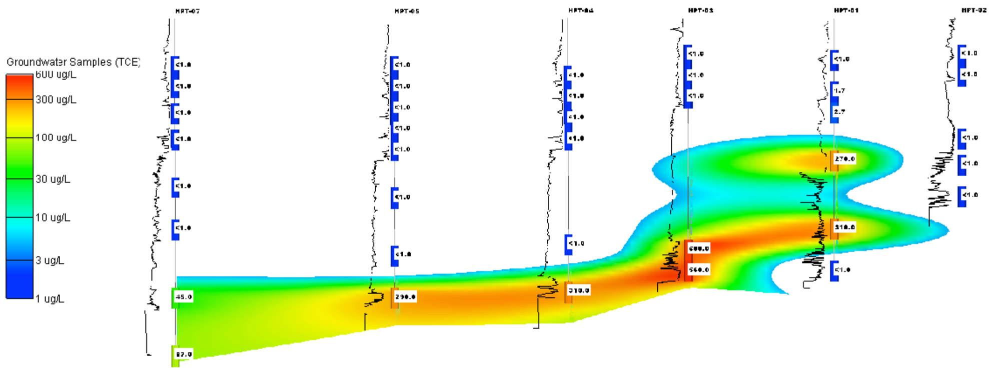


- TCE focused in deep high-K fluvial deposits
- Plume spreads into valley fill channels



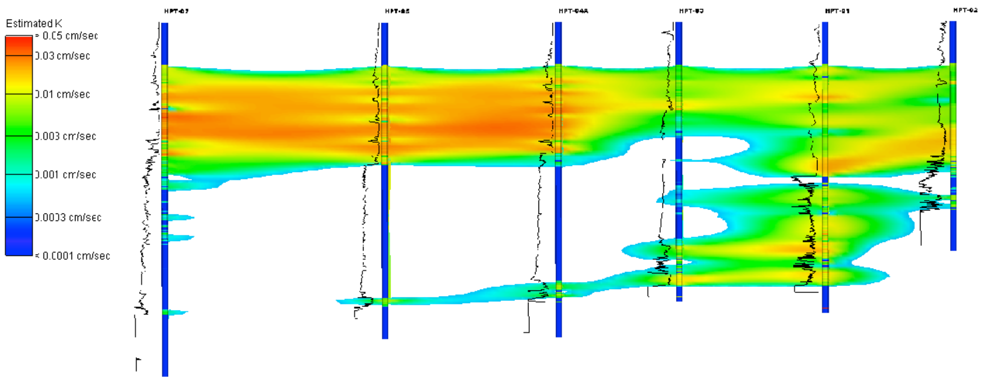


TCE Concentration (C)



