Site Characterization and Data Interpretation for Evaluation of Natural Attenuation at Hazardous Waste Sites

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Site Characterization and Data Interpretation for Evaluation of Natural Attenuation at Hazardous Waste Sites

Kelly Hurt

National Research Council

R.S. Kerr Environmental Research Center
Ada, OK
(580) 436-8987
hurt.kelly@epa.gov

The most common site characterization question.

How many wells are enough?

The Two Most Common Answers

- **As many as you can get.**
- **It's site specific.**

Review of the current state of practice for site characterization.

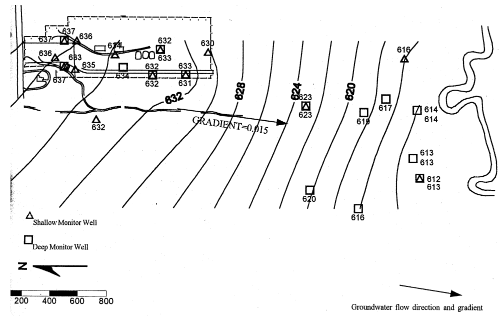
"State of the Practice"

- **Install monitoring wells to determine ground-water flow direction.**
- **Install additional monitoring wells downgradient of the source area to define the extent of contamination.**

“State of the Practice”

- Determine whether the plume is expanding, steady-state or shrinking.
- Determine whether the plume has impacted or will impact receptors.

A Typical Site

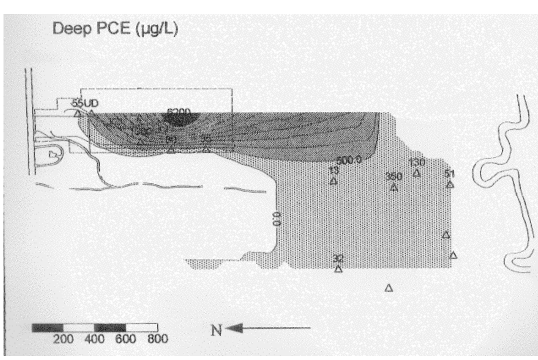


- **Upgradient monitoring wells were used to define background conditions in the aquifer.**
- **Additional wells were installed along the *inferred* centerline of the plume.**
- **Wells were placed on the lateral and terminal edges of the plume.**

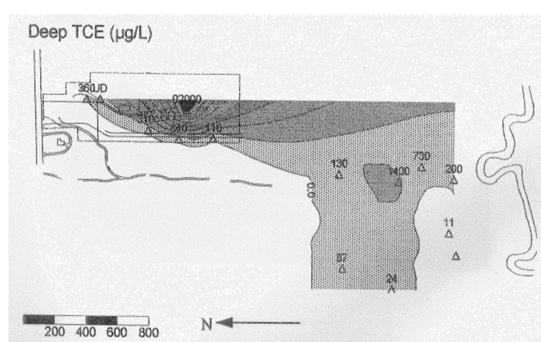
Typical Data Presentation

- **Contour maps depict concentration profiles of a variety of parameters.**
- **These maps show the *size* and *shape* of the contaminant plume and distribution of geochemical parameters.**
- **Data are presented in terms of surface area impacted.**

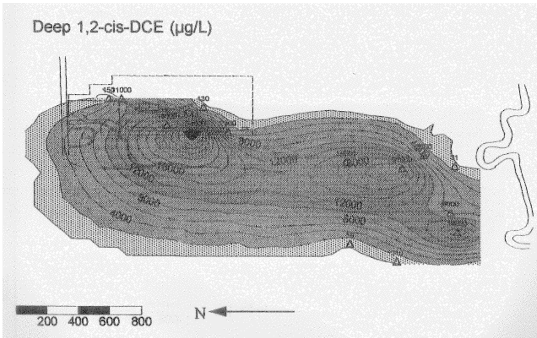
PCE (ppb)



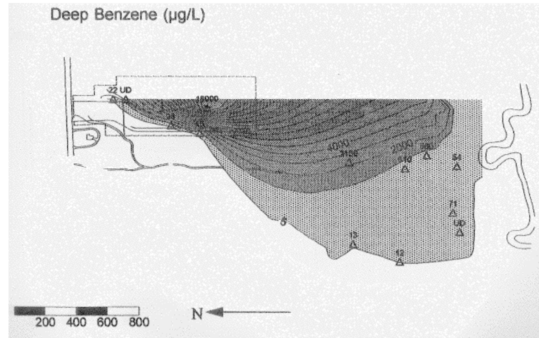
TCE (ppb)



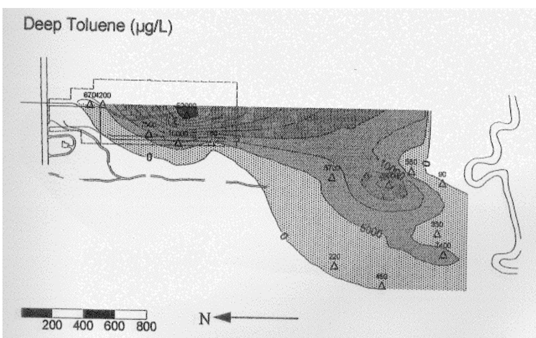
cis-DCE (ppb)



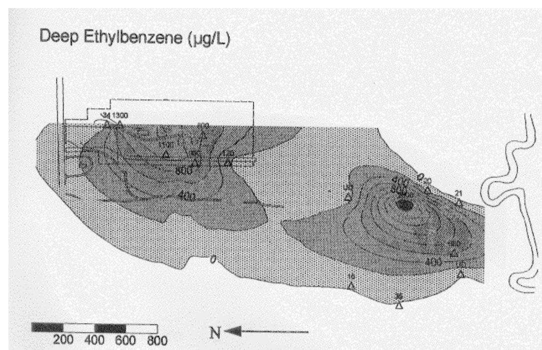
Benzene (ppb)



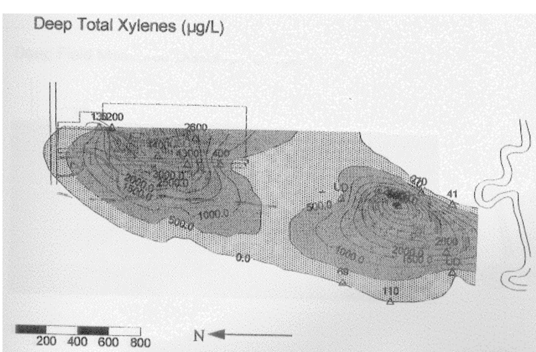
Toluene (ppb)



