High Resolution Site Characterization and the Triad Approach

Seth Pitkin

Triad Investigations: New Approaches and Innovative Strategies

June 2008

STONE ENVIRONMENTAL INC

A Fact-Based Fresh Look: 2” horizontal, 1.02” vertical

Needs Analysis Study: 2” horizontal, 1.97” vertical

Lesley Allen: 1.91” horizontal, 4.72” vertical

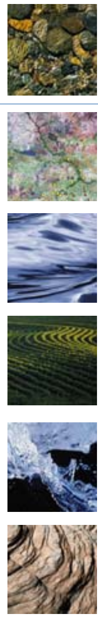
Date: 1.99” horizontal, 5.17” vertical

Images (grouped): 0.5” horizontal, 0.5” vertical

Top blue rule: 0” horizontal, 1.6” vertical

Bottom blue rule: 0” horizontal, 5.08” vertical

Logo: 6.38” horizontal, 7.42” vertical

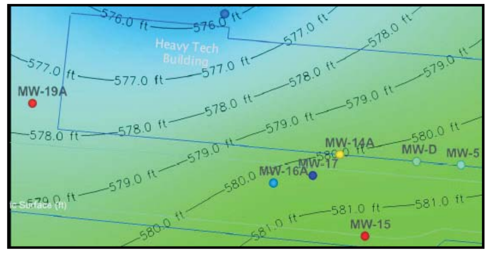


Contents

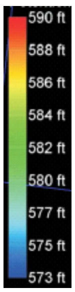
STONE ENVIRONMENTAL INC

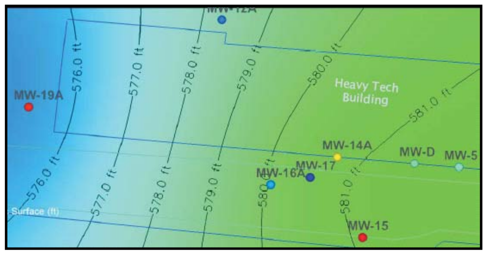
Gasoline Plume Site in Vermont
Variability of Hyd. Gradient w/ Depth

Shallow – 585 ft amsl



Intermediate – 574 ft amsl



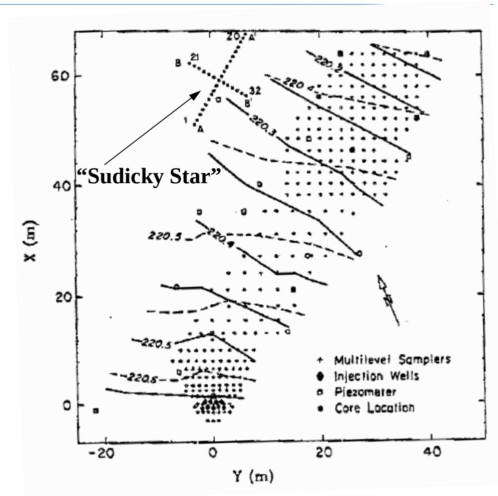


Deep – 557 ft amsl

STONE ENVIRONMENTAL INC

Hydrodynamic Dispersion

- Natural Gradient Tracer Tests
    - Stanford/Waterloo – 1982
    - USGS Cape Cod – 1990(?)
    - Rivett et al 1991
- Dispersion is scale (time/distance) dependent
- **Transverse horizontal dispersion is weak**
- **Transverse vertical dispersion is even weaker**
- Longitudinal dispersion is significant

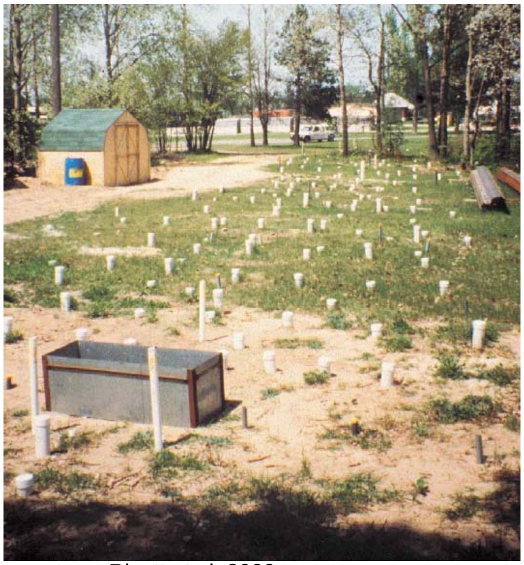


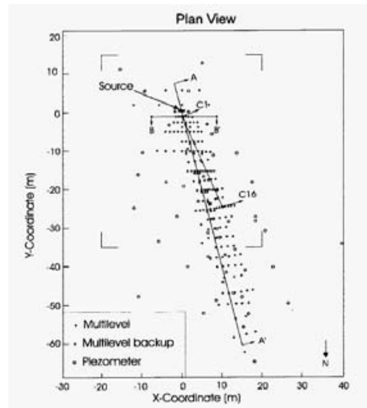
Stanford-Waterloo Natural Gradient Tracer Test Layout

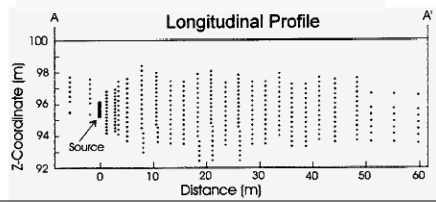
STONE ENVIRONMENTAL INC

4

Rivett's Experiment: The Emplaced Source Site



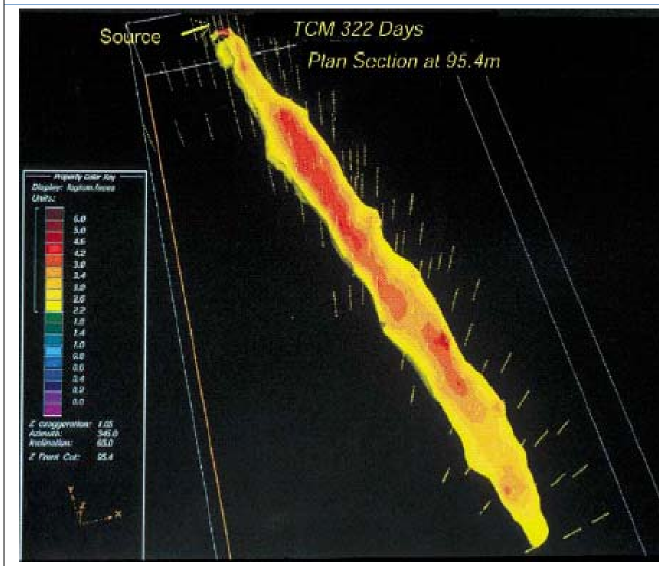


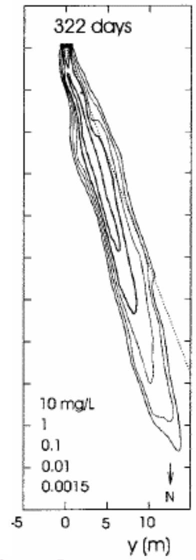


Rivett et al, 2000

5

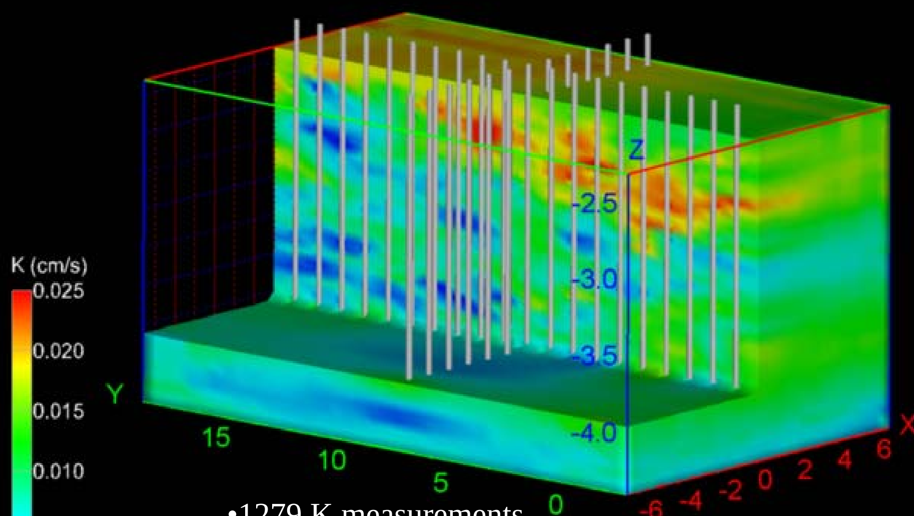
TCM Plume at 322 Days
Weak Transverse Dispersion





Rivett et al, 2000

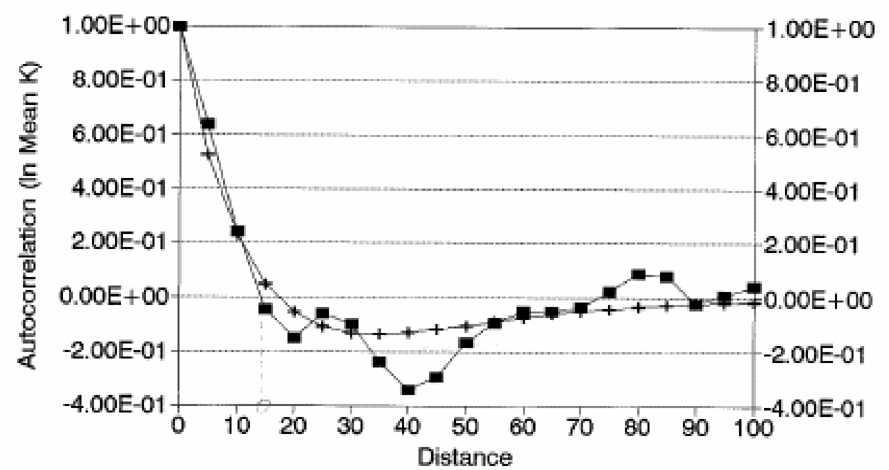
Distribution of K at CFB Borden - Beach Sand
(adapted from Sudicky, 1986)



- 1279 K measurements
- Mean K= 9.75×10^{-3} cm/sec
- Range = one order of magnitude

