Federal Remediation Technology Roundtable

Demonstration and Validation of the Fractured Rock Passive Flux Meter

ESTCP Project ER0831

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Project Team

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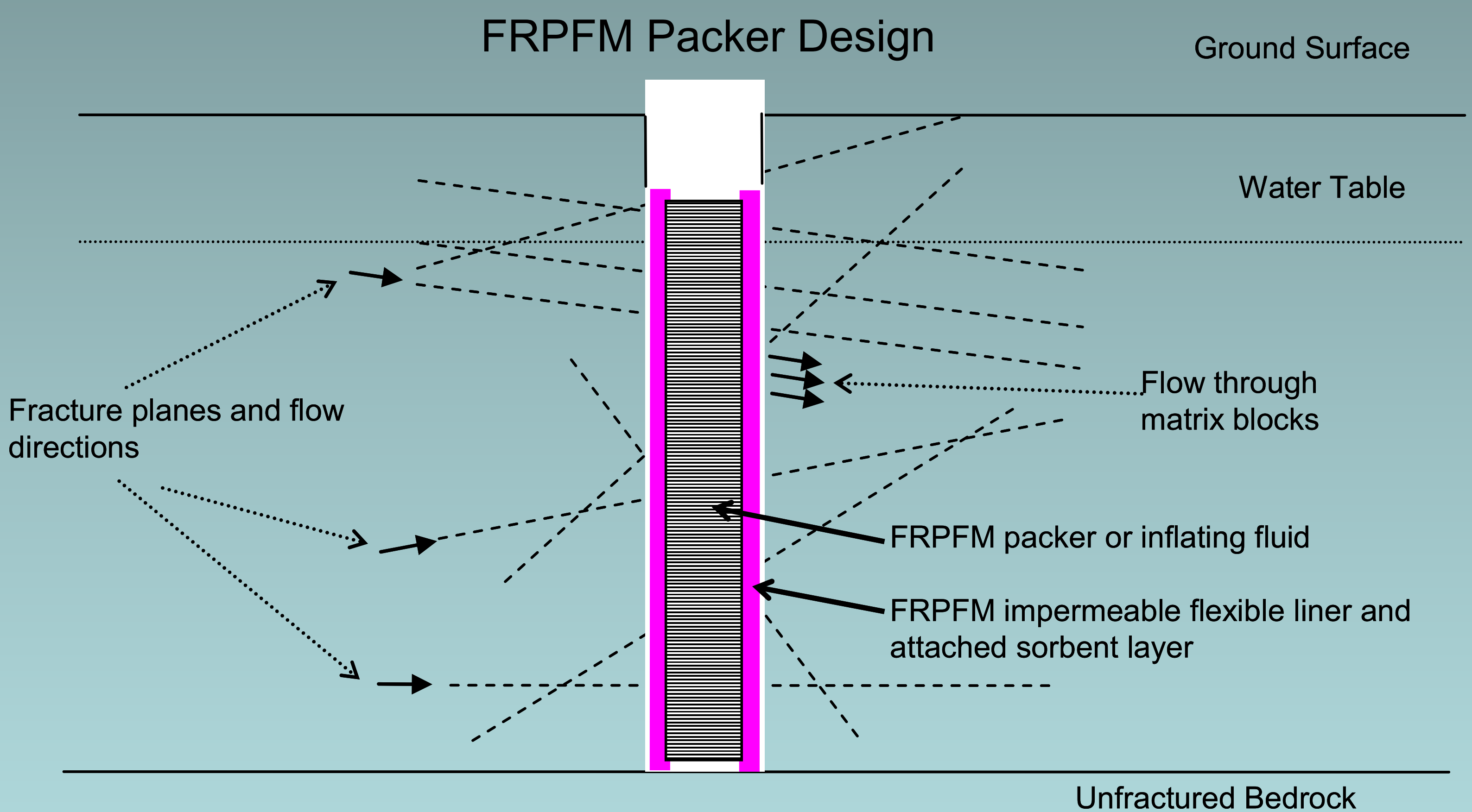
Technical Objectives

- The objective of this project is to demonstrate and validate the fractured rock passive flux meter (FRPFM) as an innovative closed-hole technology. Specific project objectives are:

  1. Demonstrate and validate an innovative technology for the direct in situ measurement of cumulative water and contaminant fluxes in fractured media

  2. Formulate and demonstrate methodologies for interpreting contaminant discharge from point-wise measurements of cumulative contaminant flux in fractured rock

Technology Description



Packer minimizes vertical cross-flow between fractures

Technology Description

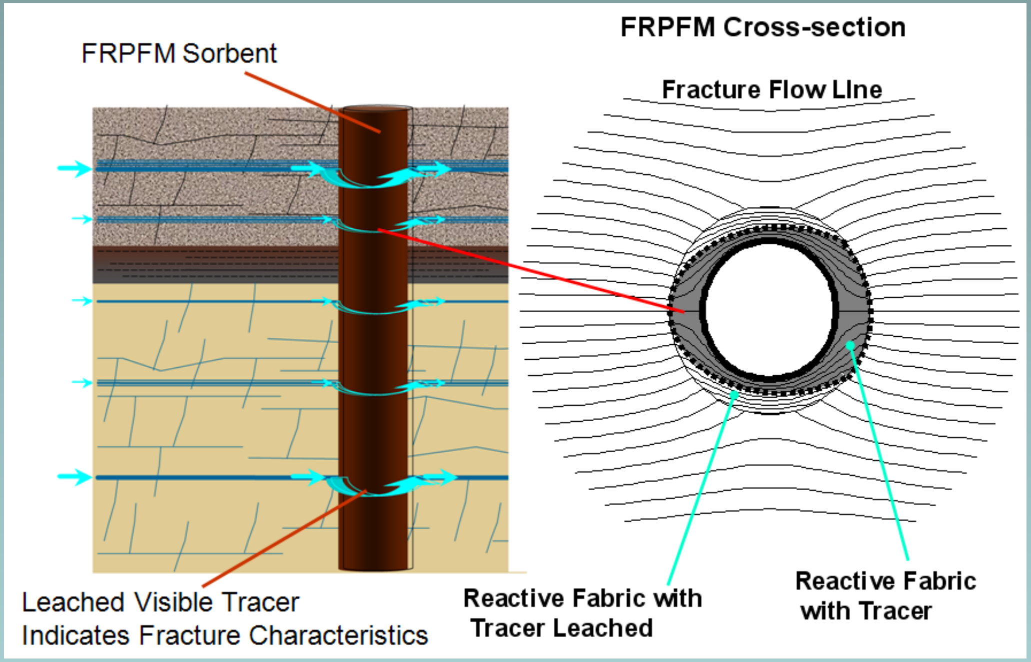
- The FRPFM is essentially an inflatable packer or impermeable flexible liner that holds a reactive permeable fabric against the wall of the borehole and to any water-filled fractures intersected by the borehole.

- Reactive fabrics capture target contaminants and release non-toxic resident tracers (e.g., visible dyes and branch alcohols).

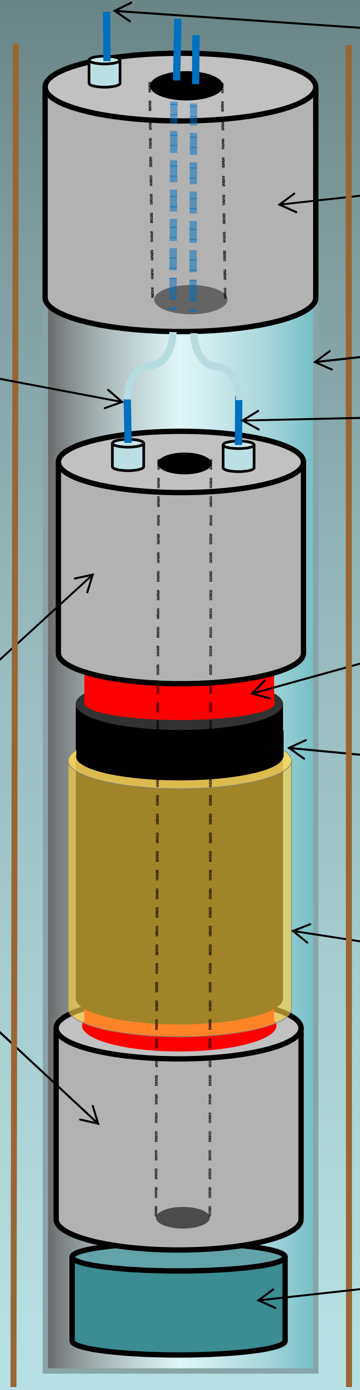
- Tracer loss is proportional to <u>ambient </u>fracture flow.