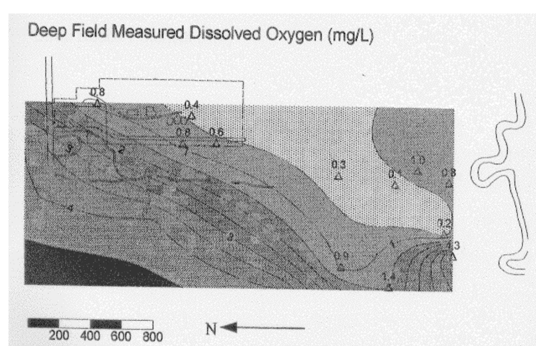
Ethylbenzene (ppb)



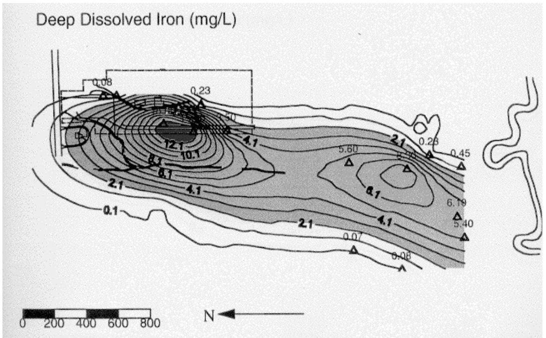
Xylene (ppb)



Oxygen (mg/L)



Iron (II) (mg/L)



Rules of Thumb for Site Investigations

- Dissolved oxygen is directly proportional to redox potential.
- Dissolved oxygen concentrations are inversely proportional to iron II and alkalinity concentrations.

Rules of Thumb for Site Investigations

- Alkalinity concentrations are directly proportional to iron II, but iron II is not necesarrily directly proportional to alkalinity.

Typical Site Characterization

- Designed to determine absence or presence of contamination.
- Not designed to describe how the plume is behaving.

Typical Site Characterization

- Typically uses permanent monitoring wells to map the contaminant plume.
- Emphasizes concentrations of contaminants of concern.

Typical Site Characterization

- Does not emphasize hydrogeologic characterization of the site. At best, it uses slug testing to estimate the transmissivity of the screened interval.

Typical Site Characterization

- Conceptualizes the plume as a static object in 2-D space

- There is a fundamental difference in the requirements for site characterization if natural attenuation is to be evaluated as a remedy.

Selection of natural attenuation as a remedy demands a higher level of understanding of mechanisms acting on the contaminant plume than needed for other remediation techniques. Therefore, more importance is given to collecting data from within the plume.

Contour maps do not provide information on the rate of ground-water flow, the flux of contamination being released from the source area, the quantity of contaminant in the plume, or the flux of contaminant to surface waters or other receptor.

An Iterative Approach to Fate and Transport

- Typically uses push technology to map the contaminant plume.
- Emphasizes the concentrations of geochemical indicators, as well as contaminants.

An Iterative Approach to Fate and Transport

- Concentration data are also organized to determine the flux of contaminant in the entire plume from the source, along the flow path and to the receptor.

Calculation of Contaminant Flux Along the Flowpath

- **The reduction in the flux along the flowpath is the best estimate of natural attenuation of the plume *as a whole*.**

Calculation of Contaminant Flux Along the Flowpath

- **The flux is the best estimate of the amount of contaminant leaving the source area. This information would be needed to scale active remedy if necessary.**

Calculation of Contaminant Flux Along the Flowpath

- **Flux estimate across the boundary to a receptor is the best estimate of loading to a receptor.**

An Iterative Approach to Fate and Transport

- **Has a greater investment in hydrogeological characterization.**
- **More conservative estimates of transmissivity are produced by conducting pumping tests.**

Benefits of an Iterative Approach to Fate and Transport

- **Higher resolution site characterization.**
- **Optimization of well placement.**
- **More representative data.**
- **Better understanding of the fate and transport of contaminants.**

Thermo Chem Case Study

Purpose of the Case Study

- Compares three levels of characterization; (1) Conventional wells widely spaced, (2) Dense array of conventional wells in transects, (3) GeoProbe transects.

Purpose of the Case Study

- The dense array of conventional wells arranged in transects are assumed to yield correct data.

Purpose of the Case Study

- Results from the dense array of conventional wells are compared to a dense array of GeoProbe samples to evaluate the performance of push techniques.

Purpose of the Case Study

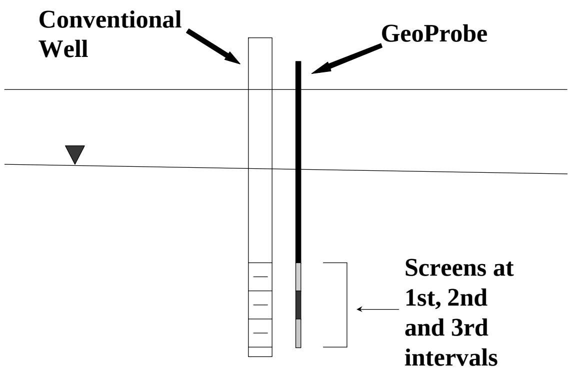
- Results from the dense array of conventional wells are compared to a conventional array of monitoring wells to determine the resolution of conventional monitoring strategies.

Benchmarking Direct-Push Technology Against Permanent Wells

- Hydraulic Conductivity Tests
- Contaminant Data
- Geochemical Data

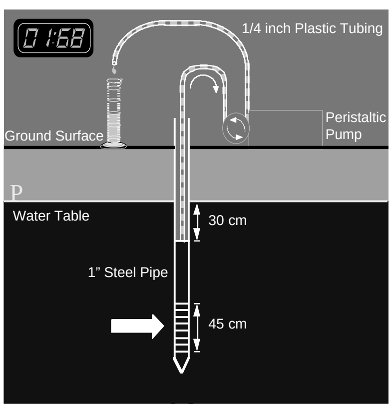
Hydraulic Conductivity Tests

- A GeoProbe unit was used to estimate hydraulic conductivity values at the same depth intervals as existing conventional monitoring wells.



K Tests

- Single well pumping test (Specific Capacity)
- Measure discharge and drawdown



K Tests

- 1.5' GeoProbe screens
- Permanent monitoring well screens ranged from 4 to 9 ft.
- Comparison was conducted over the same interval.
- Distance between the push probe and monitoring well varied from 3 to 10 feet.

Data Analysis

- Jacob's solution to the Theis equation was used to estimate transmissivity .