Autocorrelation of K

3 Cores in "Sudicky Star" CFB Borden



STONE ENVIRONMENTAL INC

8

Hydraulic Conductivity Correlation Lengths

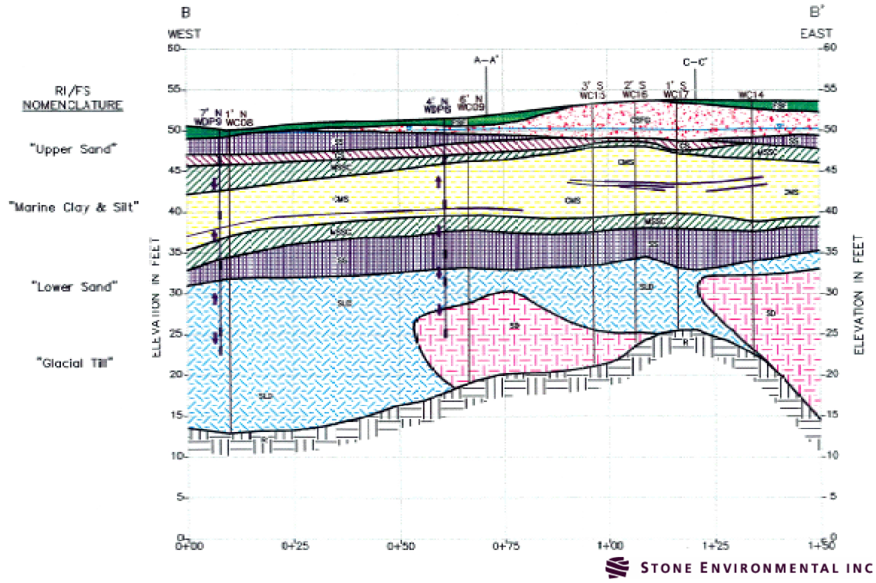
Location	Horizontal K Correlation Length (m)	Vertical K Correlation Length (m)	Investigator
Borden, Ontario	2.8	0.12	Sudicky (1986)
Otis, ANGB	2.9 – 8	0.18 – 0.38	Hess et al (1992)
Columbus AFB	12.7	1.6	Rehfeldt et al
Aefligan	15 – 20	0.05	Hess et al (1992)
Chalk River, Ontario	1.5	0.47	Indelman et al (1999)

STONE ENVIRONMENTAL INC

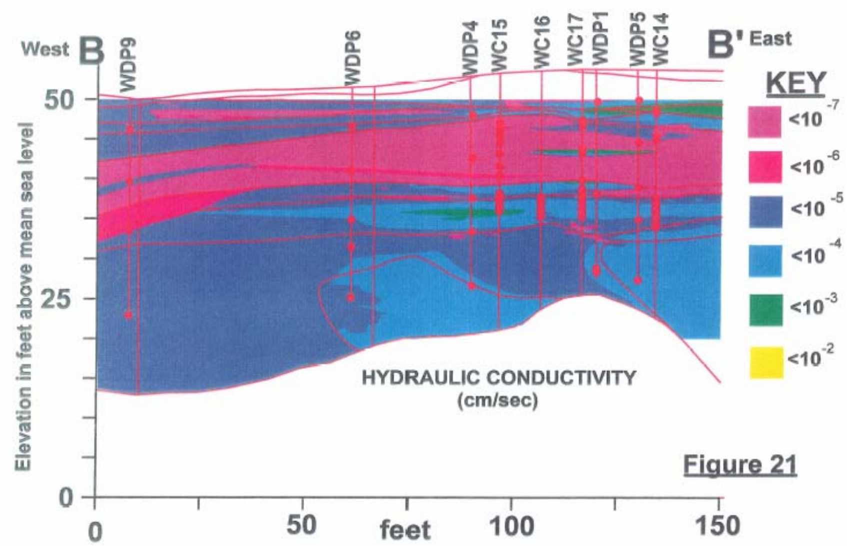
9

Other investigators have since performed similar studies and have found similar results. With the exception of Columbus AFB, all of the investigators have found vertical correlation lengths of less than 50 cm. in a given hydrostratigraphic unit. This is not a good sign for those using five foot long well screens.

Pease AFB, NH - Site 32
Section B – B'



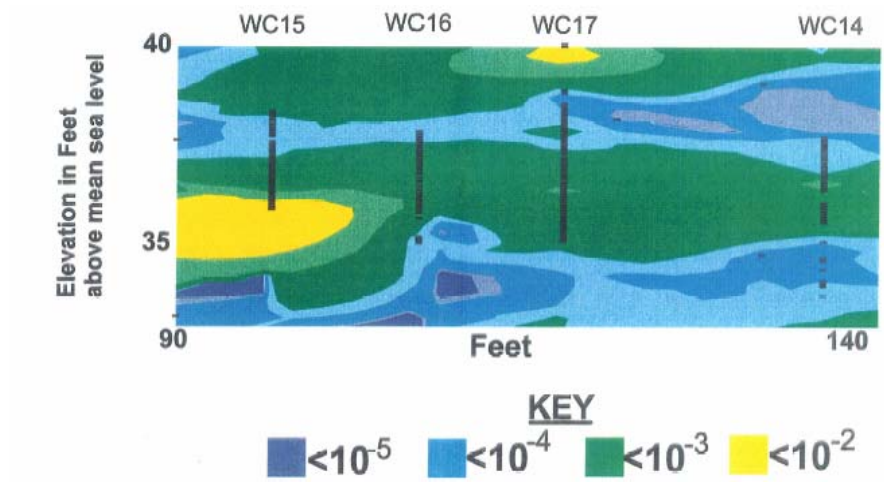
Hydraulic Conductivity Distribution on B – B'



STONE ENVIRONMENTAL INC

11

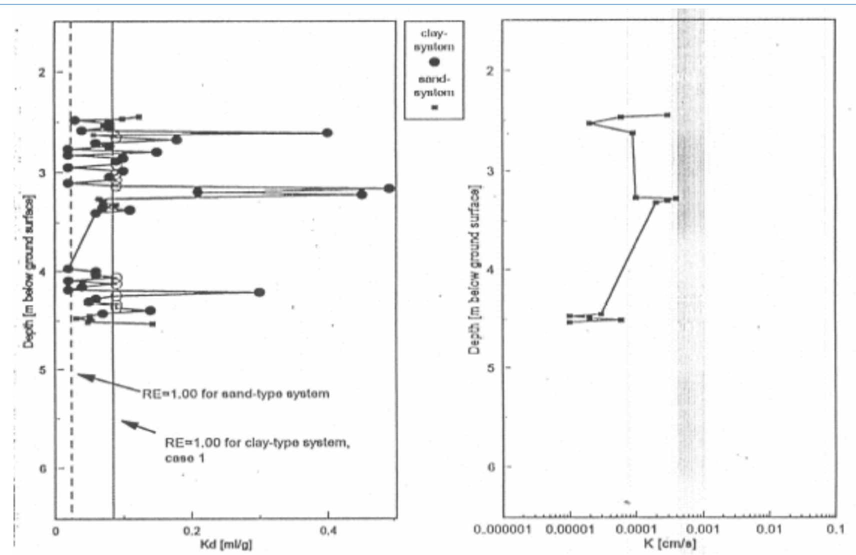
K (cm/sec) Distribution in Lower Sand on B – B"



STONE ENVIRONMENTAL INC

12

Pease AFB Site 32
K_d and K variability with Depth



STONE ENVIRONMENTAL INC

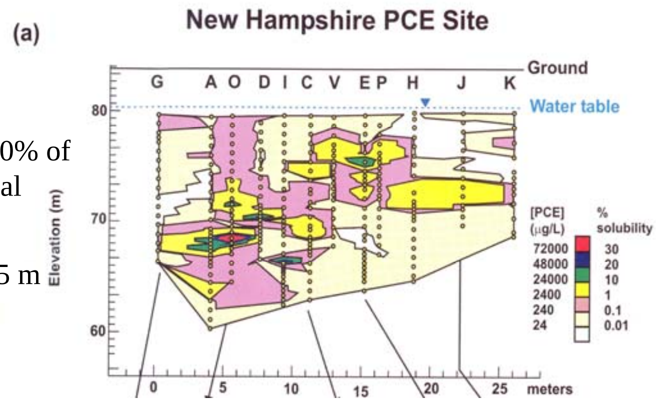
13

Mass Flux Distribution

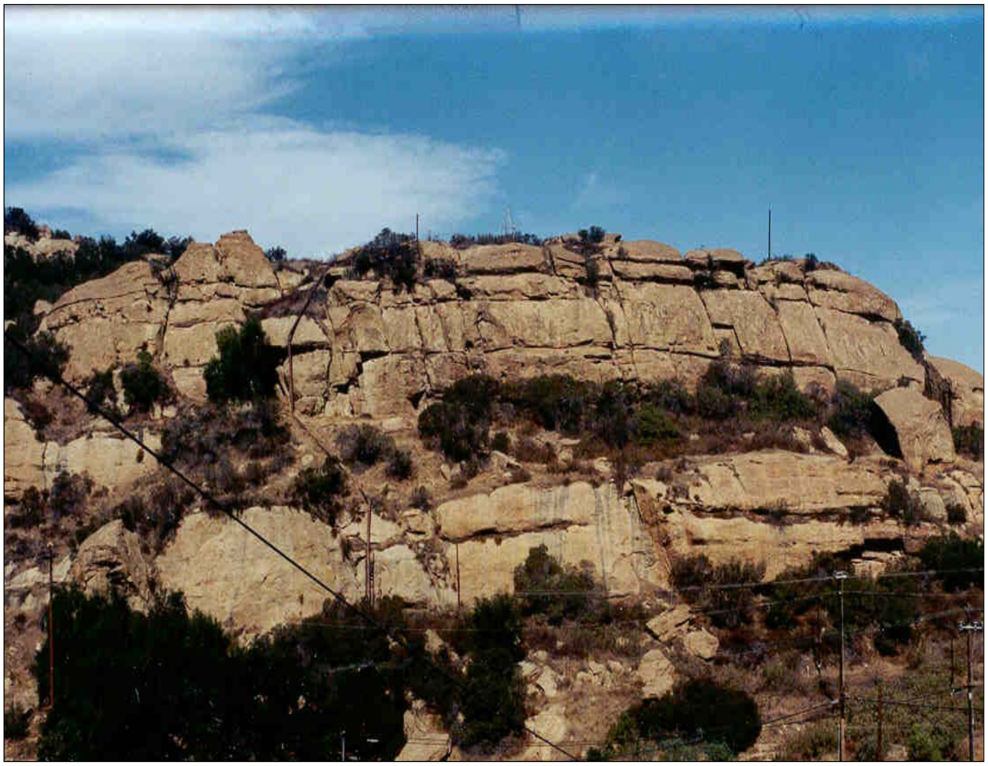
Guilbeault et. al. 2005

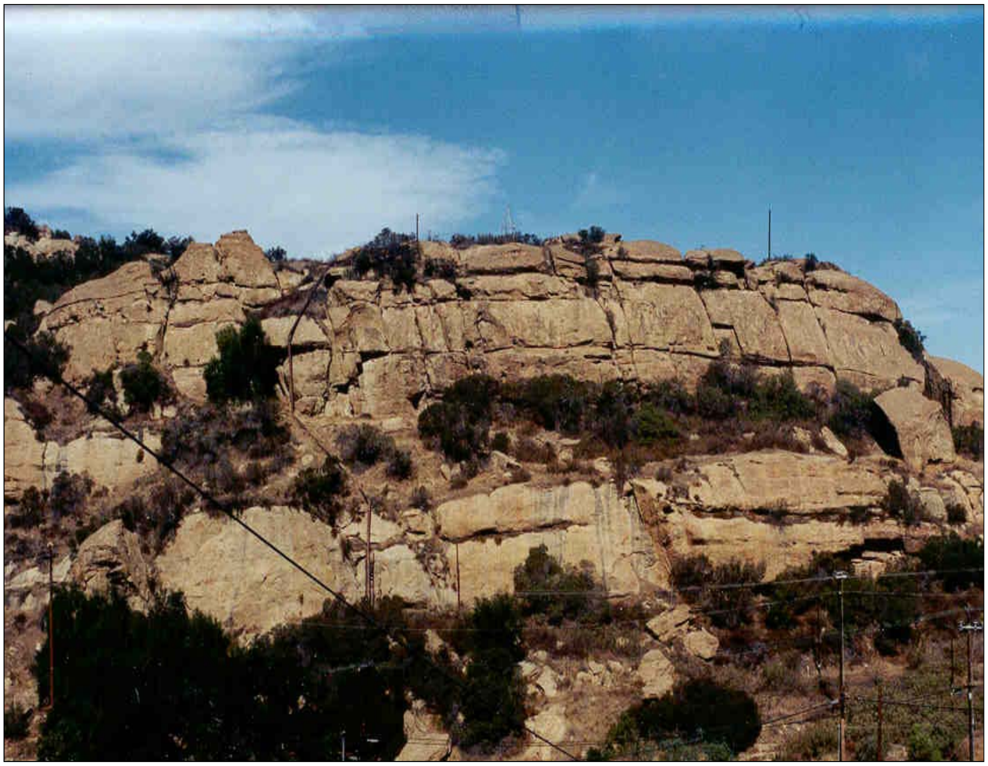
75% of mass discharge occurs through 5% to 10% of the plume cross sectional area.