- Leached visible tracers reveal location and orientation of active fractures and flow direction.

- Contaminant mass captured is proportional to <u>ambient</u> contaminant flux.



FRPFM Prototype with Shield



Dimensions

Borehole ID = 3.8 in (9.652 cm)
Nominal 4 in borehole

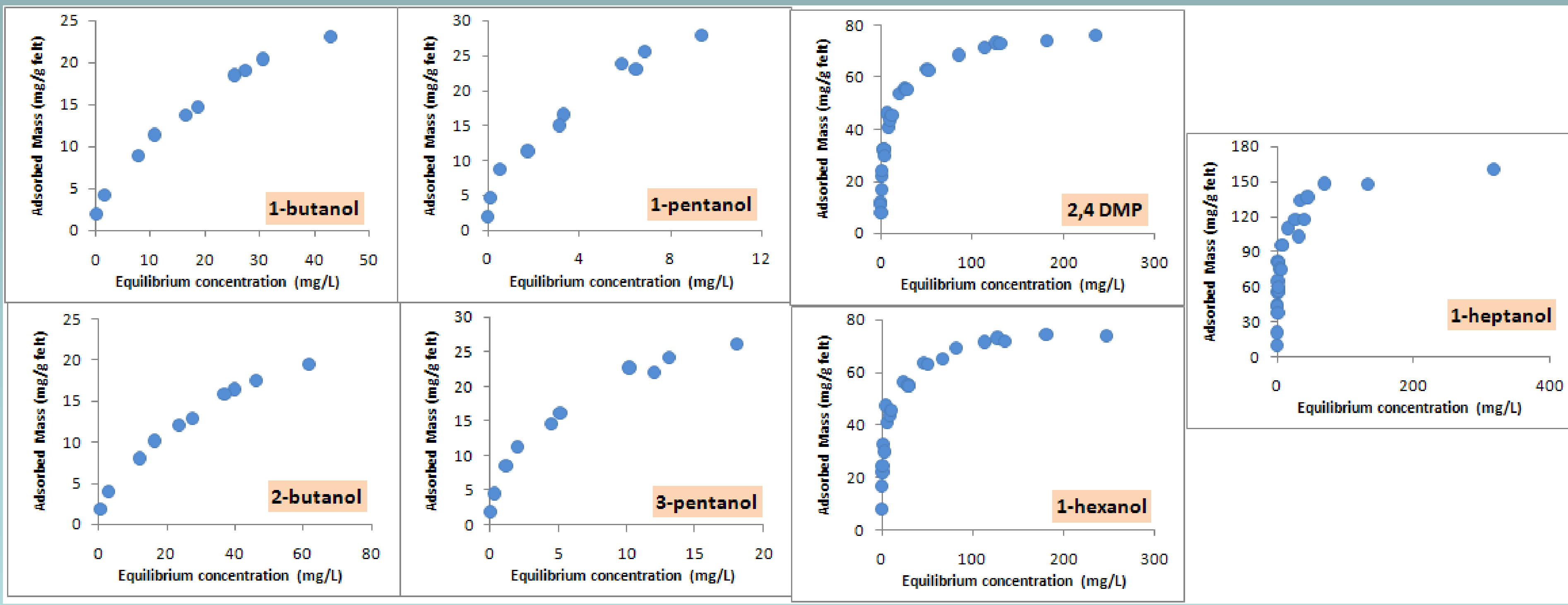
<u>Un-Inflated Dimensions</u>
Shield packer OD = 3.5 in
Shield OD = 3.5 in
Packer OD = 3.3 in
Core OD = 3.2 in
(with sorbent and sock)

Note: When inflated all dimensions match borehole ID

Selection of Sorbents and Resident Tracers

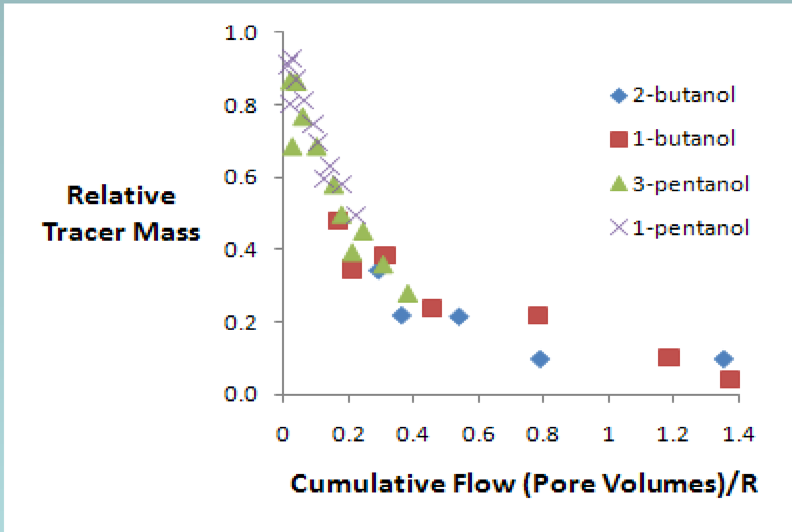
Suite of Non-toxic Branched Alcohols

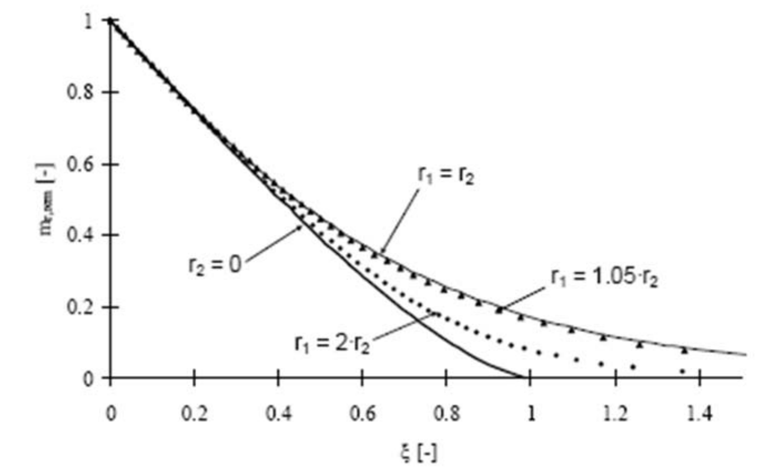
Batch Tracer Sorption Isotherms on Felt 1300



Resident Tracer Results

- Water Flux Measurements can be interpreted from resident tracer losses.
- Tracer retardation factors and elution functions are sensitive to the nonlinear sorption isotherms.
- Consistent use of tracers and sorbents is critical!





Elution curves for varying thickness of sorbent material (Klammler, 2004).