Jacob's Solution (1946) to the Theis Equation

$$\frac{Q}{\Delta s} = \frac{T}{264 \log\left(\frac{0.3Tt}{r^2 S}\right)}$$

- Q = pumping rate, gpm
- s = drawdown in the well, ft
- T = transmissivity, gpd/ft (assume 30,000 gpd/ft initially, then revise with first estimate from calculations)
- t = time since pumping started, days

- r = radius of the well, ft
- S = storativity, dimensionless (.001 for a confined aquifer, .075 for unconfined aquifers)

The known parameters can be substituted into the equation and simplified for easier use.

For example, when using a direct push well

- T = 30,000 gpd/ft
- t = 0.01 days
- r = 0.04 ft
- S = .075

The equation can be simplified to

$$T = 1550\left(\frac{Q}{\Delta s}\right)$$

For example, when using a direct push well

- T = 30,000 gpd/ft
- t = 0.01 days
- r = 0.16 ft
- S = .075

The equation can be simplified to

$$T = 1230\left(\frac{Q}{\Delta s}\right)$$

Then substitute the measured Q and drawdown to get an estimate of T.

Divide T by screen length to get a relative estimate of K for the interval tested.

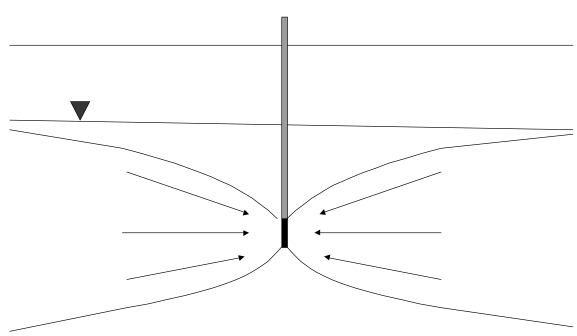
Assumptions

- **Borehole storage is negligible**
- **Horizontal flow.**
- **Late-time conditions are reached quickly.**
- **100% efficient wells.**
- **Laminar flow exists throughout the well and aquifer.**

Partial Penetration

- **Since the GeoProbe screens are only partially penetrating, estimates of K average conductivities from above and below the interval being tested due to radial flow.**

Partial Penetration of an Aquifer by a GeoProbe Screen



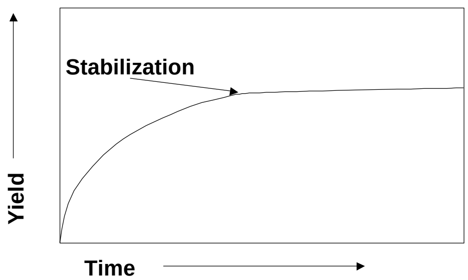
Late Time Conditions

- **Early time data may be invalid for use with the Jacob Solution to the Theis equation.**

Late Time Conditions

- **The Jacob equation largely ignores the effect of time on pumping yield. The calculation of u, an evaluation parameter, is necessary to ensure that the asymptote has been reached.**

Late Time Conditions



Late Time Conditions

- **If the calculated u is less than 0.05, then the assumption of late time conditions is justified.**

Late Time Conditions

$$u = \frac{1.87\ r^2\ S}{Tt}$$

Late Time Conditions

- **For example, when r = 0.5 in. (0.04 ft), S = 0.075, T = 5000 gpd/ft, and t = 20 min (0.01 days):**

Late Time Conditions

$$u = \frac{1.87\,(0.04)^2\,0.075}{(5000)(0.01)}$$

Late Time Conditions

$$u = 0.000004$$

Laminar Flow

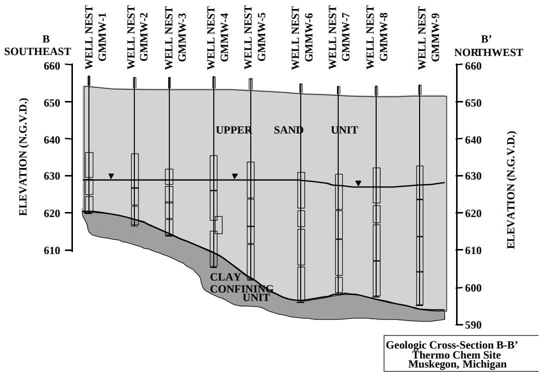
- Q = VA
- Q = maximum pumping rate at which laminar flow exists
- V = entrance velocity {can not exceed 0.1 ft/sec (0.03 m/sec)}
- A = open screen area

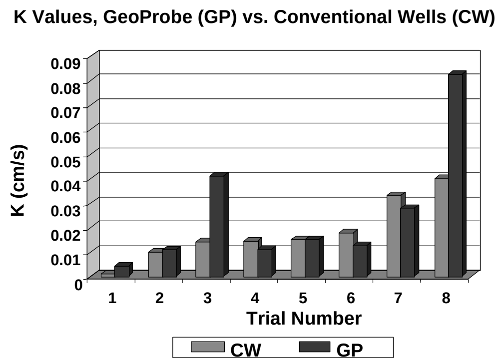
Laminar Flow

- For example, when A = 0.0042 ft^2
- Q = 0.1 ft/sec (0.0042 ft^2)
- Q = 0.00042 ft^3/sec or approximately 700 mL/min

- This calculation is necessary because of the limited open screen area in the GeoProbe point. Exceeding the maximum discharge will result in well efficiency concerns and invalid estimates of K.

Results





In the glacial-outwash sands at this site, the GeoProbe test and permanent monitoring wells produced comparable estimates of hydraulic conductivity.

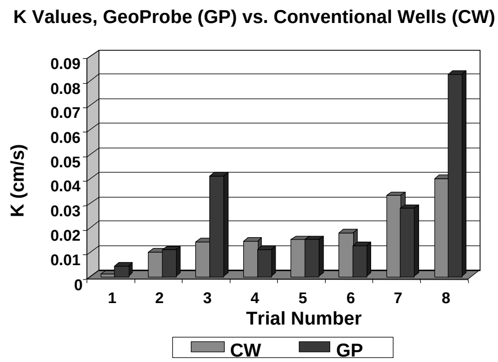
Range of Values

- **K values ranged from 0.00005 cm/s to 0.1 cm/s.**
- **Certainly both methods had enough sensitivity to differentiate between low and high flow zones during site characterization.**