Optimal Spacing is ~0.5 m



STONE ENVIRONMENTAL INC

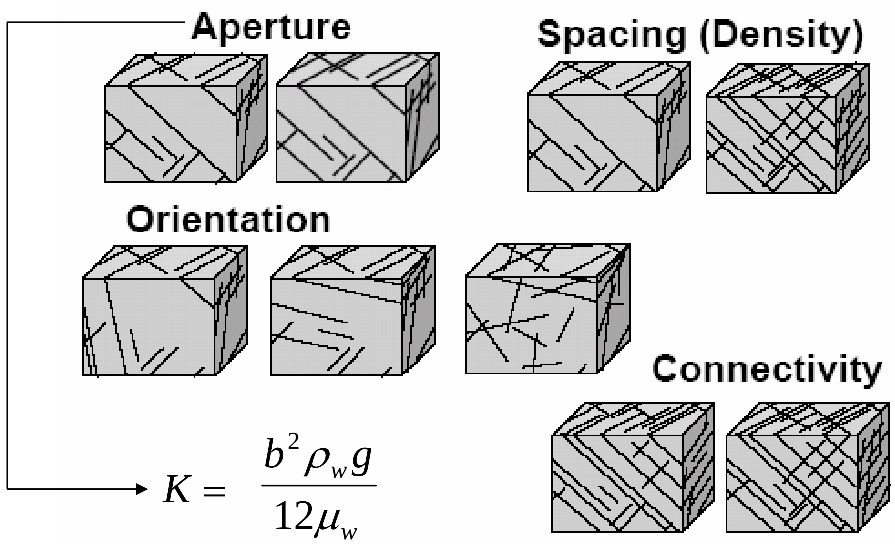




•Example of fractures exposed at outcrop.

•Fractures are orthogonal, interconnected, widely spaced, large matrix blocks.

Factors Governing Flow in Fractured Media

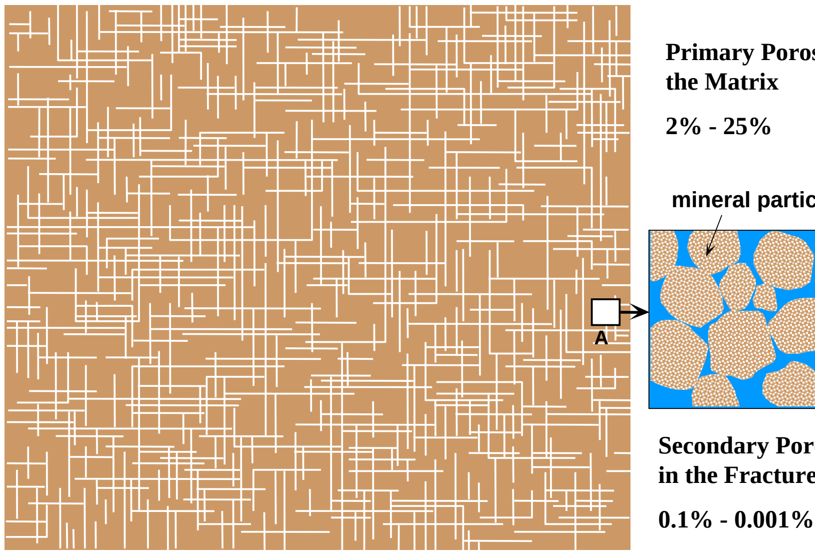


$$K = \frac{b^2 \rho_w g}{12\mu_w}$$

STONE ENVIRONMENTAL INC

17

Dual Porosity Media



Primary Porosity in the Matrix

2% - 25%

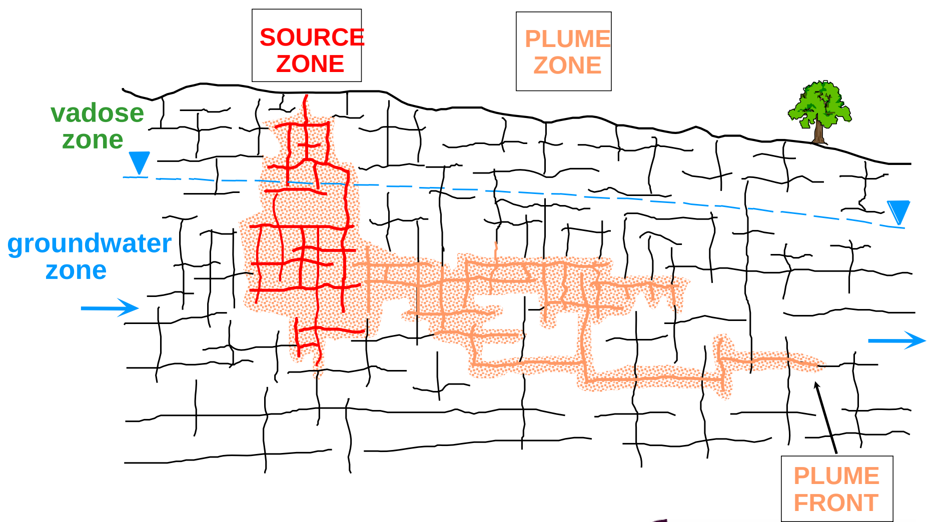
Secondary Porosity in the Fractures

0.1% - 0.001%

STONE ENVIRONMENTAL INC

18

Nature of Contamination in Fractured Porous Media



B.L. Parker

STONE ENVIRONMENTAL INC

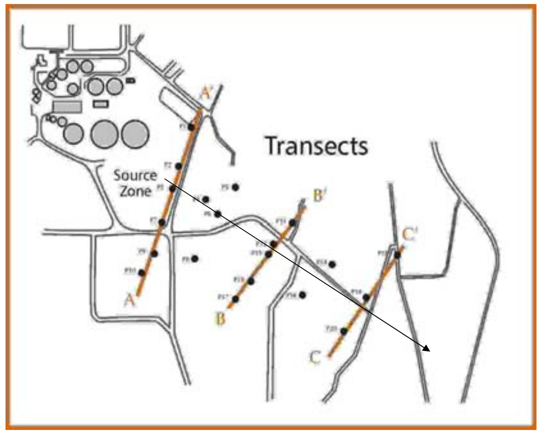
20

Contents

STONE ENVIRONMENTAL INC

High Resolution Approach

- **<u>Transect</u>**: Line of vertical profiles oriented normal to the direction of the hydraulic gradient (Horizontal spacing)
- **<u>Short Sample Interval</u>**: Vertical dimension of the sampled portion of the aquifer
- **<u>Close Sample Spacing</u>**: Vertical distance between samples
- Real-time/Near Real-time Tools
- Dynamic/ Adaptive Approach



STONE ENVIRONMENTAL INC

22

High Resolution Tools

- Cone Penetrometer
- Laser Induced Fluorescence (LIF, aka UVOST, TarGOST)
- Membrane Interface Probe (MIP)
- NAPL Ribbon Sampler
- Waterloo^{APS}
- Soil Coring and Subsampling
- On Site Analytical
- Bedrock Toolbox
  - CORE^{DFN}
  - Borehole Geophysics
  - FLUTe K Profiler
  - Multilevels (Westbay, Solinst, FLUTe)

STONE ENVIRONMENTAL INC

23

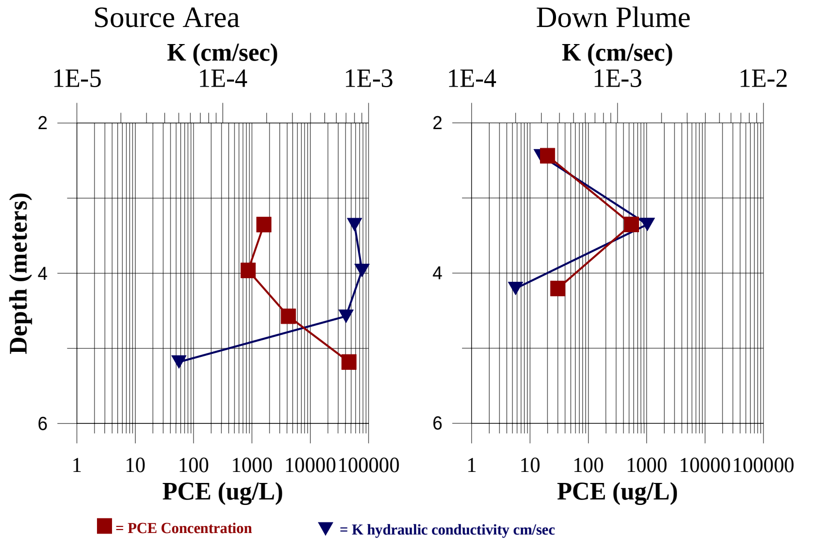
Collaborative Data in Porous Media:
MIP, Wateroo^{APS,} Soil Subcore Profiling and Onsite Analytical

- MIP: Rapid screening tool
  - Use to rapidly screen site and select sample locations for detailed difinitive sampling
- Waterloo^{APS}: Detailed definitive data in aquifers
- Soil Subcore Profiling: Detailed definitive data in aquitards
- On site analytical: Near real-time defensible data