Laboratory Fracture Simulator

Fracture Dimensions:
- Horizontal
- Aperture = 500 μm
- Width = 26 cm
- Length = 53 cm
- Conductivity ~0.7 cm/s

Borehole:
- Diameter 10.16 cm

Flow Convergence:
- Maximum = 1.76

FRPFM Performance in the Laboratory

Visual Tracer Reveals Fracture Location and Orientation and Flow Direction

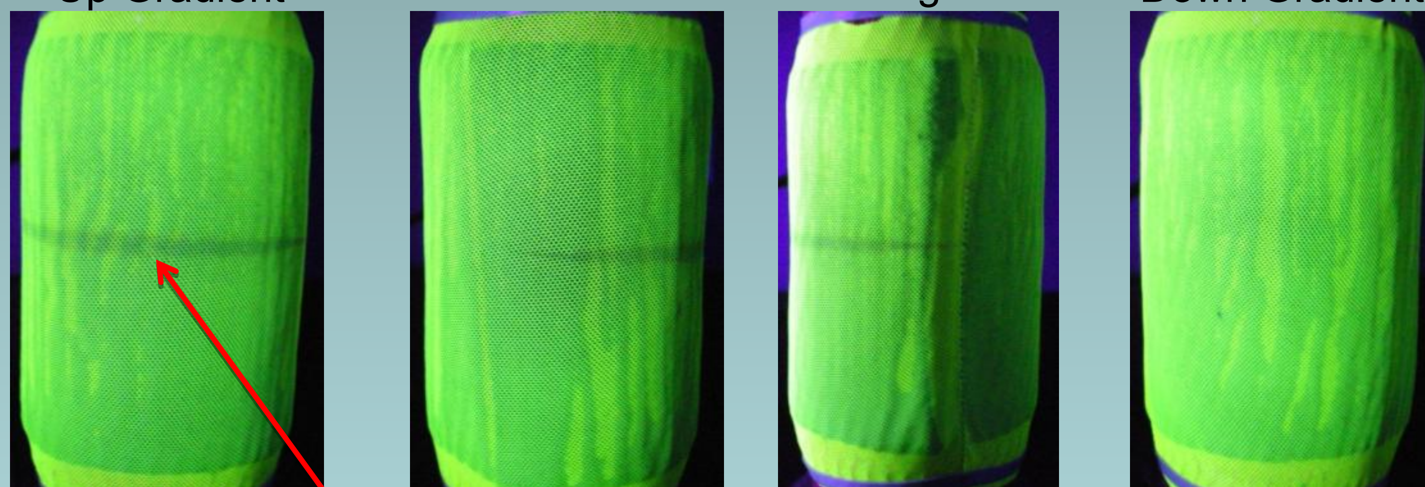
Front
Up Gradient

Left

Right

Back
Down Gradient

4 mm



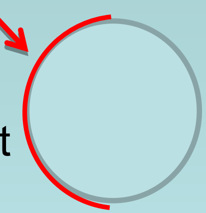
Visual indication of flowing fracture

- 0.5 mm fracture aperture
- Q = 1.5 ml/min, q = 2500 cm/day
- Duration 1 day
- Visual fracture zone (max) aperture 4 mm
- Visual fracture zone length along circumfrance147 mm