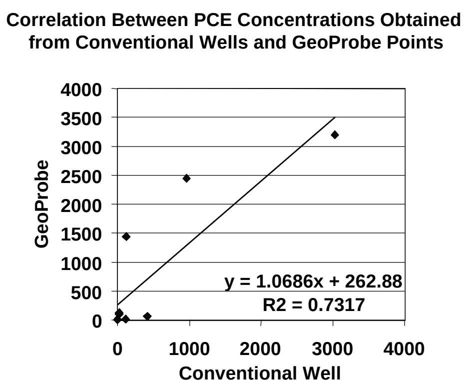
- **However, some of the assumptions associated with this method of data analysis are not met. Thus, the GeoProbe method of approximating K was used for preliminary site analysis.**

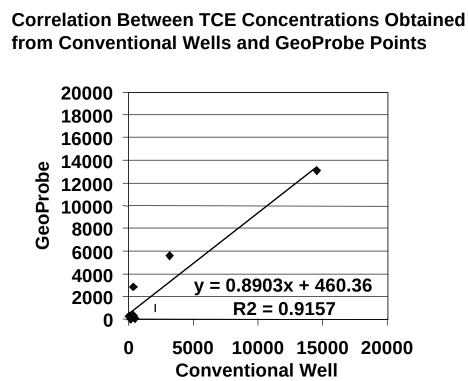
Comparing Push Technology to Permanent Wells

- **When the two estimates of K differed, the estimate acquired using the GeoProbe was larger.**

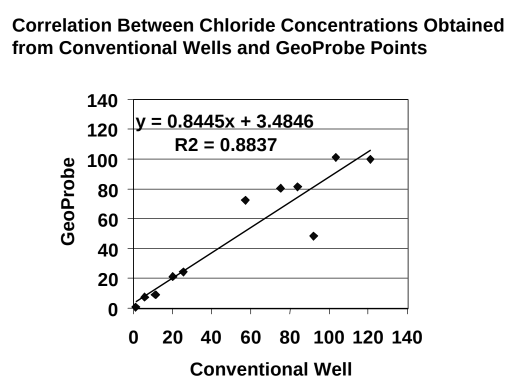


Contaminant Data

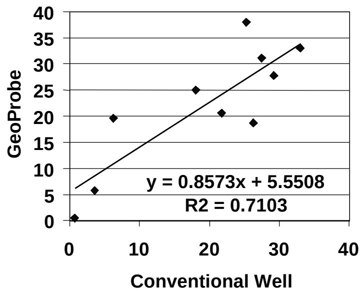




Geochemical Data



Correlation Between Sulfate Concentrations Obtained from Conventional Wells and GeoProbe Points

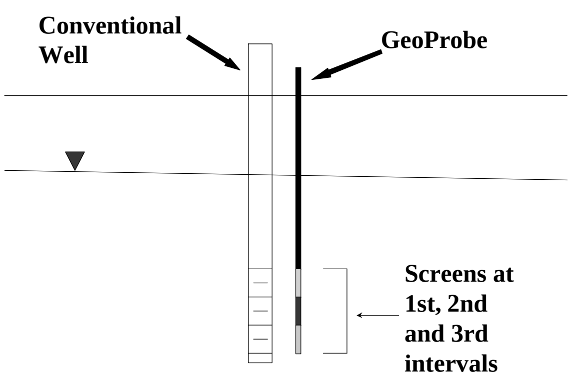


Calculation of Contaminant Flux Along the Flowpath

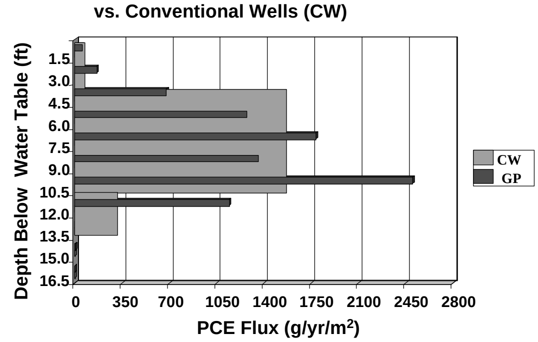
Contaminant Flux Calculations

- Flux = VAC
- V = interstitial seepage velocity
- A = cross-sectional area represented by the sample
- C = concentration

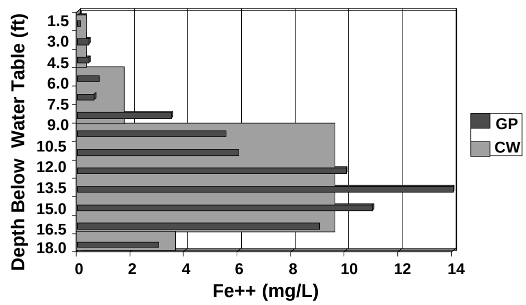
Using push-technology it is possible to see contaminant flux and geochemical distribution with greater resolution.



PCE Flux (g/yr/m²), GeoProbe (GP) vs. Conventional Wells (CW)



Fe ++ (mg/L), GeoProbe (GP) vs. Conventional Wells (CW)



Flux Estimates

- Flux estimates from permanent transect wells, GeoProbe transect wells, and a conventional array of wells (located in same area as the transect) were calculated.

Estimates of Flux Across Transect (kg/yr)

	Permanent Transect	GeoProbe Transect	Conventional Well Array
PCE	55.1	45.9	1.5
TCE	182.5	224.2	8.9
cis-DCE	311.7	918.0	19.0
VC	26.7	53.0	0.05

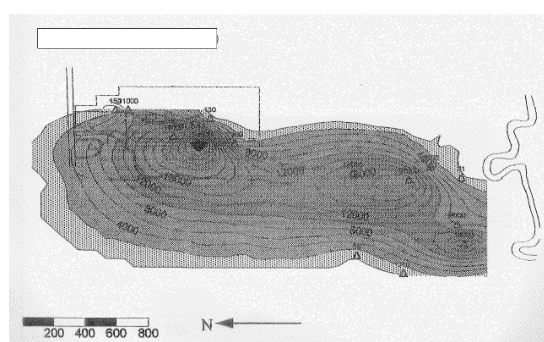
Flux Estimates

- Due to the wide spacing, the conventional array of wells fails to adequately characterize contaminant flux. The more densely sampled transects yield much more conservative estimates.