STONE ENVIRONMENTAL INC

24

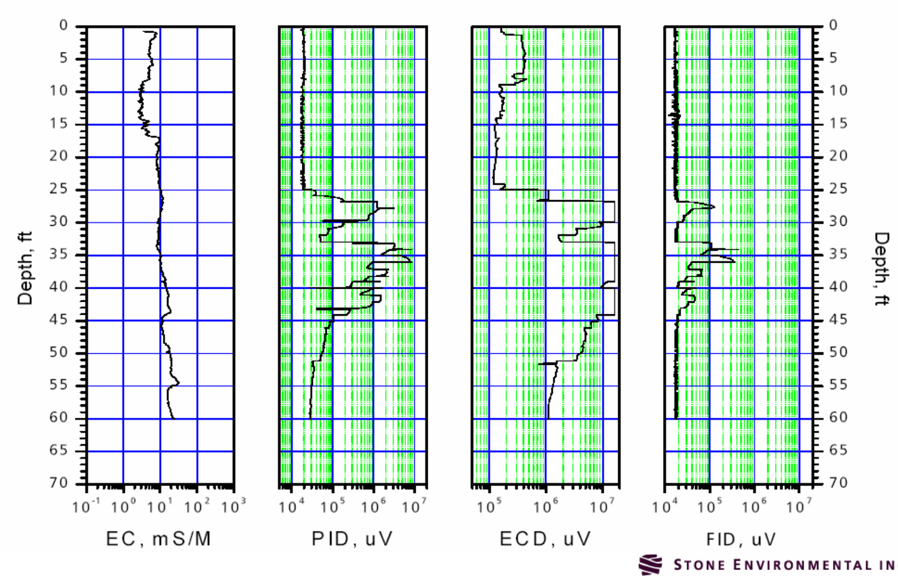
Spatial Relationships of K and C



STONE ENVIRONMENTAL INC

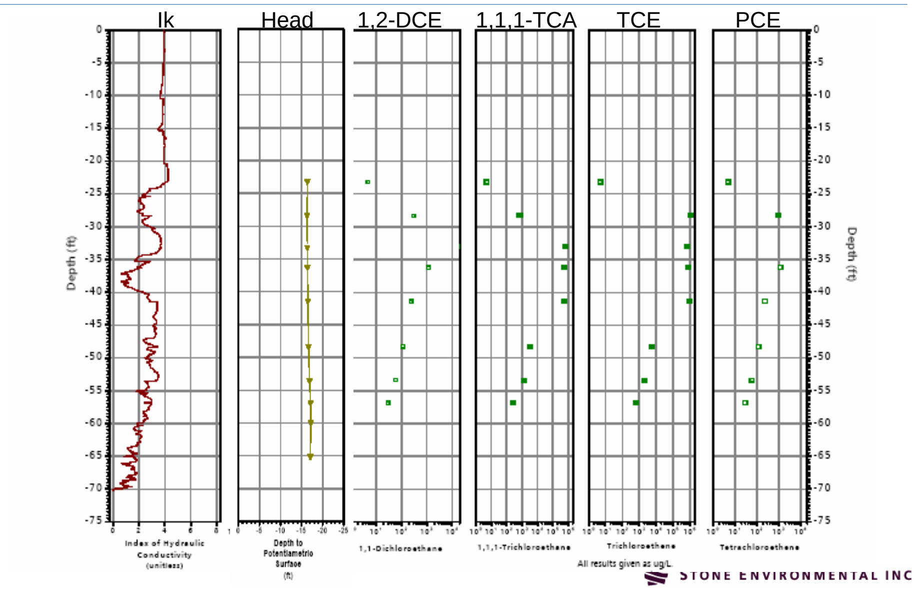
25

MIP: Continuous, Real-Time Profile



26

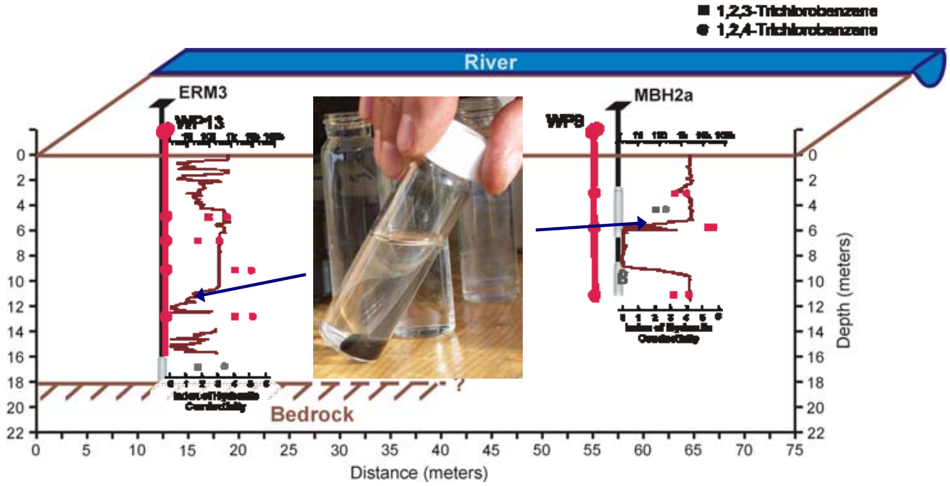
Waterloo Profiler: Near Real-Time Closely Spaced Profile



27

Waterloo APS™
ADVANCED PROFILING SYSTEM

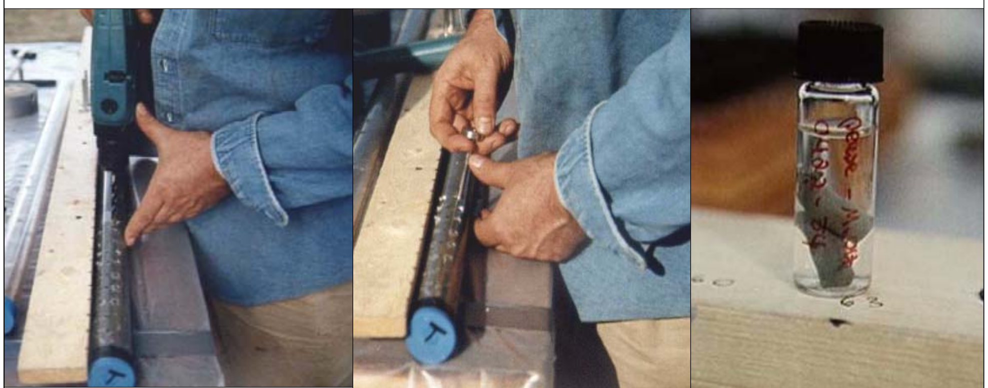
Finding What Others Missed



STONE ENVIRONMENTAL INC

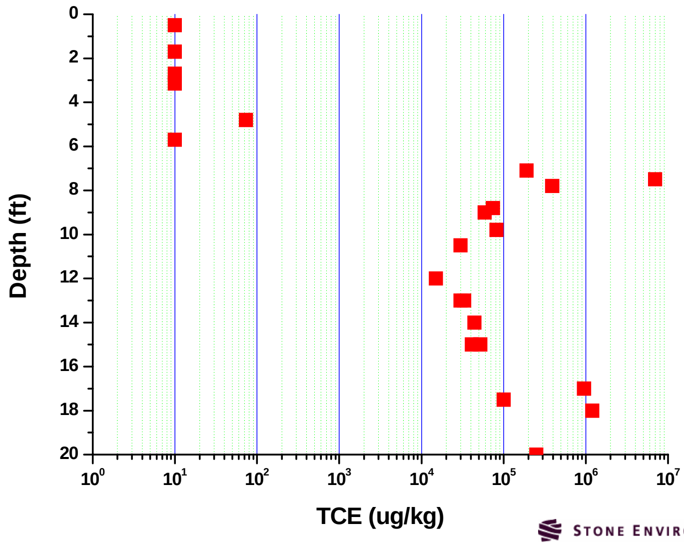
28

Soil Subcore Profiling: What's in the Aquitard?



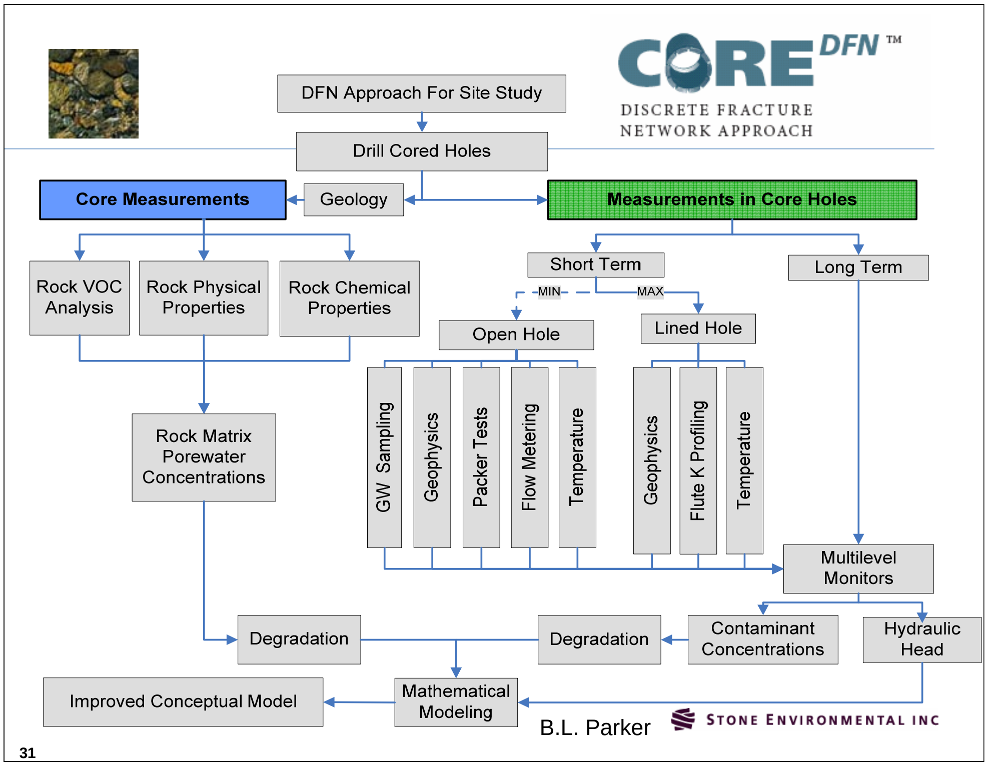
STONE ENVIRONMENTAL INC

Soil Sub-Core Sampling: Near-Real Time, Closely Spaced Profile



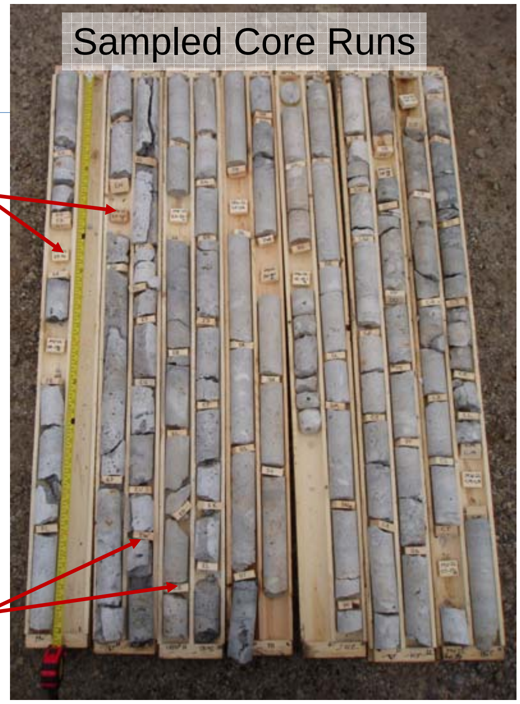
STONE ENVIRONMENTAL INC

30


CORE DFN ™
DISCRETE FRACTURE NETWORK APPROACH
DFN Approach For Site Study
Drill Cored Holes
Core Measurements
Geology
Measurements in Core Holes
Rock VOC Analysis
Rock Physical Properties
Rock Chemical Properties
Short Term
Long Term
MIN
MAX
Open Hole
Lined Hole
GW Sampling
Geophysics
Packer Tests
Flow Metering
Temperature
Geophysics
Flute K Profiling
Temperature
Rock Matrix Porewater Concentrations
Multilevel Monitors
Degradation
Degradation
Contaminant Concentrations
Hydraulic Head
Improved Conceptual Model
Mathematical Modeling
B.L. Parker
STONE ENVIRONMENTAL INC
31