Flow

Left

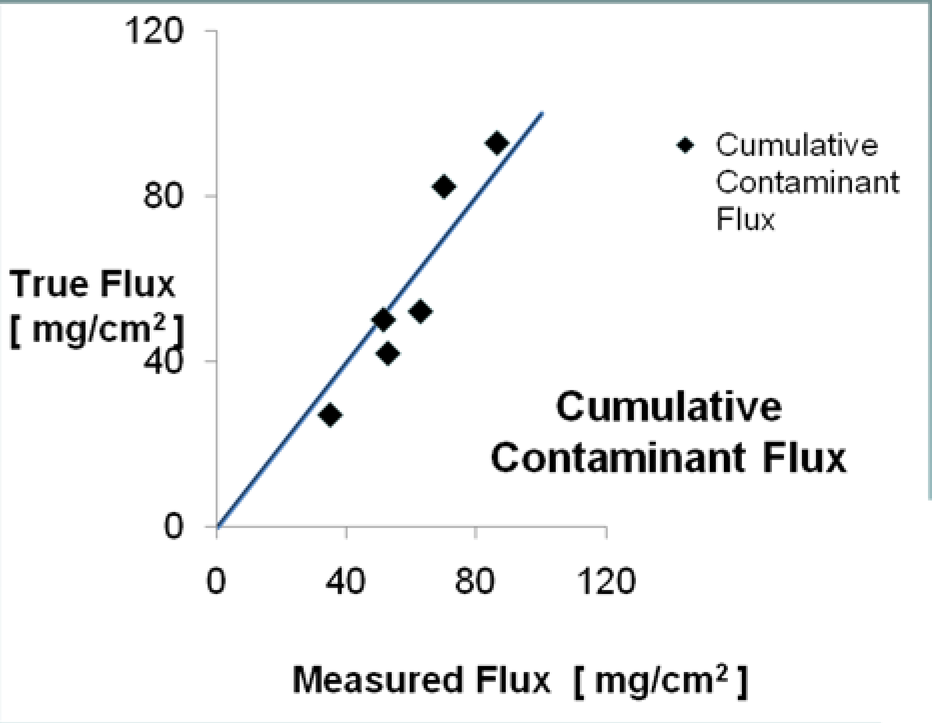
Front
Up Gradient

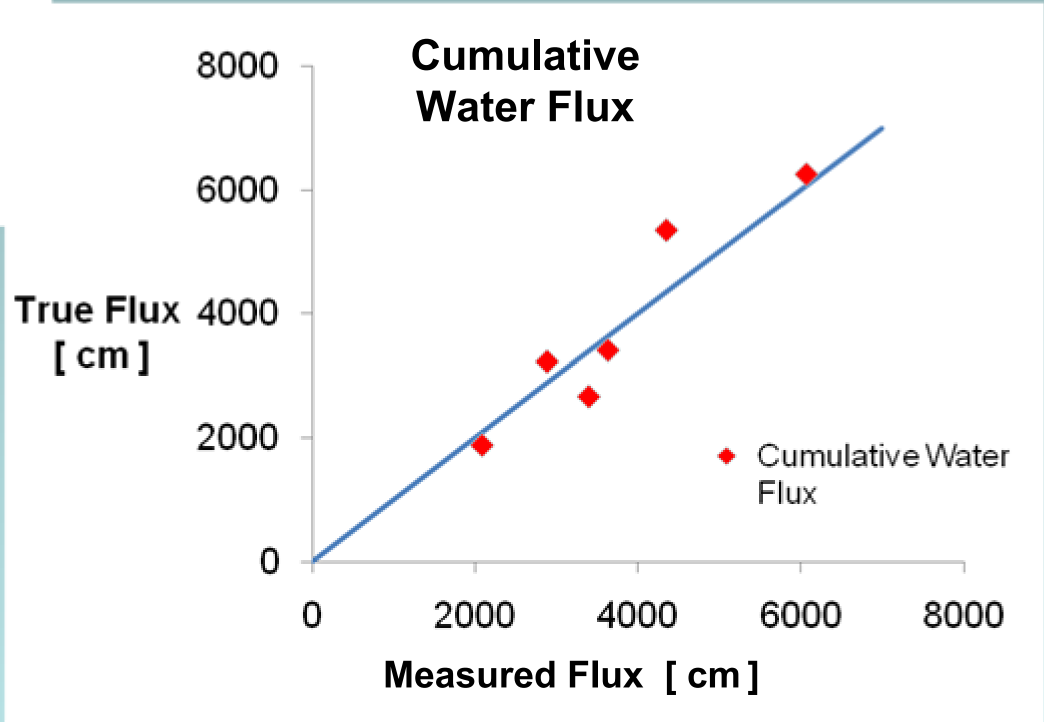


Back
Down Gradient

Right

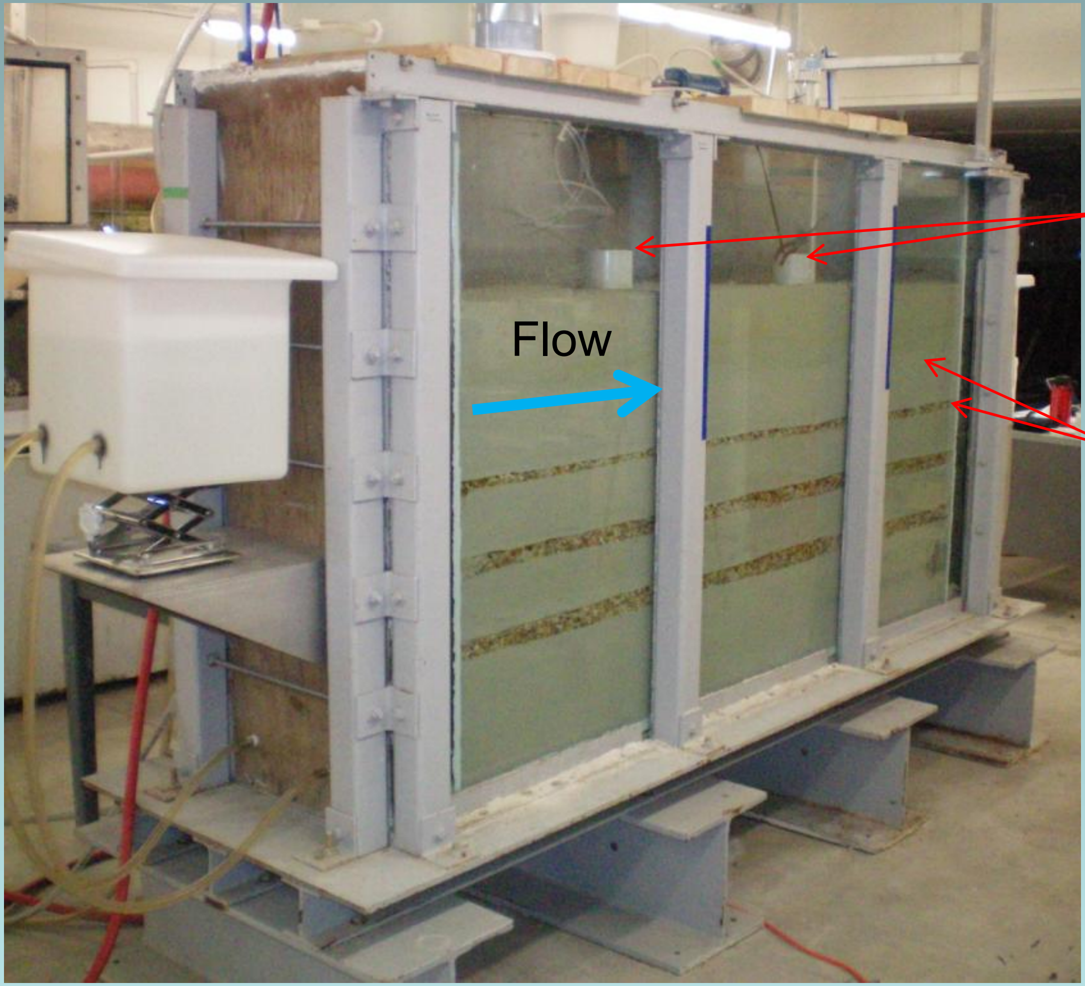
FRPFM Performance





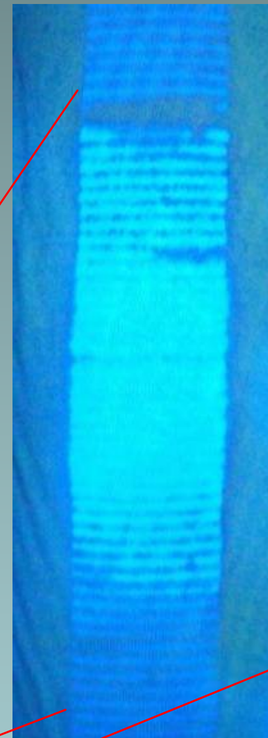
Large Aquifer Box (High contrast flow zones)

Box Dimensions
(length x width x height)
2.0 x 0.5 x 1.3 m

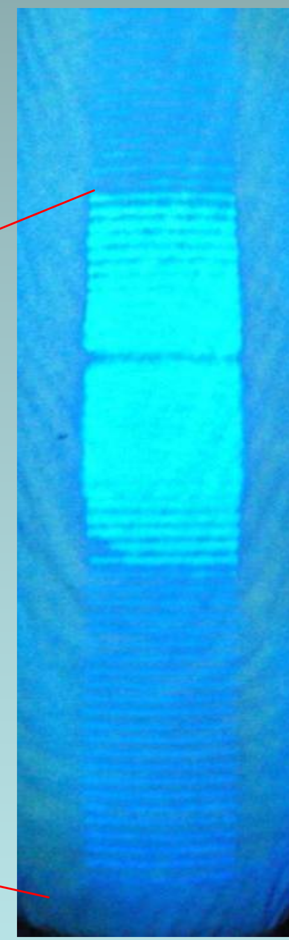


Screened Wells (4-inch diameter PVC)