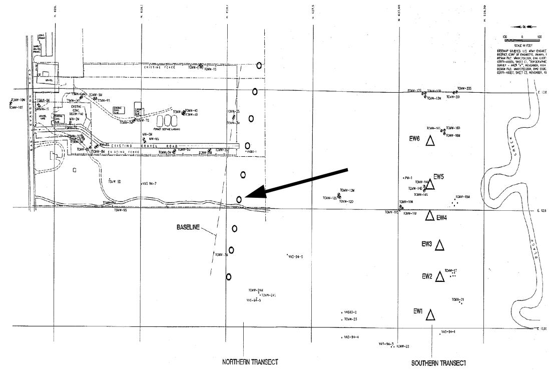
Data Use

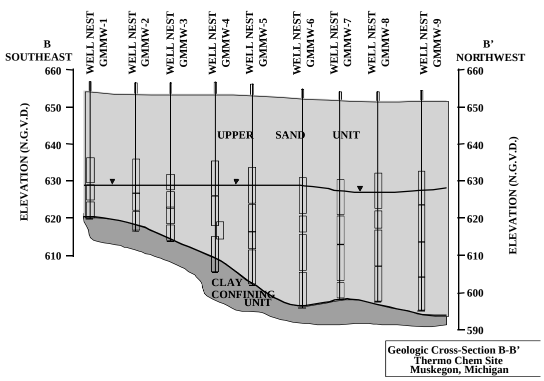
- By examining preliminary contaminant flux and geochemical data, judgements can be made about the heterogeneity of natural attenuation before proceeding further.

Location of the Plume



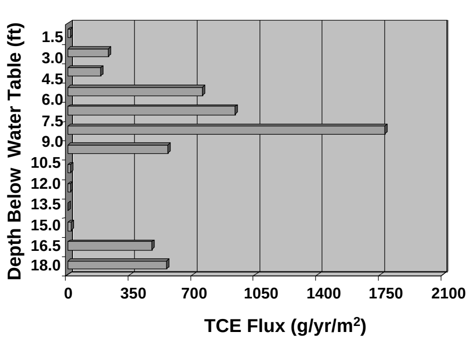
Transect Location



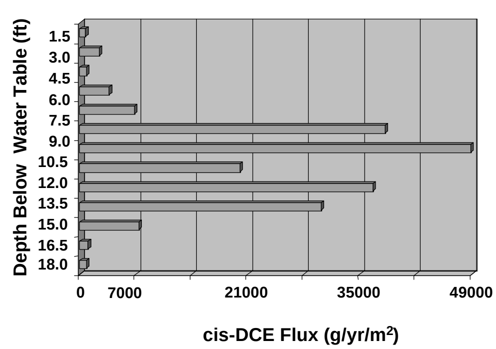


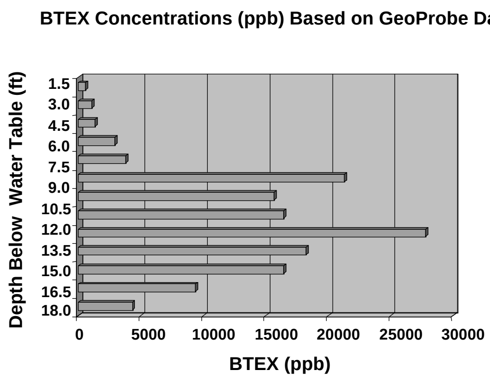
- **Data presented are from GeoProbes near well cluster 6. This is the most heavily impacted location along the transect.**

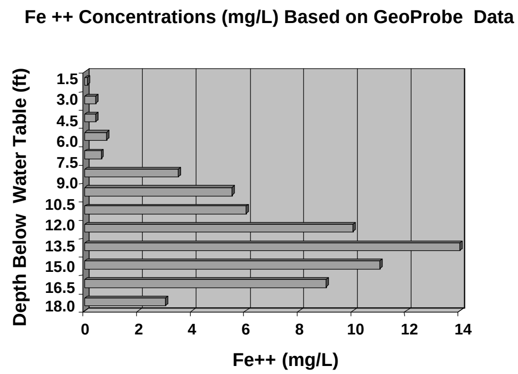
TCE Flux (g/yr/m^2) Based on GeoProbe Data

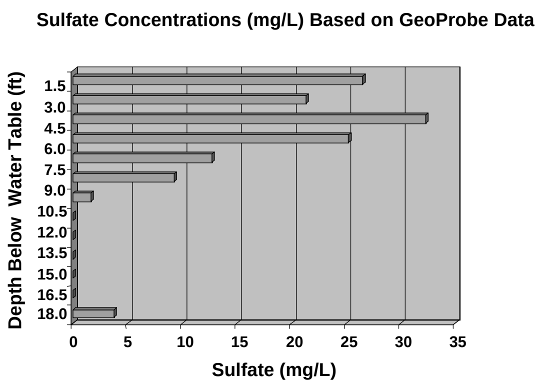


cis-DCE Flux (g/yr/m^2) Based on GeoProbe Data









Lines of Evidence

- **Disappearance of contaminants - Less flux of TCE is apparent in some of the intervals (9 - 16.5 ft).**
- **Appearance of byproducts - At this site, intervals that yield small amounts of TCE yield large amounts of cis-DCE.**

Lines of Evidence

- **BTEX is present at the appropriate interval to drive reductive dechlorination.**
- **Fe++ is being produced, and sulfate is being removed in the interval containing a higher cis-DCE flux.**

Interpretation

- **The contaminants in the interval 9 - 16.5 feet below the water table are undergoing significant biological transformation.**

Temporary Transects

- The majority of the intervals along the transect produce evidence that biological attenuation is occurring.

Temporary Transects

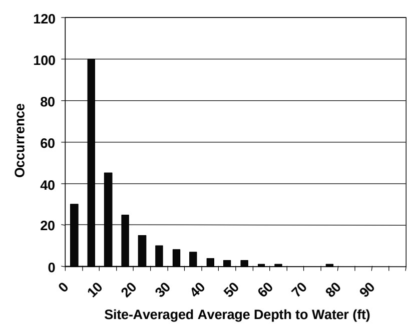
- Natural attenuation may or may not be protective of potential receptors.
- The preliminary data justifies carrying out a complete assessment of natural attenuation.