Rock Core Sampling

Physical Property Sample



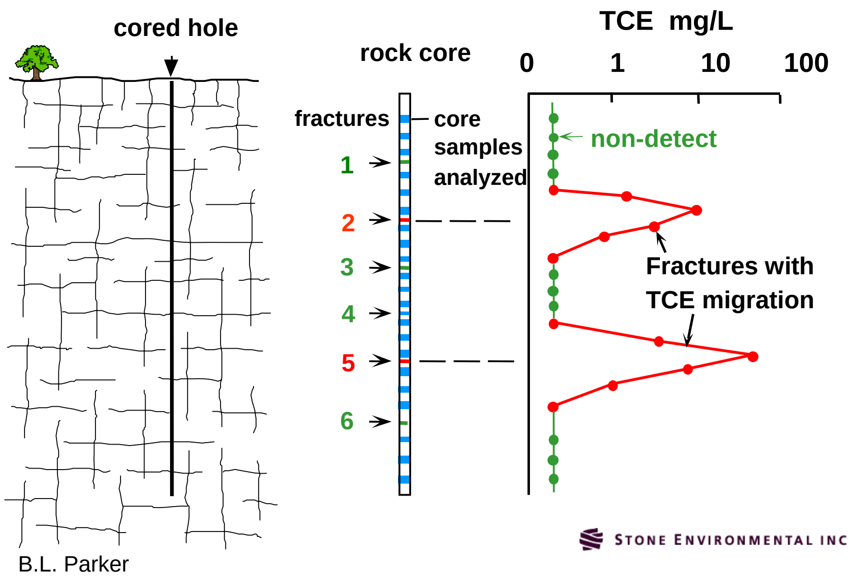
- High resolution VOC sampling
- Physical property sampling

VOC Sample

2000 voc and 250 phys prop

32

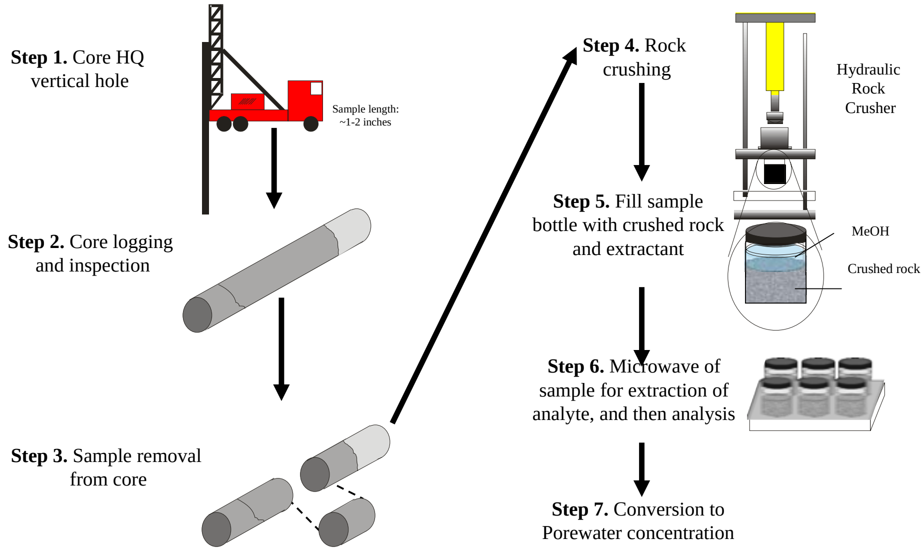
Core Sampling for Mass Distribution & Migration Pathway Identification



33

CORE DFN™

DISCRETE FRACTURE NETWORK APPROACH



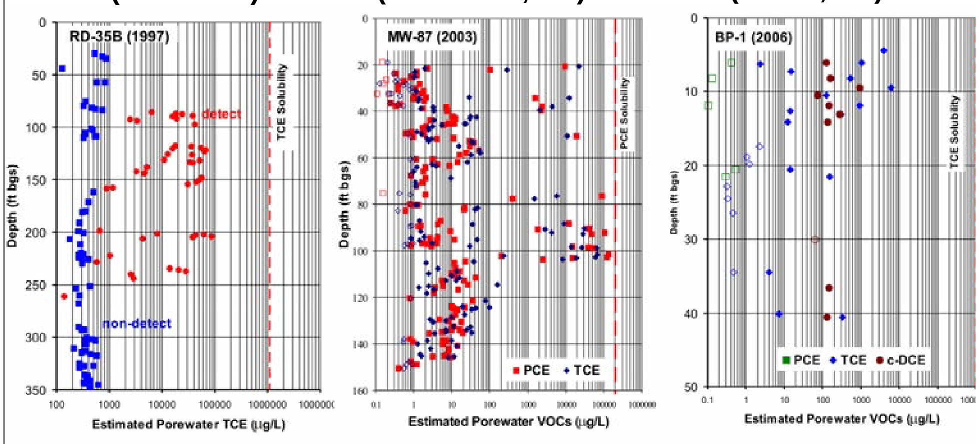
B.L. Parker (Modified from Hurley, 2002)

STONE ENVIRONMENTAL INC

34

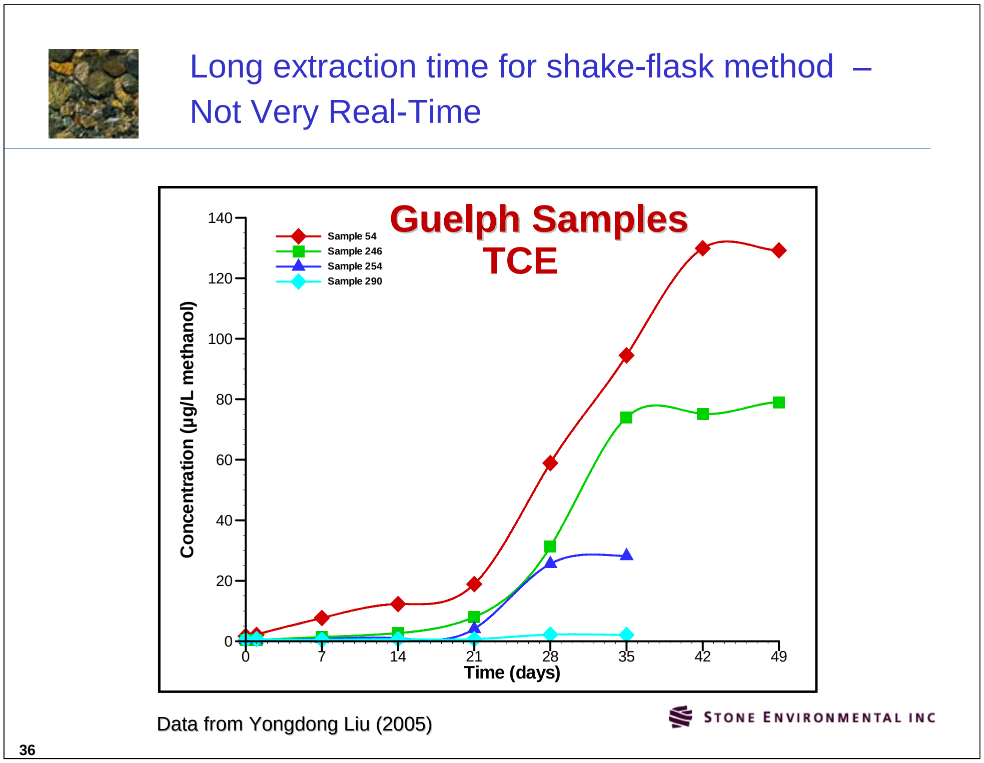
Example Rock Core VOC Concentration Profiles

Sandstone (California) | **Shale (Watervliet, NY)** | **Siltstone (Union, NY)**



B.L. Parker

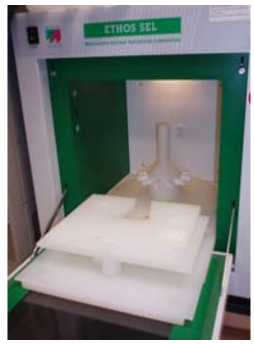
STONE ENVIRONMENTAL INC



Here you can see the amount of time for TCE to reach equilibrium between the rock sample and extractant which is the flat portion of these plots

Microwave Assisted Extraction (MAE)

- Fast - 40 min
- Extraction at higher temperature and pressure
  - Increases diffusion rate and analyte desorption rate
  - Elevated boiling point (temperatures ~ 120ºC)
  - Increased solvent penetration



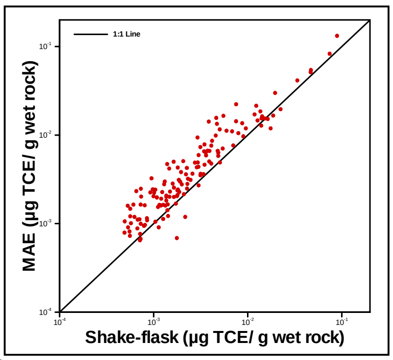
B.L. Parker   Photos courtesy of Dr. Tadeusz Górecki   STONE ENVIRONMENTAL INC

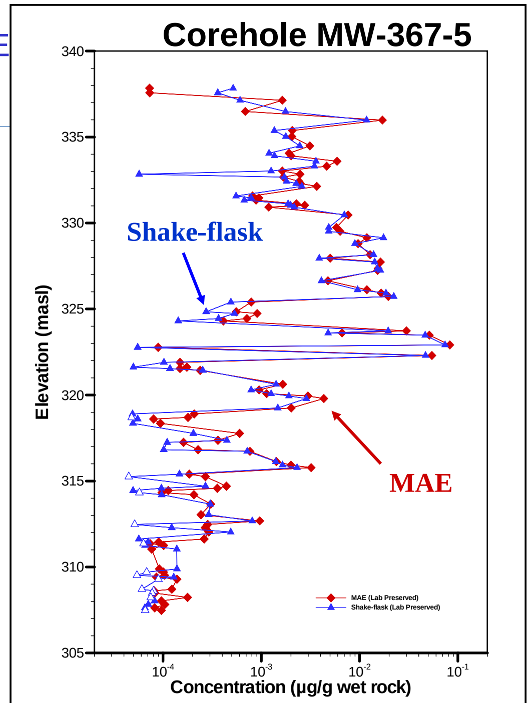
37

Shake Flask vs MAE

(TCE)

- Good correlation
- More complete extraction with MAE





B.L. Parker

38

Distillation

- Contaminant hydrogeology is all about spatial variability
- High resolution site characterization is essential
- Apply Triad Approach Principles:
  - Real-time/ near real time data collection tools
  - Dynamic Work Strategy
  - Employ collaborative data using integrated tool sets
- Triad Approach in Bedrock Plumes: Coming Soon to a Fractured Rock Aquifer Near you

THE END

STONE ENVIRONMENTAL INC

39

Hydraulic Parameter and Mass Flux Distribution Using the High-Resolution Piezocone and GMS

Dr. Mark Kram, Groundswell
Dr. Norm Jones, BYU
Jessica Chau, UConn
Dr. Gary Robbins, UConn
Dr. Amvrossios Bagtzoglou, UConn
Thomas D. Dalzell, AMS
Per Ljunggren, ENVI