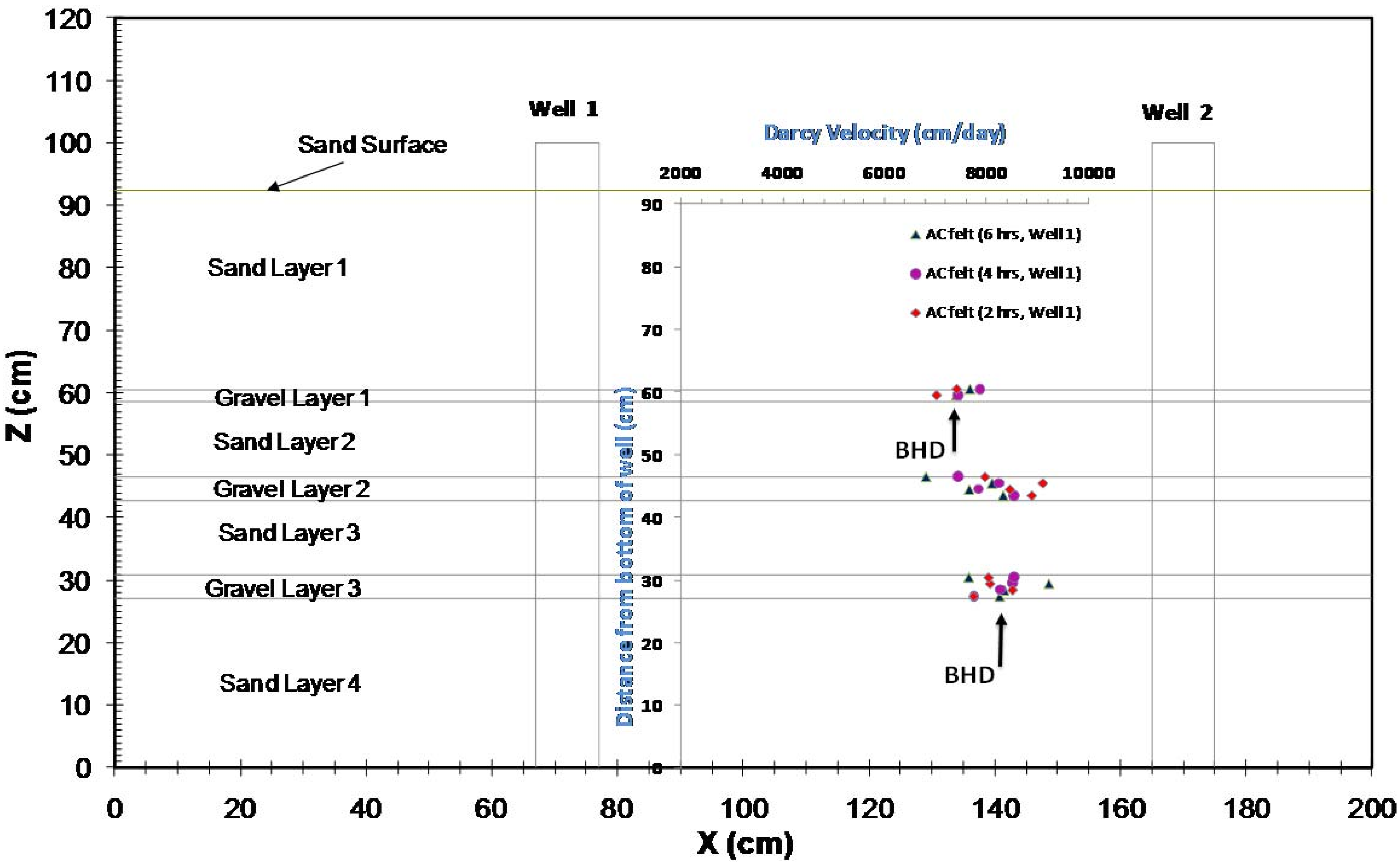
Alternating Sand and Gravel Layers



Visual Indication of Flow



FRPFM Results in Aquifer Box



Two Field Sites

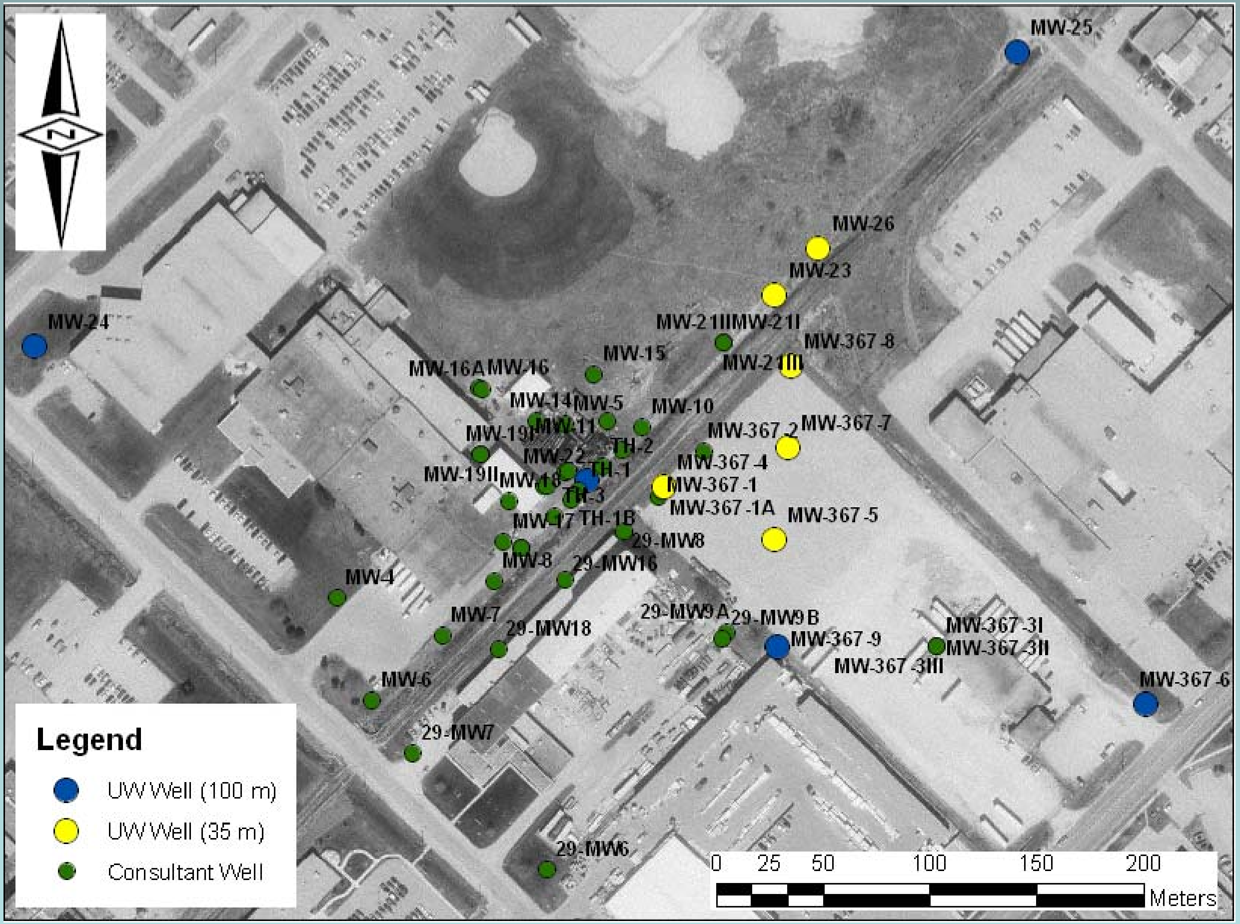
Guelph Tool Site, Ontario, Canada

Former Naval Air Warfare Center (NAWC), West Trenton, NJ

Site Description

Guelph Tool Site,
Ontario, Canada

- Guelph Tool Inc. facility
- Site is well characterized
- Fractured Dolostone
- High bulk conductivity
- Medium to large apertures
- TCE
- Natural gradient conditions
- Excellent infrastructure
- Leverage the FRFRF



Test Design

Guelph Tool Site, Ontario, Canada

Project will:

1. Validate FRPFM performance in one or two fractured rock holes or sections of holes located in a chlorinated solvent plume

2. Combine existing site data with new data generated from this study to explore potential cost-savings derived from using the FRPFM in conjunction with other borehole technologies

MW 26 (first 12 meters)

Zone	Top Depth (mbTOC)	Bot Depth (mbTOC)	T (m2/s)	Number of ATV Fractures in Test Interval	ATV Fractures Equivilent 2b (μm)
1	40.5	43.04	1.59E-05	4	185
2	39	40.5	1.78E-06	5	82
3	37.5	39	7.81E-06	4	151
3	37.5	39	1.29E-06	4	79
4	36	37.5	4.47E-07	4	58
5	34.5	36	1.97E-06	5	89
6	33	34.5	1.58E-06	6	78
7	31.5	33	2.98E-06	5	102
8	30	31.5	2.62E-06	1	159
9	28.5	30	4.47E-05	4	258