Extent, Mass, and Duration of Hydrocarbon Plumes from Leaking Petroleum Storage Tank Sites in Texas

Robert E. Mace, R. Stephen Fisher, David M. Welch, and Sandra P. Parra

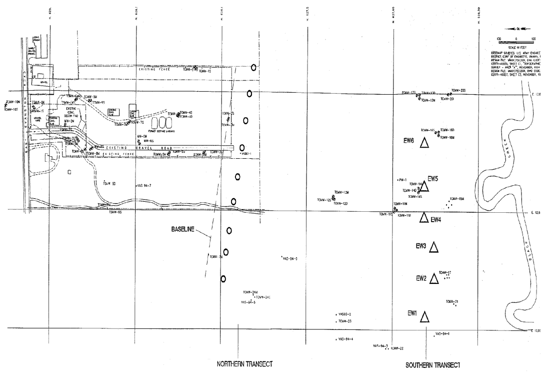
Bureau of Economic Geology
University of Texas at Austin
Austin, Texas 78713-8924

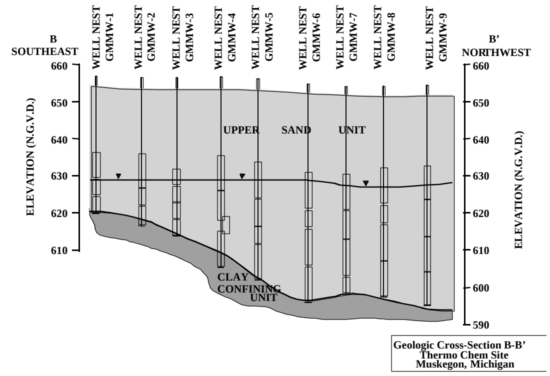
Average Depth to Water at 246 Sites



Construction of Permanent Transects

A permanent transect (designated by the circles) was constructed at the site to conduct long term monitoring of temporal trends in flux and geochemical parameters.





Benefits of Constructing Transects

- **Reveals the characteristics of a cross section of the contaminant plume.**
- **Temporal comparisons can be made on the same water with the aid of a downgradient transect.**

- **More accurate flux and degradation rate estimates due to a more comprehensive sampling of the plume.**

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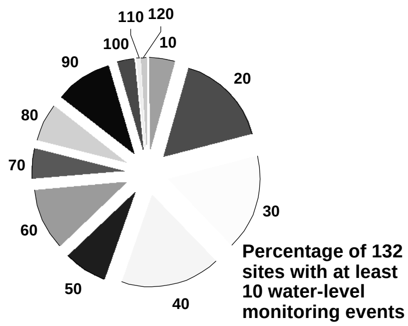
Standard Deviation of the Direction of Hydraulic Gradient (degrees)



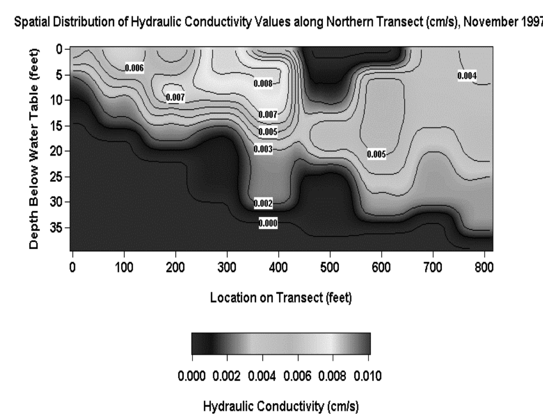
The previous cross section reveals the vertical placement of the well screens within each cluster along the transect.

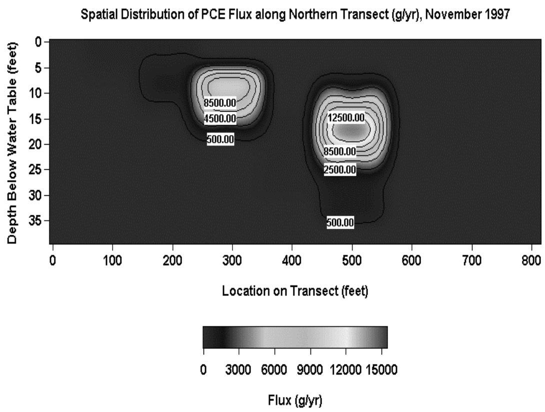
Monitoring of the Permanent Transect

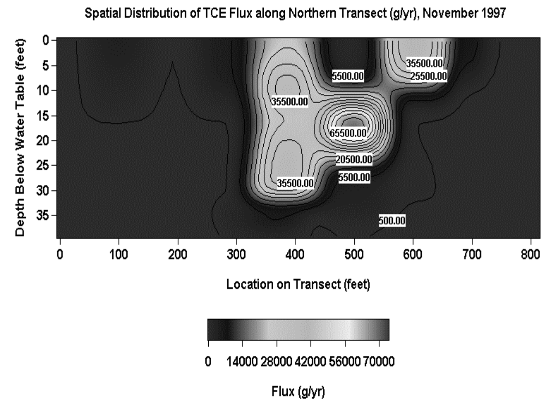
- **Using the same methods as with the site characterization, flux and geochemical data can be collected at any time.**

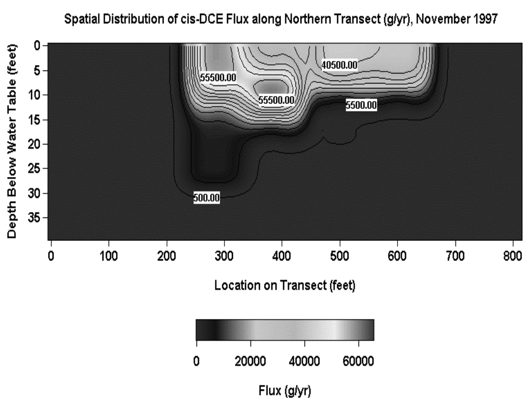
Also, the spatial relationships between contaminants, electron acceptors, and carbon sources can be demonstrated by mapping the transect.

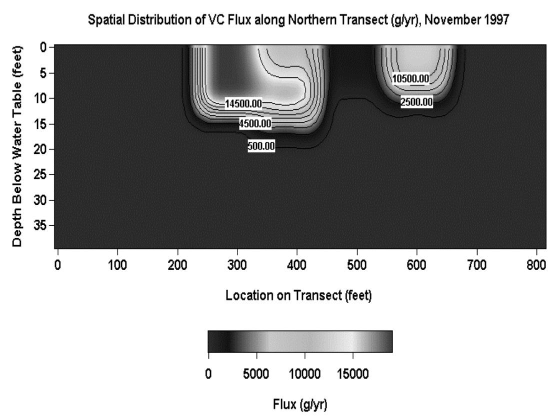
When viewing transect maps remember that ground-water flow is from the viewer into the screen.