EPA Clu-In Internet Seminar
13 August 2009

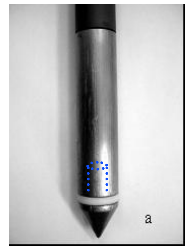
TECHNICAL OBJECTIVES

- Demonstrate Use of High-Resolution Piezocone to Determine Direction and Rate of GW Flow in 3-D
  - Compare with Traditional Methods
  - Develop Models and Predict Plume Behavior
- Integrate High-Resolution Piezocone and Concentration Data into 3-D Flux Distributions via GMS Upgrades
- Introduce New Remediation Performance Monitoring Concept

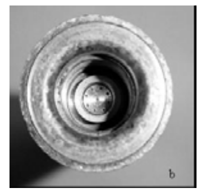
TECHNOLOGY DESCRIPTION

High-Resolution Piezocone:

- Direct-Push (DP) Sensor Probe that Converts Pore Pressure to Water Level or Hydraulic Head
- Head Values to ± 0.08ft (to >60’ below w.t.)
- Can Measure Vertical Gradients
- Simultaneously Collect Soil Type and K
- K from Pressure Dissipation, Soil Type
- Minimal Worker Exposure to Contaminants
- System Installed on PWC San Diego SCAPS
- Licensed to AMS



Custom Transducer



SEEPAGE VELOCITY AND FLUX

Seepage velocity (ν):

$$\nu = \frac{Ki}{\rho} \quad \text{(length/time)}$$

where: K = hydraulic conductivity (*Piezocone*)

i = hydraulic gradient (*Piezocone*)

ρ = effective porosity (*Piezocone/Soil*)

Contaminant flux (F):

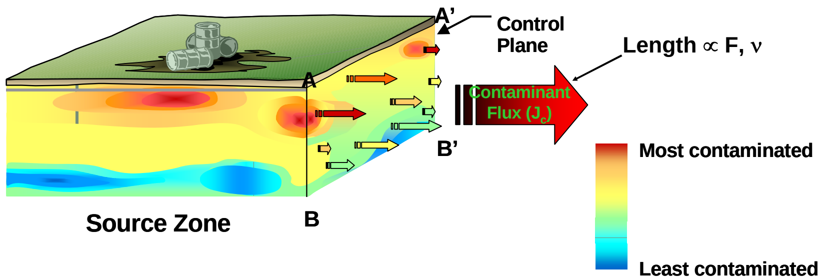
$$F = \nu\,[X]$$

(mass/length^2-time; mg/m^2-s)

where: ν = seepage velocity (length/time; m/s)

[X] = concentration of solute (*MIP, etc.*) (mass/volume; mg/m^3)

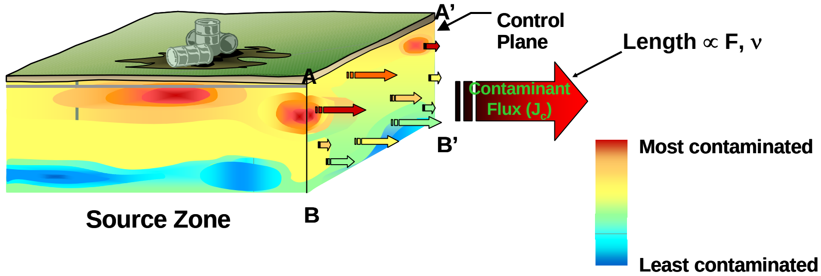
CONCENTRATION VS. FLUX



GROUNDSWELL 44

EPA Clu-In 08/13/09

CONCENTRATION VS. FLUX



High Concentration ≠ High Risk!!
Hydraulic Component - Piezocone

GROUNDSWELL 45

EPA Clu-In 08/13/09

GMS MODIFICATIONS

Gradient, Velocity and Flux Calculations

- Convert Scalar Head to Gradient [Key Step!]

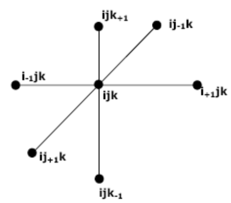
GMS MODIFICATIONS

Gradient, Velocity and Flux Calculations

- ➢ **Convert Scalar Head to Gradient [Key Step!]**

Calculating Hydraulic Gradient

For an interior node:



$$\frac{\partial h}{\partial x} = \frac{\dfrac{h_{i+1jk} - h_{ijk}}{x_{i+1jk} - x_{ijk}} + \dfrac{h_{ijk} - h_{i-1jk}}{x_{ijk} - x_{i-1jk}}}{2}$$

GROUNDSWELL 47 EPA Clu-In 08/13/09

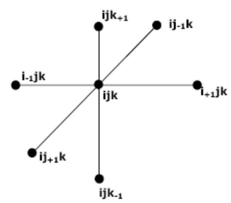
GMS MODIFICATIONS

Gradient, Velocity and Flux Calculations

- **Convert Scalar Head to Gradient [Key Step!]**
  - **Merging of 3-D Distributions to Solve for Velocity**
  - **Merging of Velocity and Concentration (MIP or Samples) Distributions to Solve for Contaminant Flux**

Calculating Hydraulic Gradient

For an interior node:



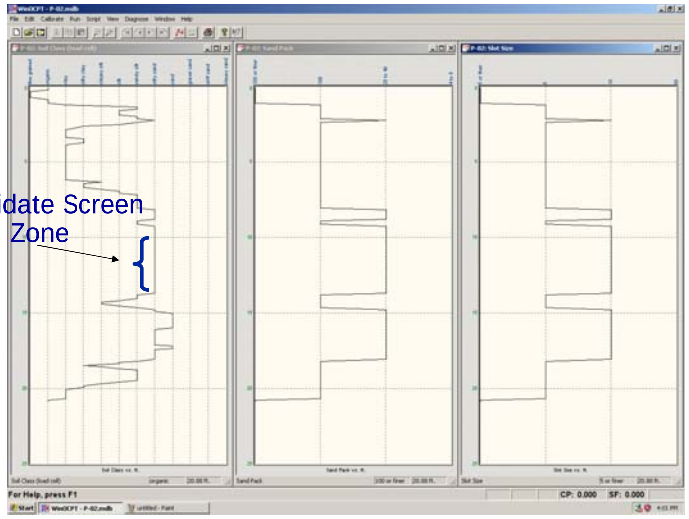
$$\frac{\partial h}{\partial x} = \frac{\frac{h_{i+1jk} - h_{ijk}}{x_{i+1jk} - x_{ijk}} + \frac{h_{ijk} - h_{i-1jk}}{x_{ijk} - x_{i-1jk}}}{2}$$

GROUNDSWELL 48 EPA Clu-In 08/13/09

APPROACH

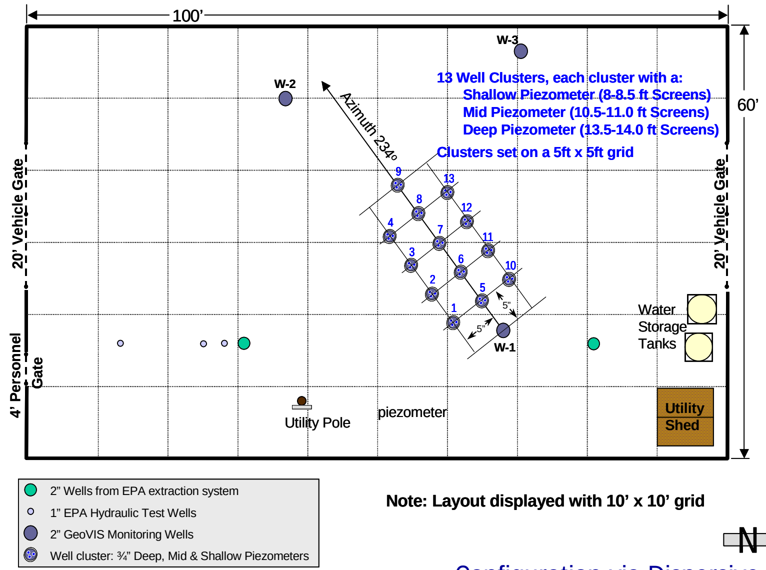
- Test Cell Orientation
  - Initial pushes for well design;
  - Well design and prelim. installations, gradient determination;
  - Initial $CaCl_2$ tracer tests with geophysics (time-lapse resistivity) to determine general flow direction
- Field Installations (Clustered Wells)
- Survey (Lat/Long/Elevation)
- Pneumatic and Conventional Slug Tests ("K – Field")
  - Modified Geoprobe test system
- Water Levels ("Conventional" 3-D Head and Gradient)
- HR Piezocone Pushes (K, head, eff. porosity)
- GMS Interpolations (ν, F), Modeling and Comparisons

CPT-BASED WELL DESIGN



Kram and Farrar Well Design Method

DEMONSTRATION CONFIGURATION



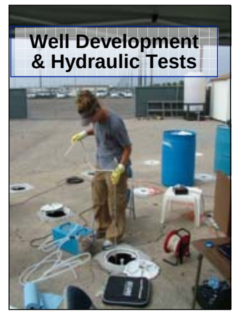
Note: Layout displayed with 10' x 10' grid

Configuration via Dispersive Model

GROUNDSWELL 51

EPA Clu-In 08/13/09

FIELD EFFORTS

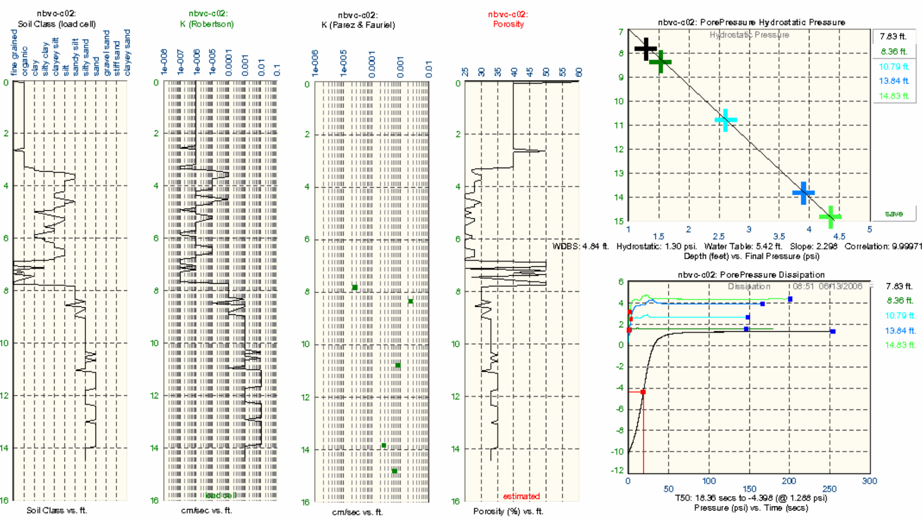


FIELD EFFORTS

Receiver

Transmitter

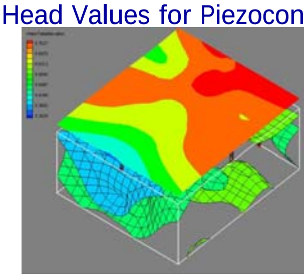
PIEZOCONE OUTPUT

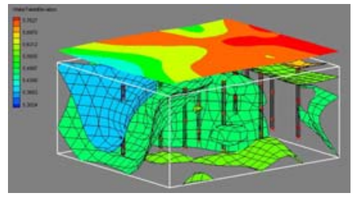


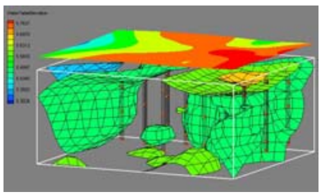
GROUNDSWELL

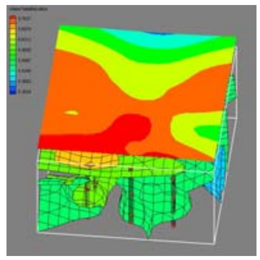
HIGH RESOLUTION PIEZOCONE TESTS (6/13/06)