Interpolated concentration between borings

Estimated K by Hydraulic Profiling Tool

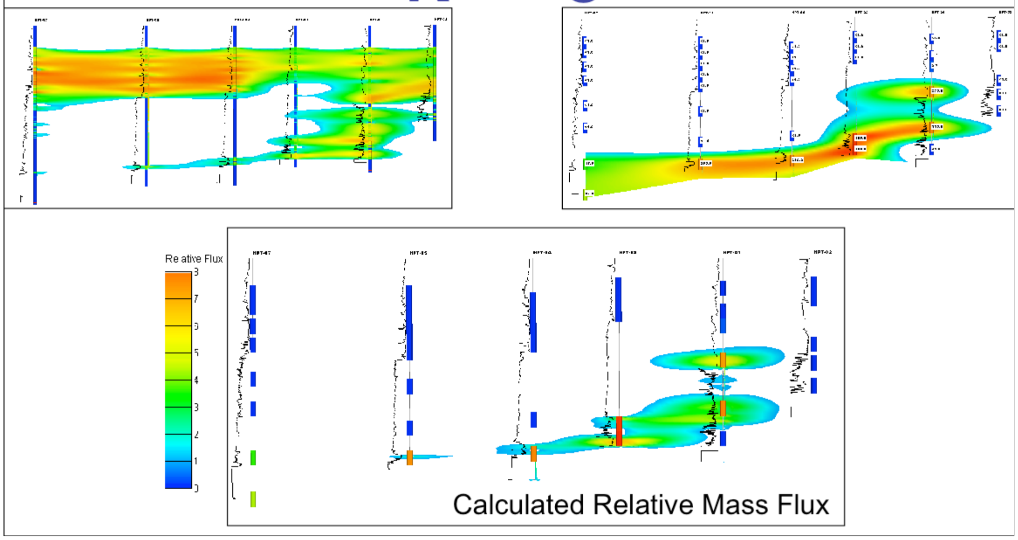


- Estimated K consistent with river valley morphology
- Fluvial morphology creates deep higher-K channel

Relative Mass Flux

Multiply calculated fields: yields a relative measure of mass flux

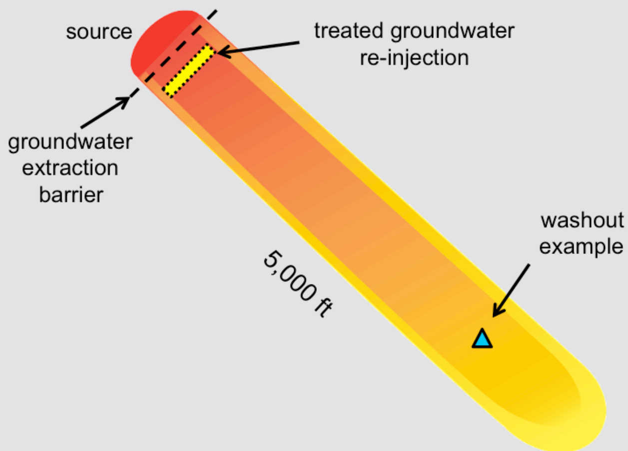
K x **C**



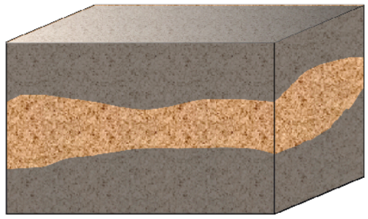
Case 2

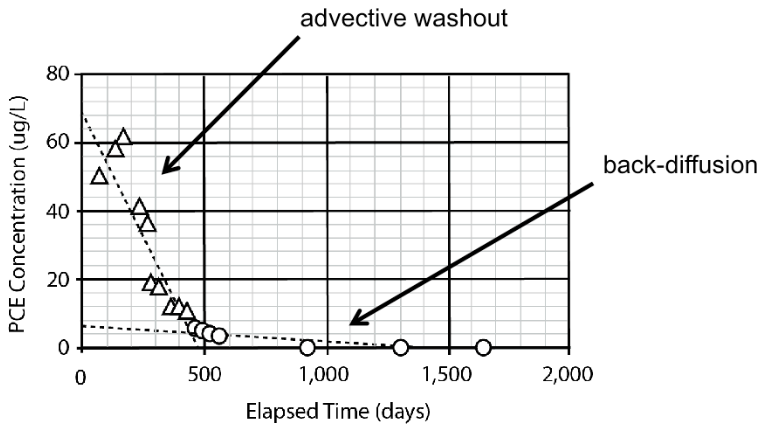
Directed Groundwater Recirculation

- Alluvial fan aquifer – 10 ft/day velocity
- Mixed NAPL source – removed
- Groundwater extraction, treatment and re-injection (directed groundwater recirculation)