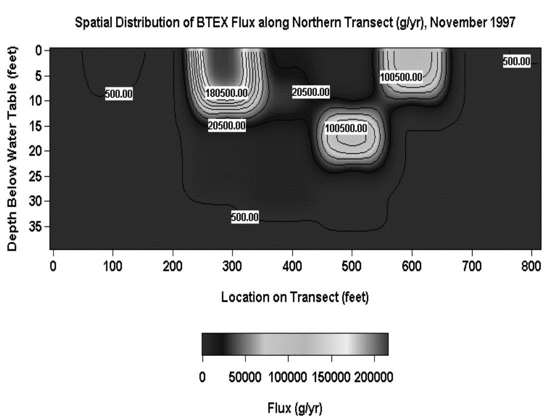








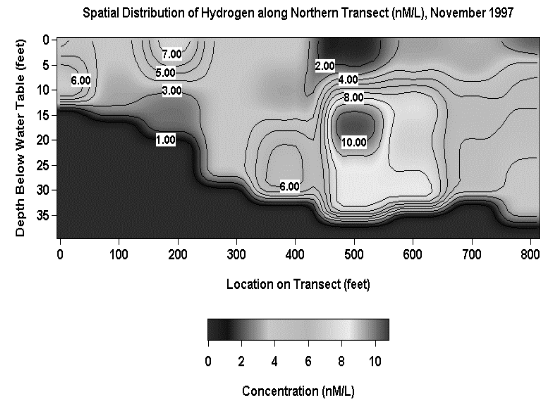


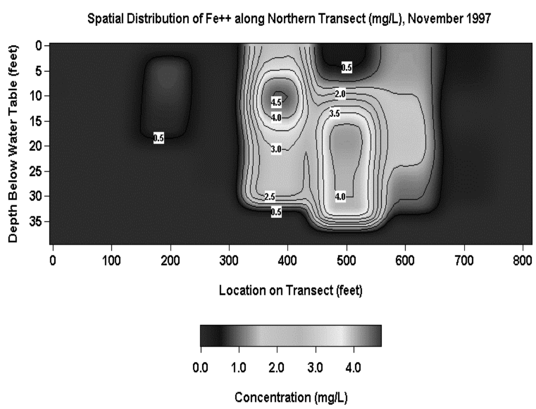


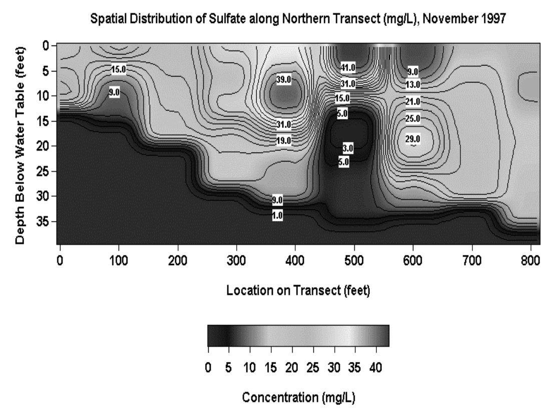
Hydrogen Data

- **Hydrogen data is an important piece of evidence used to demonstrate that intrinsic bioremediation is occurring at a significant rate.**

Due to hydrogen production during installation, direct-push wells can not be used to monitor dissolved hydrogen gas concentrations. Thus, the need for permanent wells.







Interpretation

- **Interpretation is the same as with the temporary transect. Use the transect maps to differentiate between areas that behave as is expected when natural attenuation is occurring and those that don't.**

Examples of Heterogeneity

- **At the 500 ft interval, PCE is surrounded by TCE and both are an in area that has high hydrogen concentrations, relatively high Fe++ concentrations, and low sulfate concentrations. Natural attenuation processes are at work.**

Examples of Heterogeneity

- **The upper portion of the aquifer is transmitting most of the cis-DCE and VC. Therefore, this area has undergone more reductive dechlorination.**

Examples of Heterogeneity

- **A less complete sampling regime would fail to demonstrate the complex nature of fate and transport mechanisms in the aquifer.**

What About the Geology?

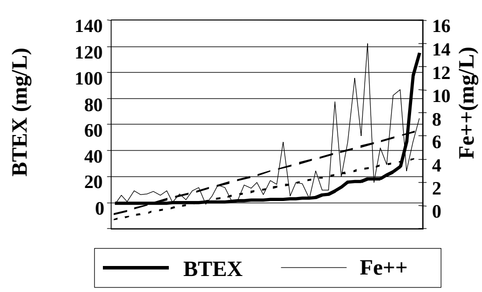
- **Push technology can also be used to take core samples of aquifer material.**
- **Core samples can be used to verify trends seen in K estimates.**

Field Techniques to Evaluate Sampling Locations in Real Time

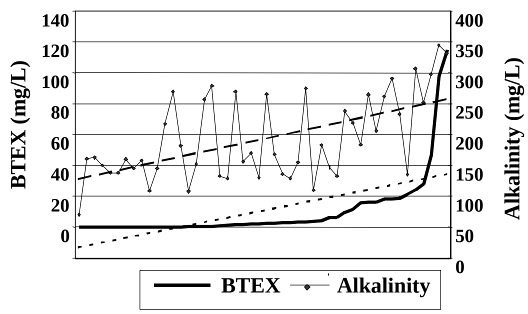
Field Test Kits

- **Test kits for Fe(II), alkalinity, and in some cases contaminants, can be used in the field to map the plume both laterally and vertically. This allows the field scientist to take the majority of samples from contaminated areas.**

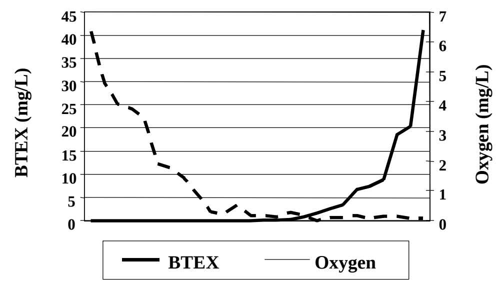
Trend Agreement Between BTEX and FE++



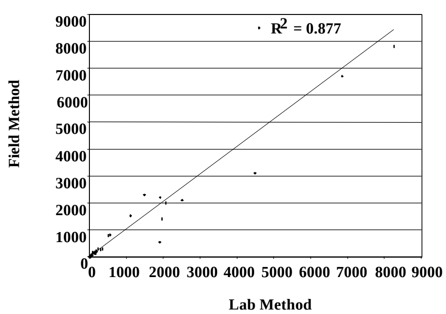
Trend Agreement Between BTEX and Alkalinity



Relationship Between BTEX and Oxygen Measurements



Correlation Between Field and Lab Determination of TCE Concentration in Water



Site Characterization Recommendations

- **Use direct-push technology to conduct site characterization, preferably by constructing temporary transects**
- **Install monitoring well transects based on the information provided by the site characterization.**