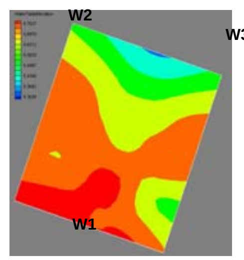
Head Values for Piezocone





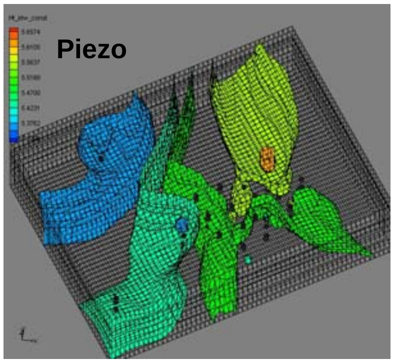


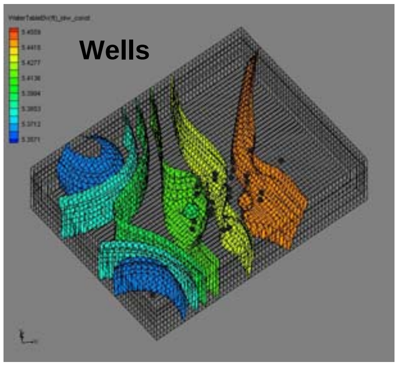




Displays shallow gradient

HEAD DETERMINATION
(3-D Interpolations)

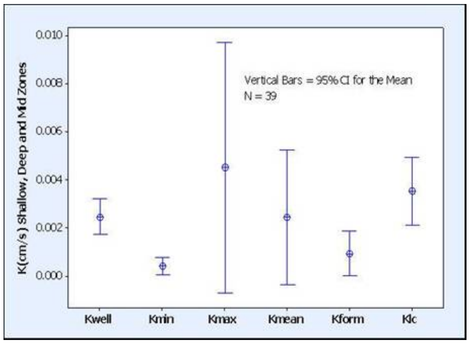


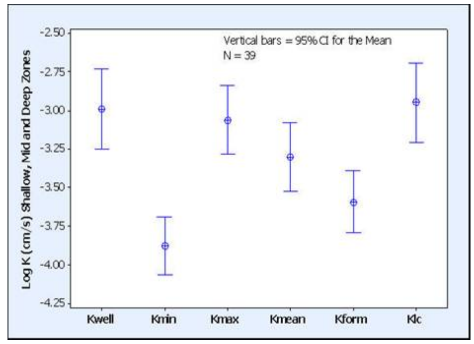


- Shallow gradient (5.49-5.41'; 5.45-5.38' range in clusters over 25')
- In practice, resolution exceptional (larger push spacing)

GROUNDSWELL 56 EPA Clu-In 08/13/09

COMPARISON OF ALL K VALUES

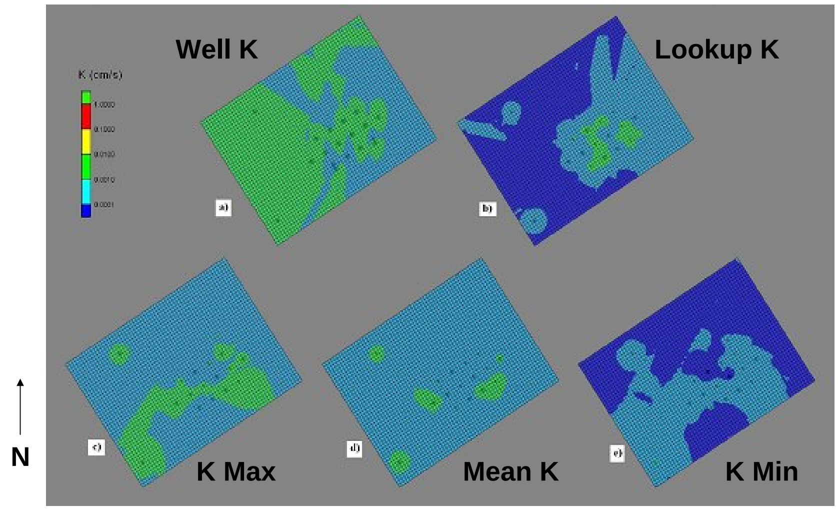




- K_{mean} and K_{lc} values within about a factor of 2 of K_{well} values;
- K_{min}, K_{max} and K_{form} values typically fall within factor of 5 or better of the K_{well} values;
- K values derived from piezocone pushes ranged much more widely than those derived from slug tests conducted in adjacent monitoring wells;
- Differences may be attributed to averaging of hydraulic conductivity values over the well screen versus more depth discrete determinations from the piezocone (e.g., more sensitive to vertical heterogeneities).

GROUNDSWELL 57 EPA Clu-In 08/13/09

K BASED ON WELLS AND PROBE
(Mid Zone Interpolations)

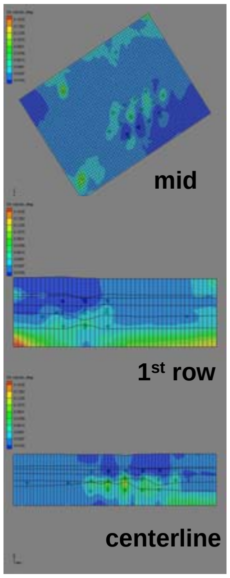


GROUNDSWELL 58

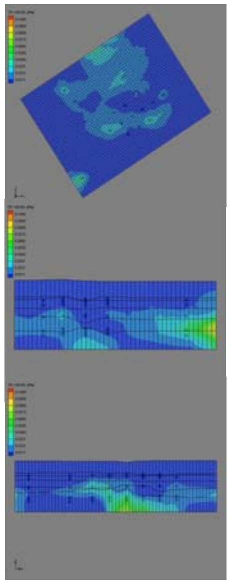
EPA Clu-In 08/13/09

VELOCITY DETERMINATION
(cm/s)

Well

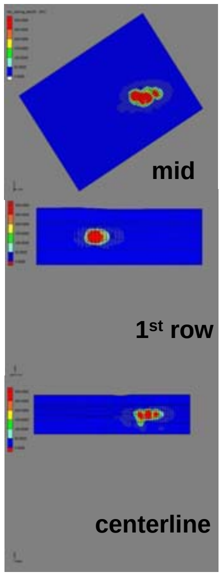


Piezo (mean K)

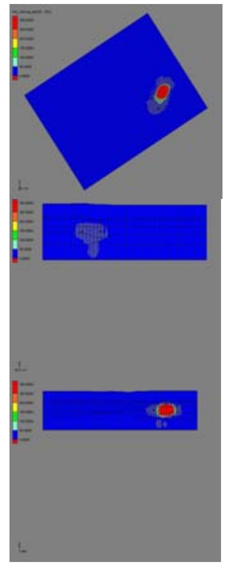


FLUX DETERMINATION
(Day 49 Projection)

Well



Piezo (mean K)

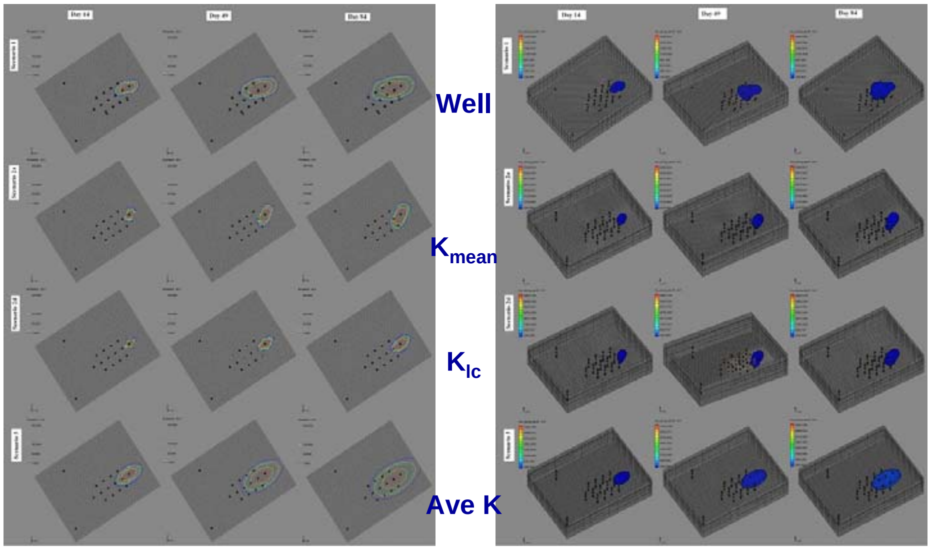


ug/ft^2-day

MODELING
Concentration and Flux

Scenario	Head	K	Porosity
1	Well	Well	Average
2a	SCAPS	SCAPS K_{mean}	SCAPS
2b	SCAPS	SCAPS K_{min}	SCAPS
2c	SCAPS	SCAPS K_{max}	SCAPS
2d	SCAPS	SCAPS K_{lookup}	SCAPS
3	Well	Well	SCAPS
4a	Well	SCAPS K_{mean}	SCAPS
4b	Well	SCAPS K_{min}	SCAPS
4c	Well	SCAPS K_{max}	SCAPS
4d	Well	SCAPS K_{lookup}	SCAPS
5	Unif. grad.	Average	Average

MODELING
Concentration and Flux



ppb

ug/ft^2-day

GROUNDSWELL 62

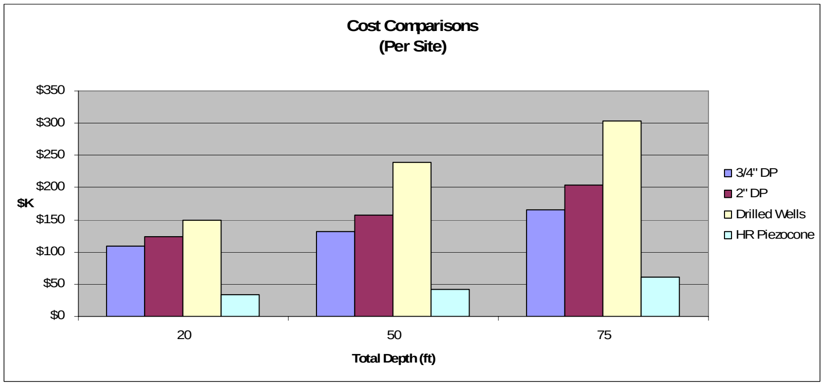
EPA Clu-In 08/13/09

PERFORMANCE

Performance Summary.