Bi-Modal Washout in an Alluvial Fan



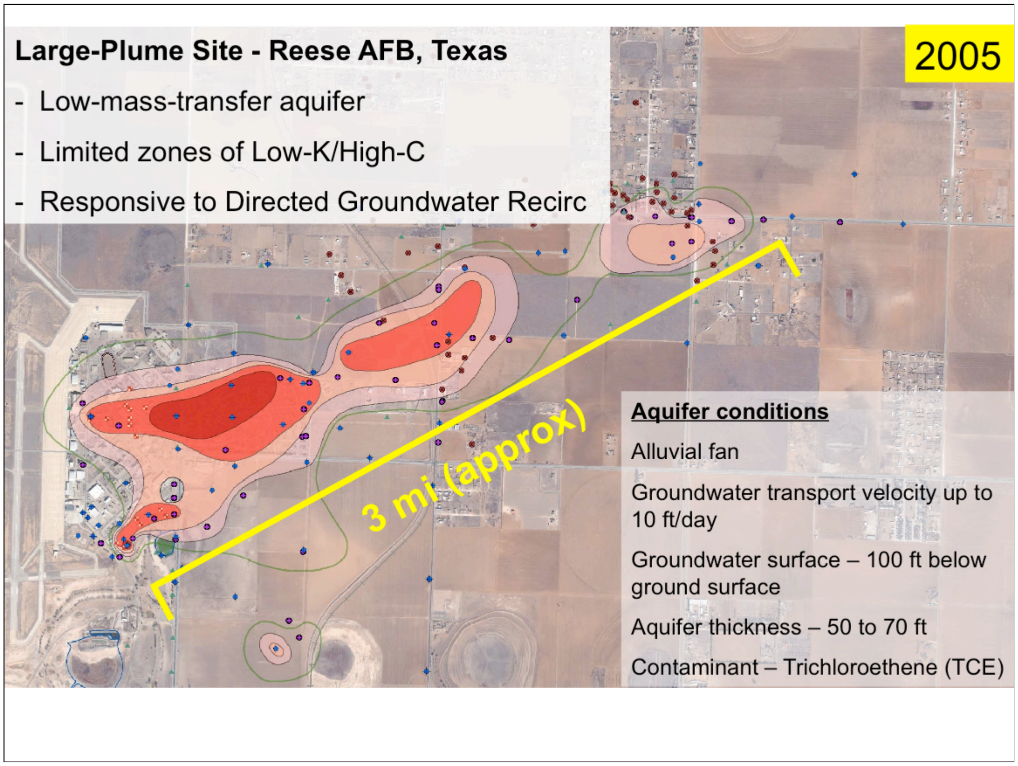


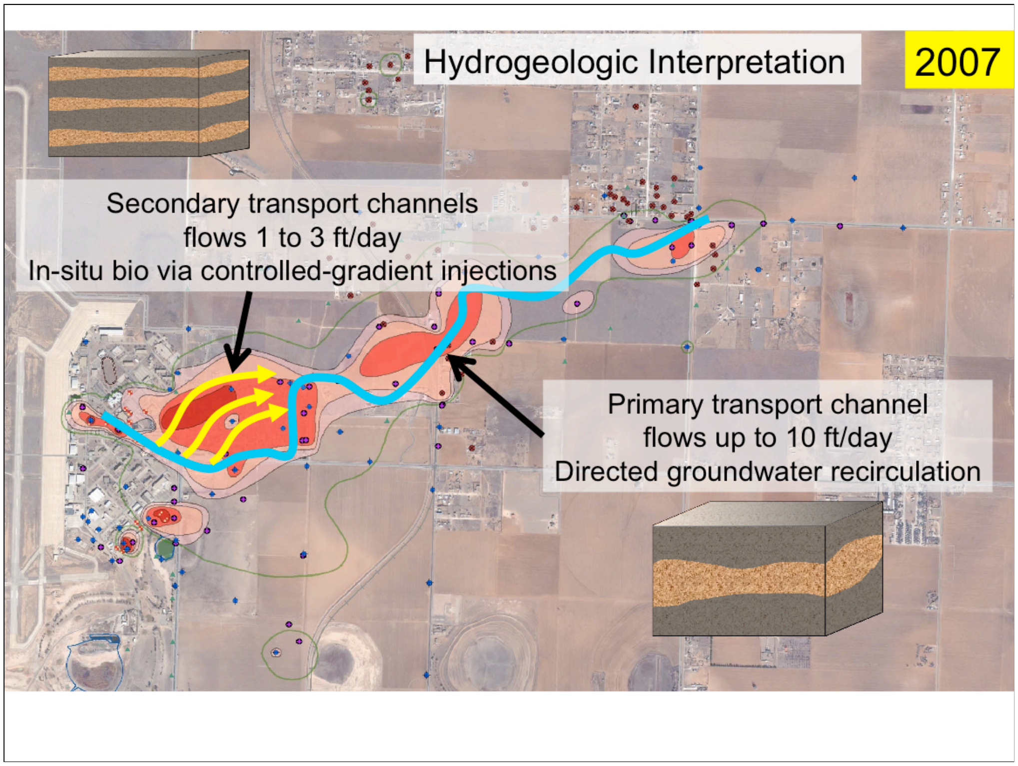
Case 3

Directed Groundwater Recirculation

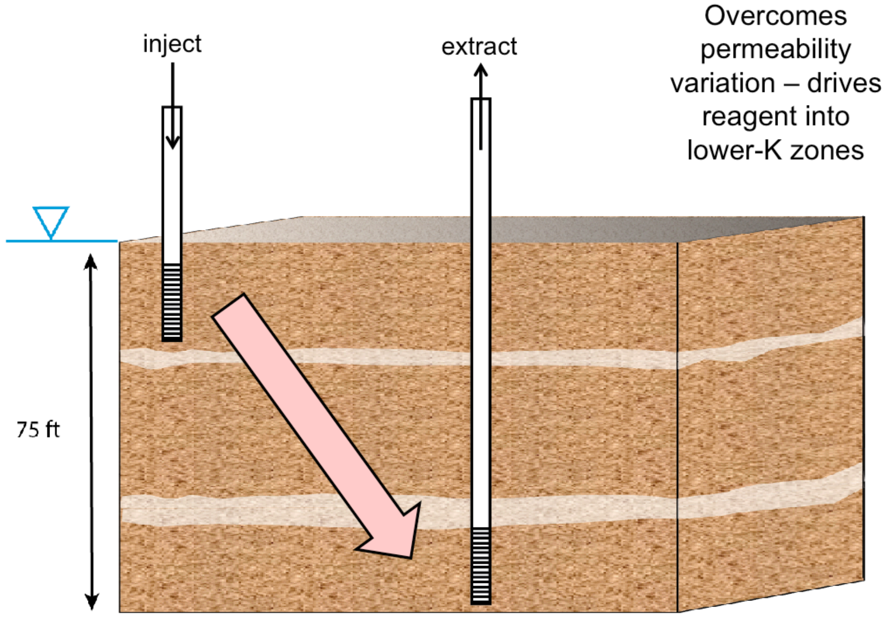
Reese AFB

- Ogallala (alluvial fan) aquifer – 1 to 10 ft/day velocity
- Vadose zone TCE source – removed
- 18,000-ft dissolved-phase plume
- Controlled-gradient reagent injection (approximately 100 acres)
- Groundwater extraction, treatment and re-injection (directed groundwater recirculation)