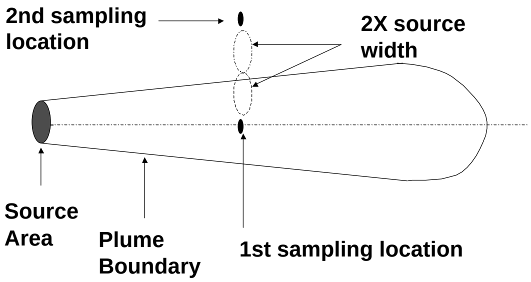
Site Characterization Recommendations

- **Use monitoring well transects to *<u>monitor temporal trends</u>*.**

GeoProbe Spacing on Temporary Transect

- **Probe locations are determined by starting at the inferred center of the plume and moving out in a stepwise fashion at intervals of two times the source area width.**

Spacing on Temporary Transect



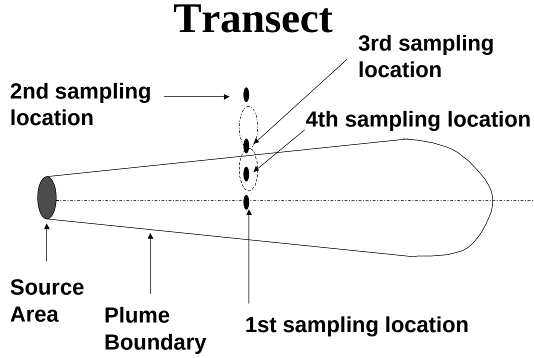
GeoProbe Spacing on Temporary Transect

- If the 2nd sampling location is contaminated, then sample 2x the source area width further along the transect.

GeoProbe Spacing on Temporary Transect

- If the 2nd sampling location is not contaminated, then double the sampling location density between the 1st and 2nd location until the plume is delineated.

Spacing on Temporary Transect



Vertical Profiling

- Follow the same logic as used with lateral well placement. Start at the water table, especially if the contaminant is a LNAPL, and proceed at an interval appropriate for the site.

Vertical Profiling

- Aquifer thickness, contaminant properties and distance from the source area must be considered when determining the initial sampling interval.

Vertical Profiling

- The goal of vertical profiling is to ensure that variations in physical and biological systems are adequately characterized.

Vertical Profiling

- As site characterization proceeds, then the sampling intervals can be refined. Typically, this will involve increasing sampling density until distinct patterns in physical and geochemical parameters are obvious.

Vertical Profiling

- One of the most important physical characteristics is hydraulic conductivity. Use the specific capacity test to estimate relative differences in flow of different intervals.

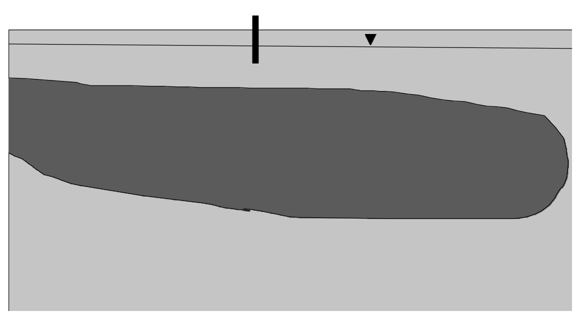
Vertical Profiling

- Use field test kits such as alkalinity, Fe II, sulfide, and dissolved oxygen to detect variations in biological processes in the aquifer.

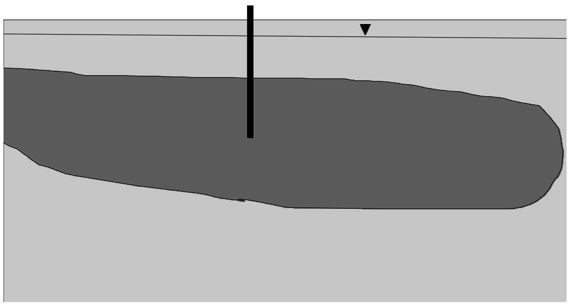
Vertical Profiling

- If possible, conduct continuous vertical profiling. This will reduce the amount of uncertainty in site characterization.

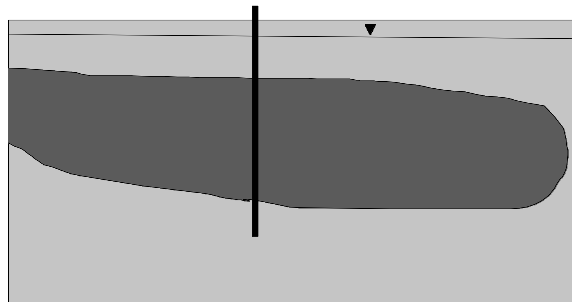
Vertical Profiling



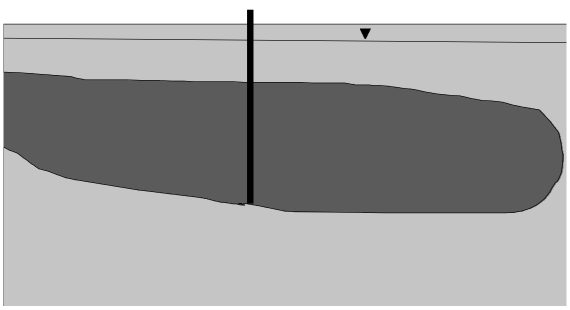
Vertical Profiling



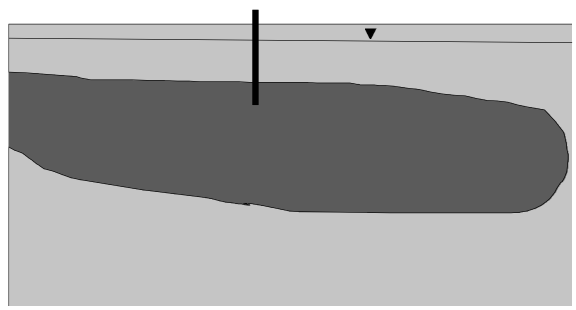
Vertical Profiling



Vertical Profiling



Vertical Profiling



Resource Allocation

- **At this site, 80 monitoring wells were installed to characterize and monitor the site.**
- **Twenty of the wells do not contribute to the interpretation of the site.**

- **One conventional well cost as much as three complete temporary push locations.**
- **That includes installation, well development, and sampling.**

- **So, 60 temporary push locations (continuous vertical sampling) could have been completed for the same cost as the 20 wells that didn't yield any additional information.**

At this site, as with many sites, a more thorough site characterization and permanent transect installation could have been achieved for the same cost as a conventional site characterization and monitoring network.

Take Home Points

- **It doesn't cost the PRP's more.**
- **Consultants don't lose money.**
- **Regulators can make their decisions easier.**