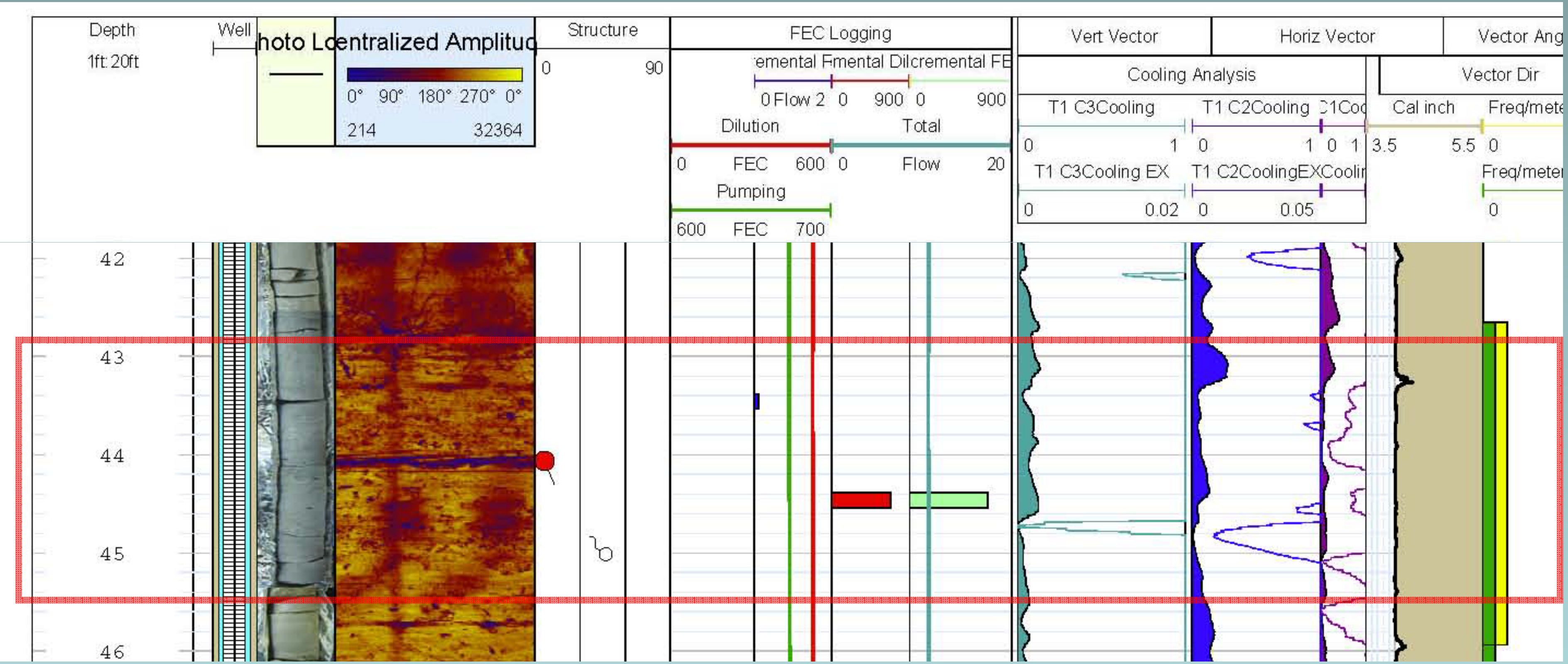
Test Design

Performance Tests		
Target Measurement	**FRPFM Technology**	**Competing Technology**
Water Flux	Resident Tracers	Borehole Dilution
Contaminant Flux	Contaminant Sorption	Modified Borehole Dilution
Detection of Flowing Fractures	Visual Tracer	Hydrophysical Logging (open hole) , Temperature Logging (closed hole)
Flow Direction	Visual Tracer	Scanning Colloidal Borescope
Fracture Orientation	Visual Tracer	Optical and Acoustic Televiewer

Field-Scale Prototype Test: Deployment

Well MW-26: Nominal 4-inch open borehole.

MW-26
Target Zone for Deployment



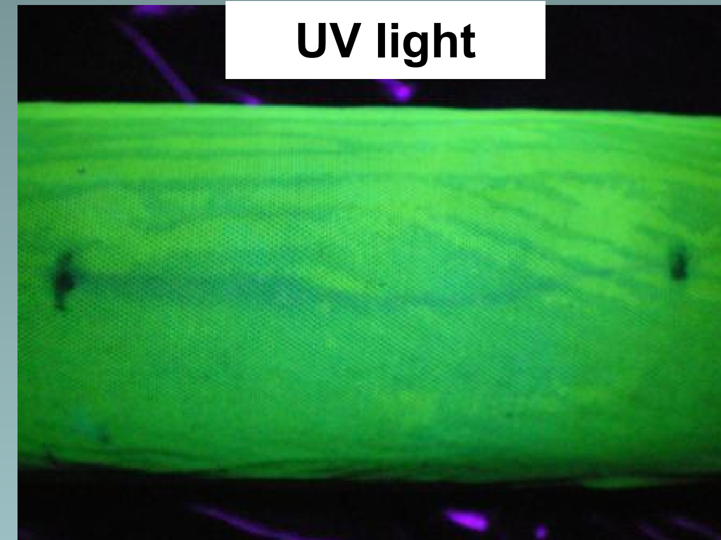
Selected zone for location of FRPFM based upon ATV, Tadpoles, HPL, HRTP, and Caliper data

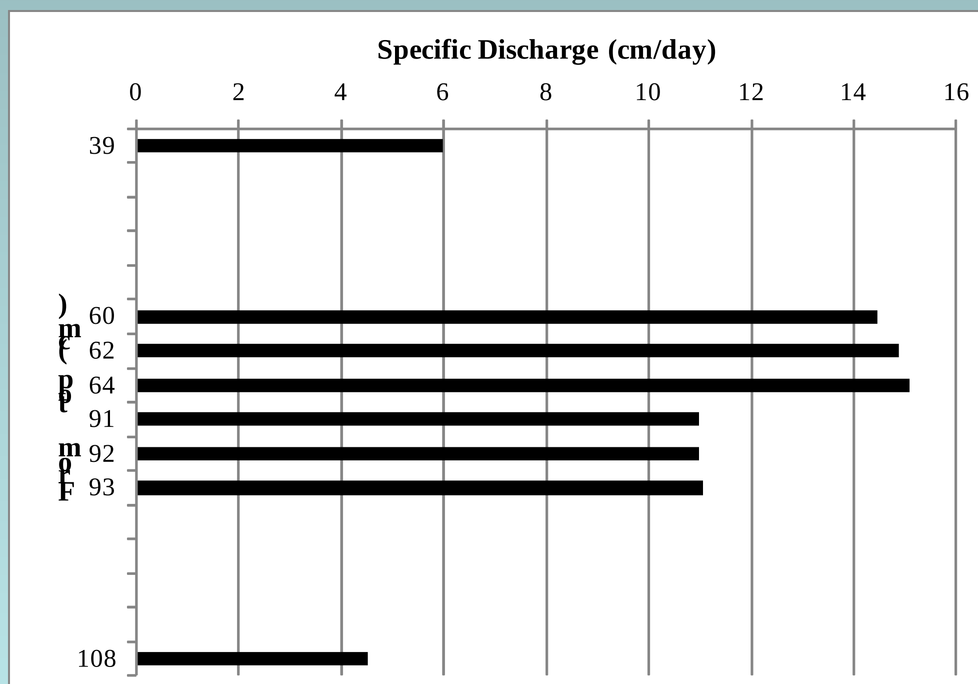
FRPFM Measured Water Fluxes:

- **9.6 cm/d average specific discharge**
- **36-180 m/d fracture flow**

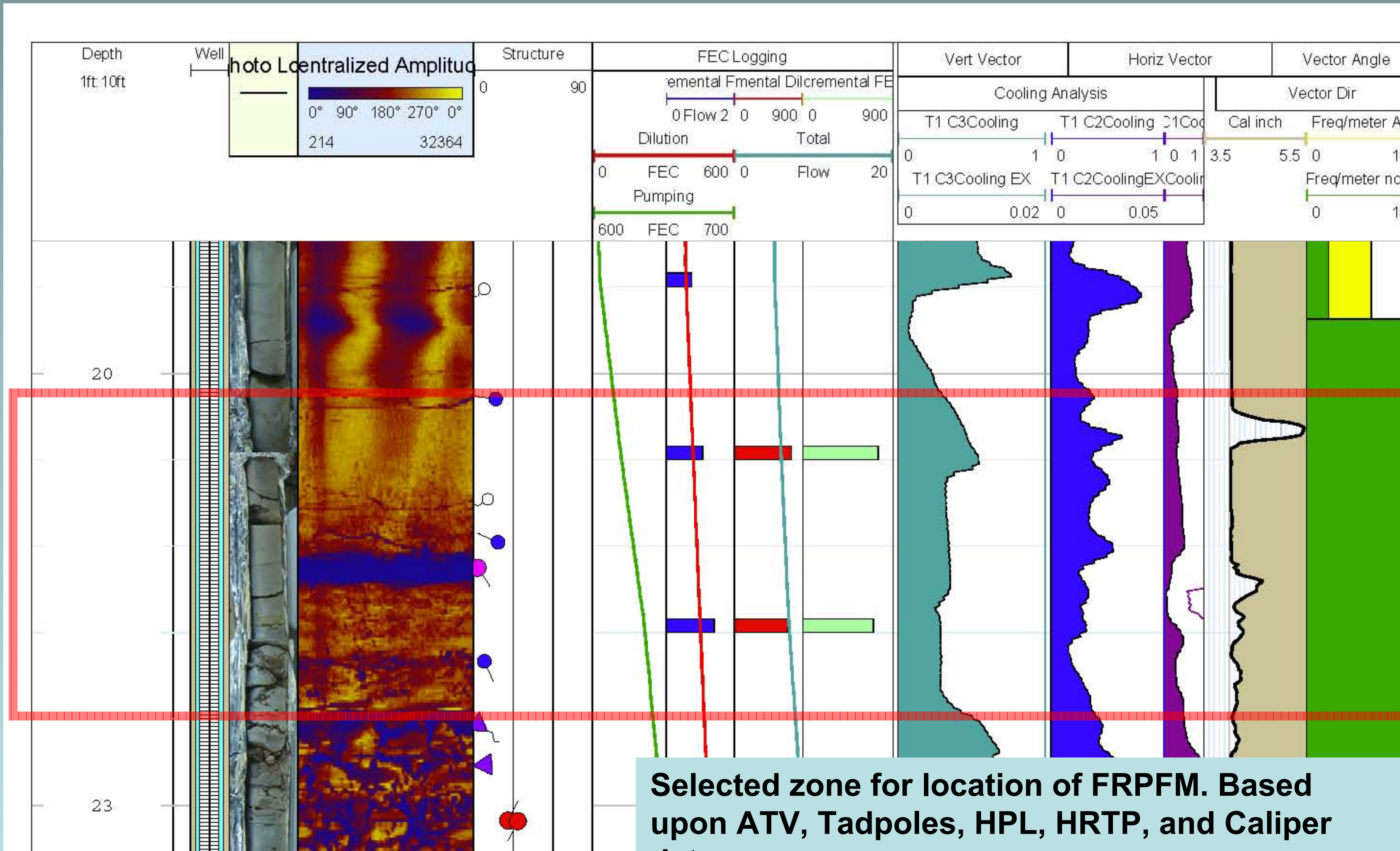
Visual indication of discrete flow intercepting FRPFM (MW-26 at 13.87 m below TOC) Sample zone 88-98cm