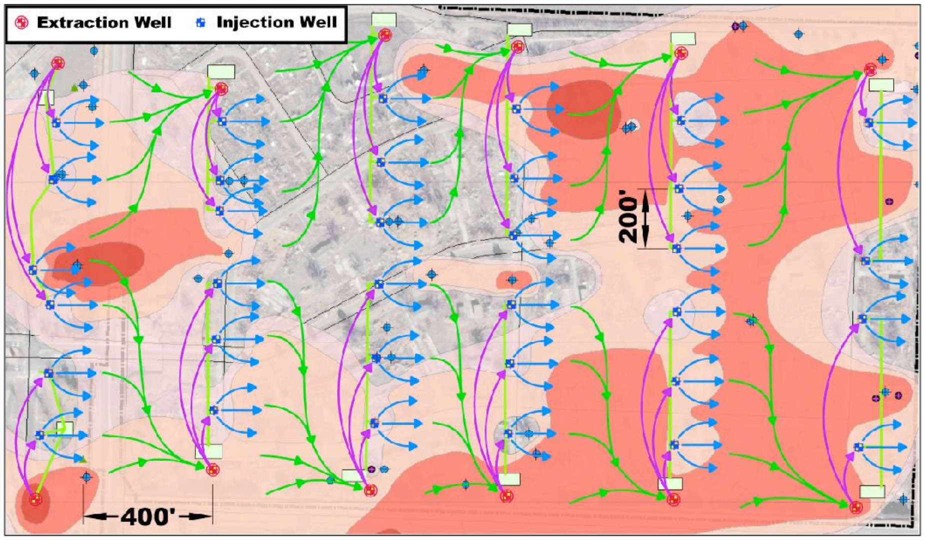

Large-Plume Site - Reese AFB, Texas
- Low-mass-transfer aquifer
- Limited zones of Low-K/High-C
- Responsive to Directed Groundwater Recirc
2005
3 mi (approx)
Aquifer conditions
Alluvial fan
Groundwater transport velocity up to 10 ft/day
Groundwater surface – 100 ft below ground surface
Aquifer thickness – 50 to 70 ft
Contaminant – Trichloroethene (TCE)


Hydrogeologic Interpretation
2007
Secondary transport channels
flows 1 to 3 ft/day
In-situ bio via controlled-gradient injections
Primary transport channel
flows up to 10 ft/day
Directed groundwater recirculation

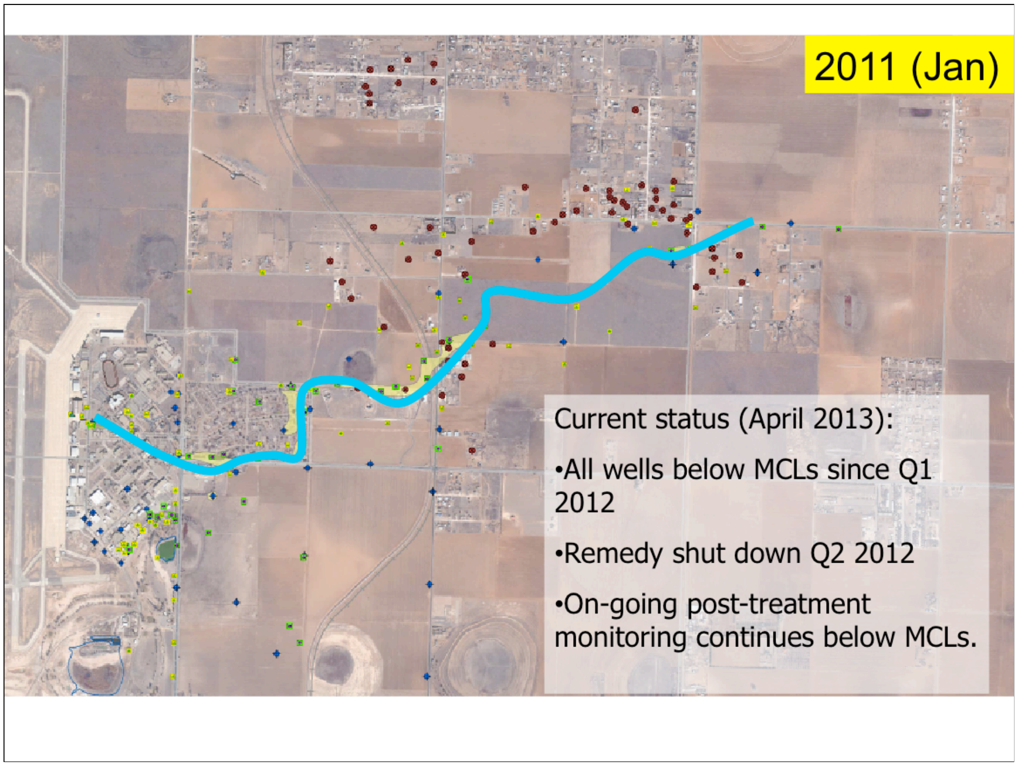
Controlled-Gradient Reagent Distribution



Controlled-Gradient ERD Zone




2010
Primary transport channel


2011 (Jan)
Current status (April 2013):
•All wells below MCLs since Q1 2012
•Remedy shut down Q2 2012
•On-going post-treatment monitoring continues below MCLs.


Questions and Discussion
For more information, contact:
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Fred.Payne@arcadis-us.com
ARCADIS