Performance Criteria	**Expected Performance Metric**	**Results**
Accuracy of high-resolution piezocone for determining head values, flow direction and gradients	± 0.08 ft head values	Met Criteria
Hydraulic conductivity (dissipation or soil type correlation)	± 0.5 to 1 order of magnitude	Met Criteria
Transport model based on probes	Predicted breakthrough times and concentrations within one order of magnitude; probe based model efficiency accounts for more than 15% of the variance associated with well based models	Met Criteria
Time required for generation of 3-D conceptual and transport models	At least 50% reduction in time	Met Criteria

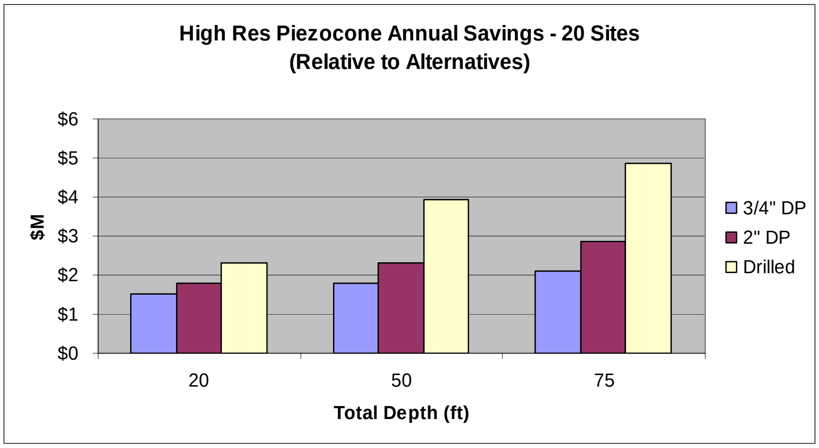
FLUX CHARACTERIZATION
Cost Comparisons



"Apples to Apples" – HR Piez. with MIP vs. Wells, Aq. Tests, Samples
10 Locations/30 Wells

GROUNDSWELL 64 EPA Clu-In 08/13/09

FLUX CHARACTERIZATION
Cost Comparisons



Early Savings of ~$1.5M to $4.8M

GROUNDSWELL 65 EPA Clu-In 08/13/09

FLUX CHARACTERIZATION
Time Comparisons

	Days to Complete		
Depth (ft)	Direct-Push Wells	Drilled Wells	HR Piezocone
20	90	104	13
50	99	137	15
75	111	151	19

"Apples to Apples" – HR Piez. with MIP vs. Wells, Aq. Tests, Samples
10 Locations/30 Wells

FUTURE PLANS

Tech Transfer

- Industry Licensing (AMS/ENVI - Market Ready by September '09)
- ITRC Guidance (Flux Methods – First Draft by September '09)
- ASTM D6067

Final Reports

- Final:
  (*http://www.clu-in.org/s.focus/c/pub/i/1558/*)
- Cost and Performance:
  (*http://costperformance.org/monitoring/pdf/Char_Hyd_Assess_Piezocone_ESTCP.pdf)*

"Single Mobilization Solution" Integration

- Expedited Chem/Hydro Characterization/Modeling
- Expedited LTM Network Design
- Sensor Deployment
- Automated Remediation Performance via Flux

CONTAMINANT FLUX MONITORING STEPS

(Remediation Design/Effectiveness)

- Generate Initial Model (Seepage Velocity, Concentration Distributions)
  - Conventional Approaches
  - High-Resolution Piezocone/MIP
- Install Customized 3D Monitoring Well Network
  - ASTM
  - Kram and Farrar Method
- Monitor Water Level and Concentrations (Dynamic/Automate?)
- Track Flux Distributions (3D, Transects)
- Evaluate Remediation Effectiveness
  - Plume Status (Stable, Contraction, etc.)
  - Remediation Metric
  - Regulatory Metric?

EXPEDITED FLUX APPROACH
"Single Mobilization Solution"

Plume Delineation
- MIP, LIF, ConeSipper, Waterloo^{APS}, Field Lab, etc.
- 2D/3D Concentration Representations

Hydro Assessment
- High-Res Piezocone (2D/3D Flow Field, K, head, eff. por.)

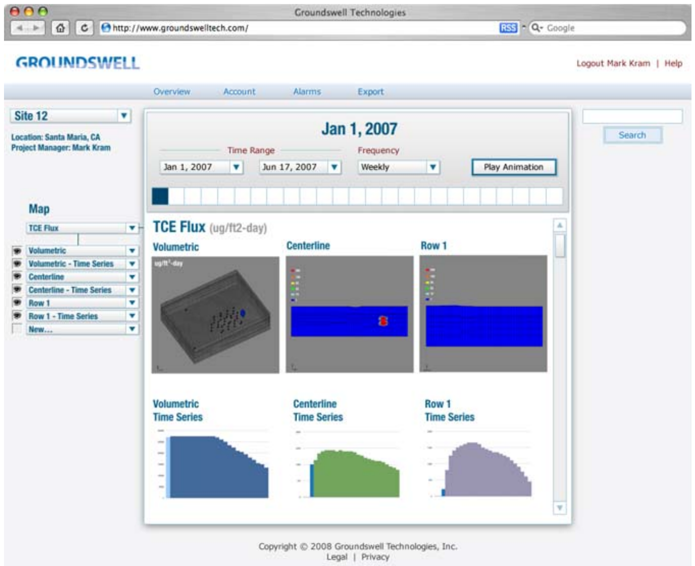
LTM Network Design
- Well Design based on CPT Data
- Field Installations (Clustered Short Screened Wells)

Surveys (Lat/Long/Elevation)

GMS Interpolations (ν, F), Conceptual/Analytical Models

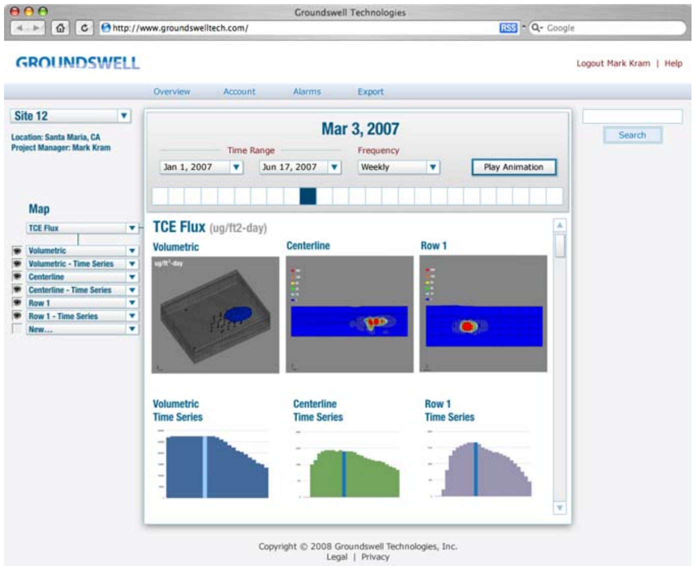
LTM Flux Updates via Head/Concentration
- Conventional Data
- Automated Modeling

Conceptual / Analytical Model

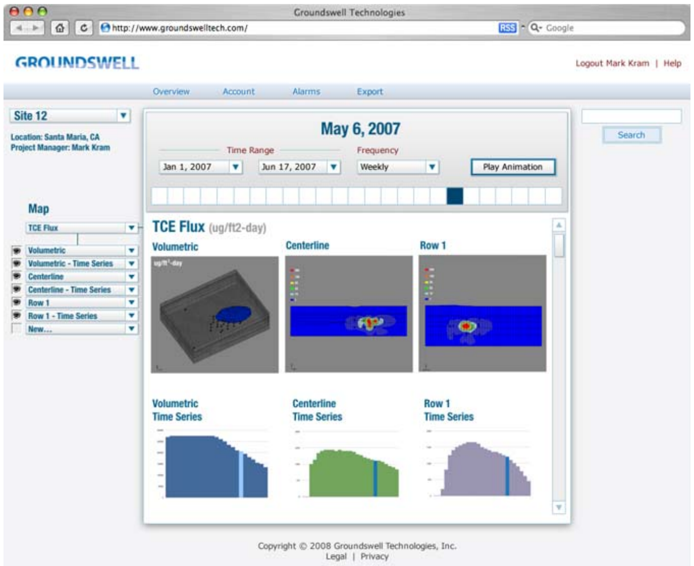


GROUNDSWELL 70 EPA Clu-In 08/13/09

Conceptual / Analytical Model

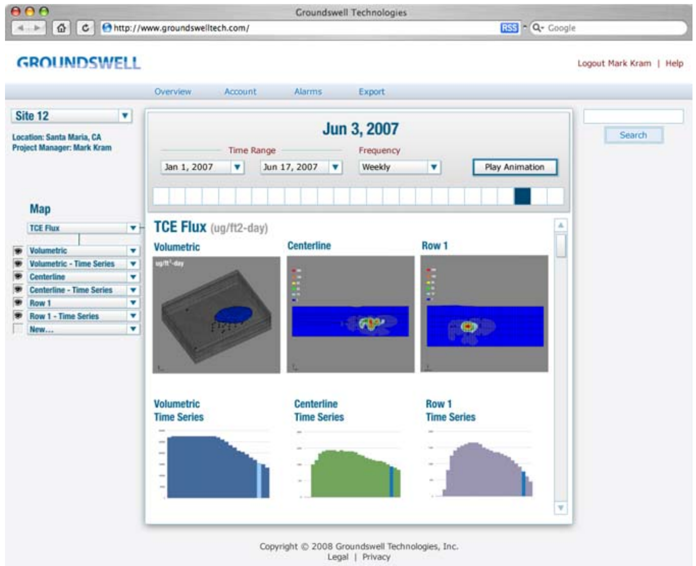


Conceptual / Analytical Model



GROUNDSWELL 72 EPA Clu-In 08/13/09

Conceptual / Analytical Model



CONCLUSIONS

- High-Res Piezocone Preliminary Results Demonstrate Good Agreement with Short-Screened Well Data
- Highly Resolved 2D and 3D Distributions of Head, Gradient, K, Effective Porosity, and Seepage Velocity Now Possible Using HRP and GMS
- When Know Concentration Distribution, 3D Distributions of Contaminant Flux Possible Using DP and GMS
- Single Deployment Solutions Now Possible
- Exceptional Capabilities for Plume “Architecture” and Monitoring Network Design
- Significant Cost Saving Potential
- New Paradigm - LTM and Remediation Performance Monitoring via Sensors and Automation (4D)

ACKNOWLEDGEMENTS

SERDP – Funded Advanced Fuel Hydrocarbon Remediation National Environmental Technology Test Site (NETTS)

ESTCP – Funded Demonstration

Field and Technical Support –

Project Advisory Committee
Jessica Chau (U. Conn.)
Gary Robbins (U. Conn.)
Ross Batzoglou (U. Conn.)
Merideth Metcalf (U. Conn.)
Tim Shields (R. Brady & Assoc.)
Craig Haverstick (R. Brady & Assoc.)
Fred Essig (R. Brady & Assoc.)
Jerome Fee (Fee & Assoc.)
Dr. Lanbo Liu and Ben Cagle (U. Conn.)
U.S. Navy

Dorothy Cannon (NFESC)
Kenda Neil (NFESC)
Richard Wong (Shaw I&E)
Dale Lorenzana (GD)
Kent Cordry (GeoInsight)
Ian Stewart (NFESC)
Alan Vancil (SWDIV)
Dan Eng (US Army)
Tom Dalzell (AMS)
Per Ljunggren (ENVI)


THANK YOU!
For More Info:
Mark Kram, Ph.D. (Groundswell)
805-844-6854
Tom Dalzell (AMS)
208-408-1612

Thank You

After viewing the links to additional resources, please complete our online feedback form.