Black marks provide frame of reference.



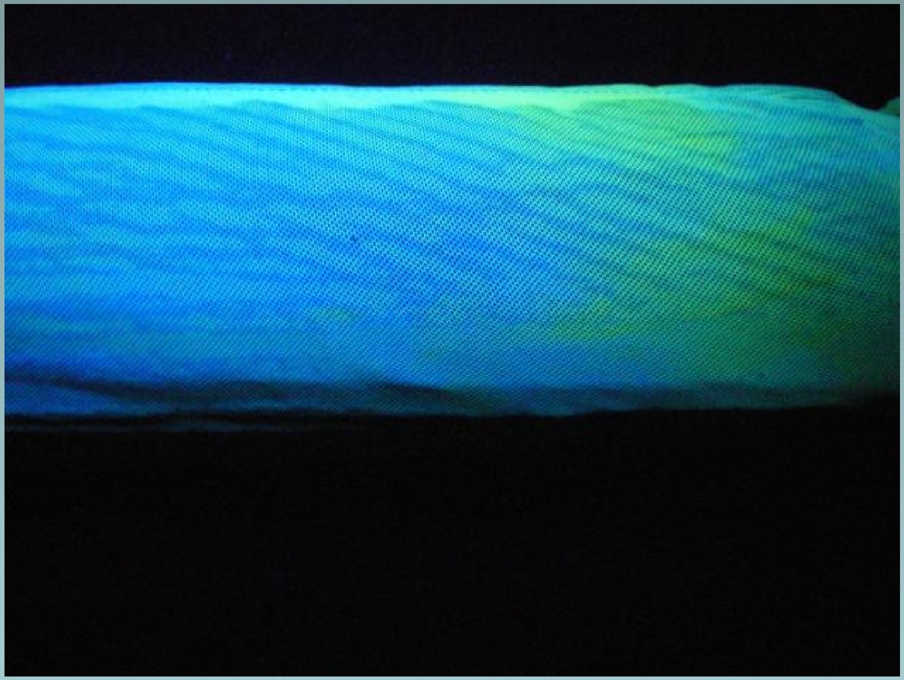


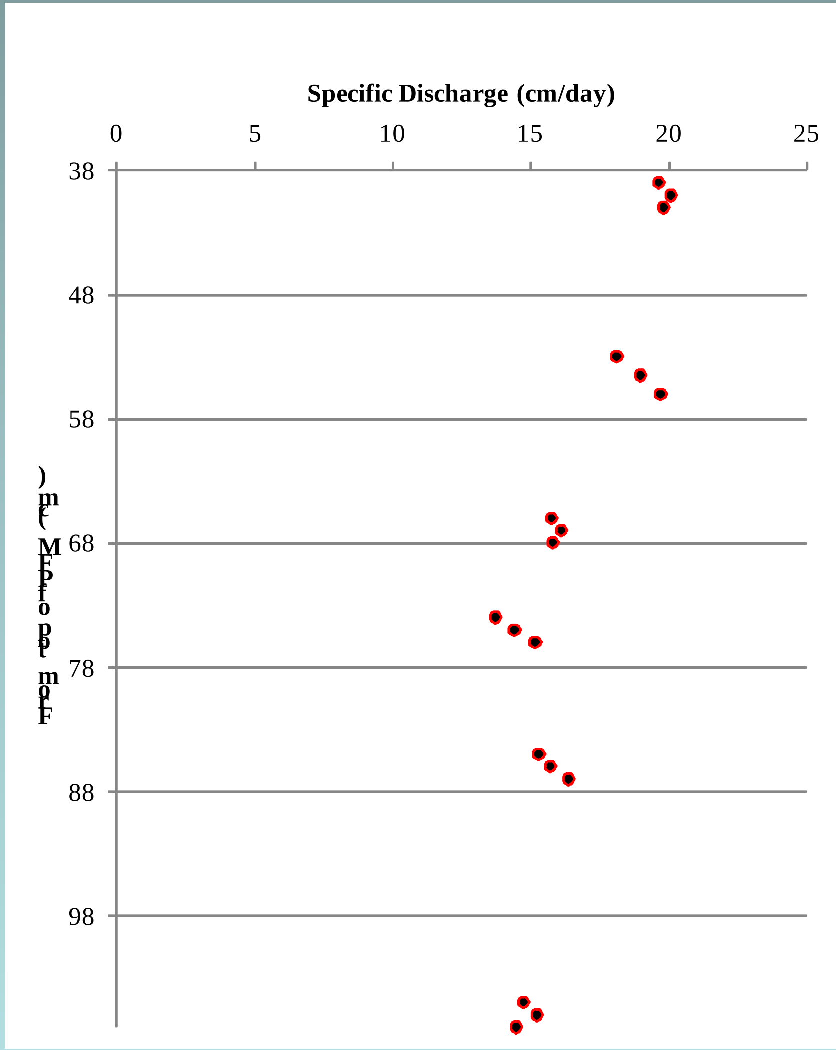
MW-26
Target Zone for Deployment (Upper high permeability zone)



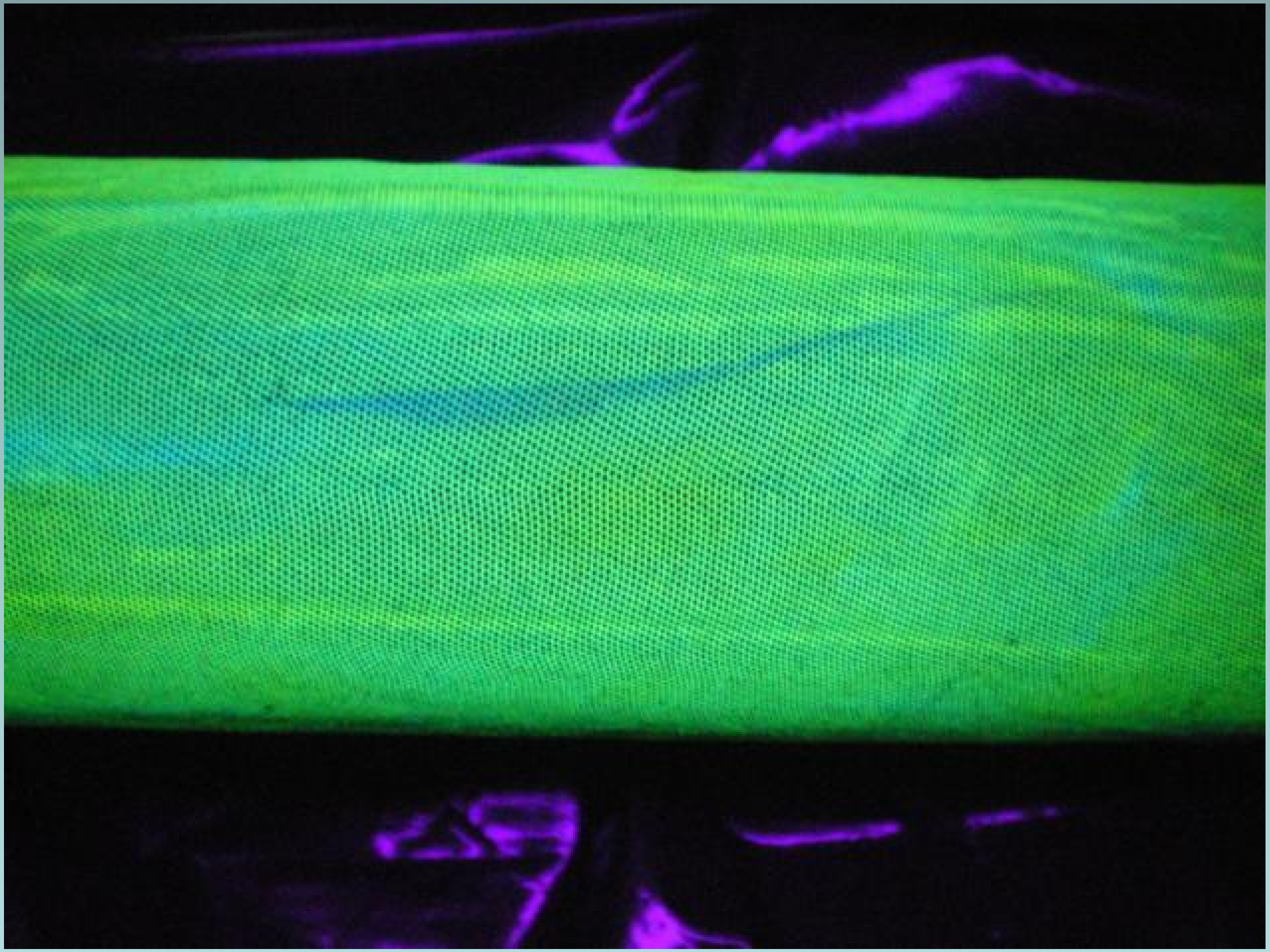
Selected zone for location of FRPFM. Based upon ATV, Tadpoles, HPL, HRTP, and Caliper data.

Visual indication of tracer washout (under UV light) from high permeability zone in upper portion of MW-26

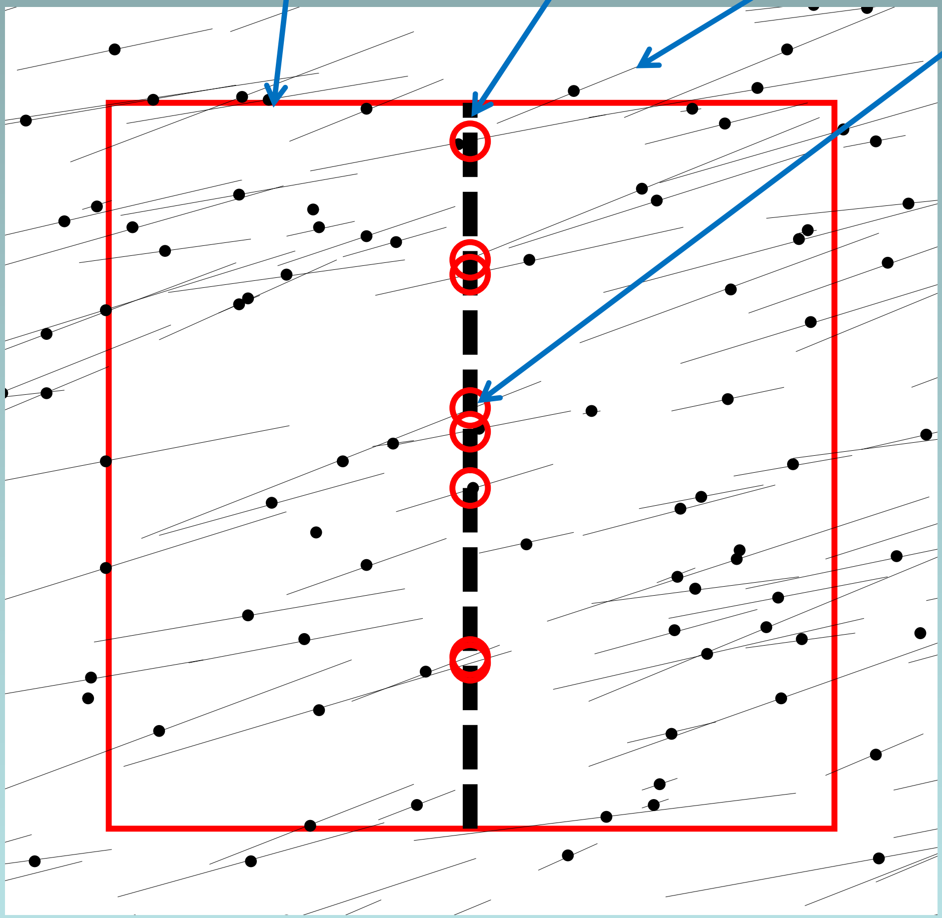




Visual indication of discrete flow intercepting FRPFM MW-25 at 26ft bgs (under UV light)



Physical Setup:
Transect, Borehole(s), Traces, Intersections



Problems:

(1)Estimate discharge Q through traces in transect from measured fluxes q_i at borehole-trace intersections

(2)Quantify estimation uncertainty

Parameters Involved

- **Intersections:** number $\mathbf{N_i}$, orientations $\boldsymbol{\theta}_\mathbf{i}$
- **Fluxes $\mathbf{q_i}$*** (at each intersection perpendicular to transect): flow per unit trace length = velocity times aperture

→ As $\mathbf{q_i}$* are measured directly, fracture aperture, roughness and gradients are not required.

- **Transect:** width **W**, height **H**, number of wells
- **Traces:** number $\mathbf{N_t}$ (in transect) or areal fracture density $\boldsymbol{\lambda_A}$, lengths $\boldsymbol{l}_\mathbf{t}$, mean flux $\mathbf{q_t}$, orientations $\boldsymbol{\theta}_\mathbf{t}$

True discharge (in L^3/T):

$$Q = \sum_{t=1}^{N_t} l_t q_t$$

Discharge Estimation at Transects

- Total number of fractures $\mathbf{N_t}$, Areal fracture density $\boldsymbol{\lambda_A}$ and facture length $\boldsymbol{l}$ are not easily determined from borehole data
- However fracture frequency $\boldsymbol{\lambda_L}$ (# of fractures intersected per unit length of borehole) is directly measured at each borehole
- Fracture frequency is a measure of the product of fracture density and length (Robertson, 1970; Baecher et al., 1977):

$$\boxed{\lambda_L / \overline{\cos\theta} = \lambda_A \bar{l}}$$

Ground Water Discharge Estimation

- For each borehole:

$$Q = \left(\sum \left(q \frac{\lambda_L}{\cos\theta}\right) \right) (\text{transect area})$$

Q : groundwater discharge estimated at the borehole L^3/T]

q : FRPFM groundwater flux measurement [L^2/T]

(q = Darcy velocity*aperture)

λ_L /cosθ : measured fracture frequency corrected for orientation bias

θ : orientation angle between joint normal and borehole

Contaminant Discharge Estimation

- At each borehole:

$$M_Q = \left(\sum (J_c \frac{\lambda_L}{\cos\theta}) \right) (\text{transect area})$$

M_Q : contaminant mass discharge estimated at the borehole [M/T]

J_c : FRPFM mass flux measurement [M/LT]

(J_c = contaminant mass flux*aperture)

λ_L /cosθ : measured fracture frequency corrected for orientation bias

θ : orientation angle between joint normal and borehole

Project Status

- FRPFM was validated in the laboratory.
- FRPFM is being demonstrated and validated in thefield.
- Stochastic methods for estimating contaminant discharge look promising.

Questions?