Vertebrae™ Segmented Horizontal Wells for Monitoring Contaminant Mass Discharge

ESTCP ER20-5026

Kristen Hasbrouck, PG

May 9, 2023

Battelle 2023 Bioremediation Symposium

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Project Team

ARCADIS

	Craig Divine, PhD, PG	Principal Investigator, Technical Director
	Jesse Wright, MS, PG, PE	Horizontal well design expert, high-resolution site characterization
	Patrick Curry, PG	PFAS site assessment, mass flux methods

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	Kristen Hasbrouck, PG	Field implementation, 3-D modeling, mass flux methods

UNIVERSITY of GUELPH

	Beth L. Parker, PhD	Co-PI, validation of mass flux/discharge analytical and data analysis methods
	Steven Chapman, MSc, P.Eng	Mass flux/discharge methods development, field performance assessment
	Jonathan Munn, PhD, P.Geo.	DTS expertise for grout integrity and groundwater flux assessment

ENRX

	Lance Robinson, PE	Vertebrae system design, sensor technology incorporation

ESTCP

	Bonnie Packer, PhD *ARNG Cleanup and Restoration Branch*	Stakeholder collaboration

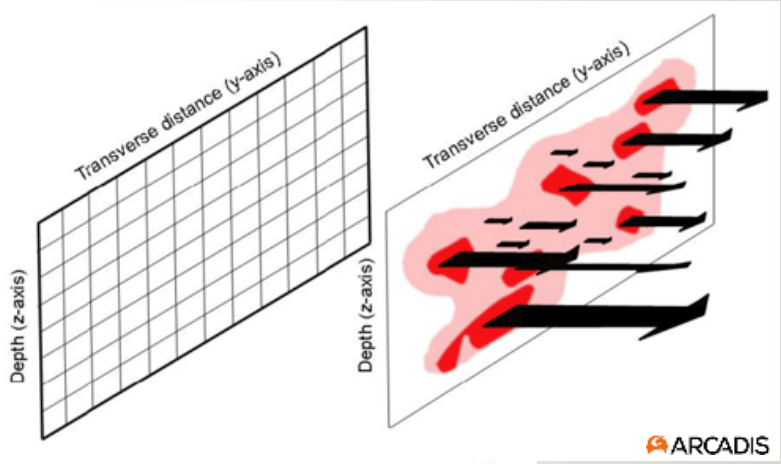
Agenda/Outline

- Mass Flux
- Technical Objectives
- Technology Description
- Full Scale Demonstration
  - Site Description
  - Field Work
  - Results
- Key Points

Why Does Flux Matter?

Contaminant maps don't tell the full story

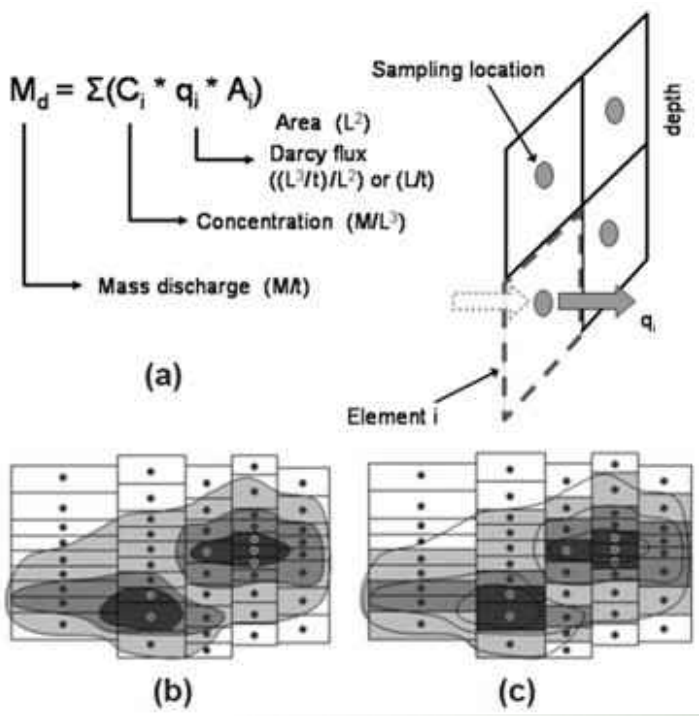
- Flux distinguishes mass in high permeability and low permeability zones to better quantify mass transport



Mass Flux describes the concentration of contaminant movement (mass/area/time)

Mass Discharge describes the mass of contaminant movement (mass/time)

- Better understanding of risk
- Better monitoring design
- Ability to focus remedy design



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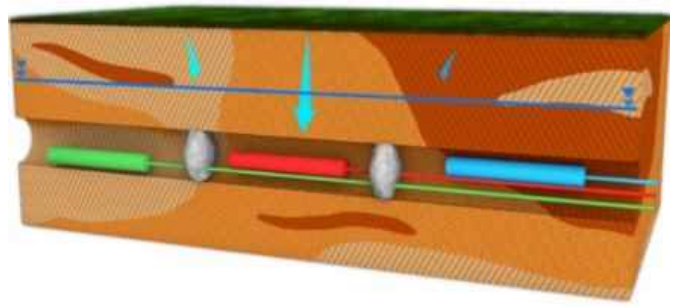
Technical Objectives

Demonstrate the Vertebrae system for reliable long-term monitoring of contaminant mass flux/discharge from source zones.

1. **Adapt and apply mass flux/discharge methods** proven for conventional vertical transect approaches to the Vertebrae system
2. **Compare Vertebrae system mass flux/discharge results** to a conventional vertical transect approach and measure changes over time
3. **Develop guidance regarding the technology**, application, limitations, anticipated performance, design considerations, and cost



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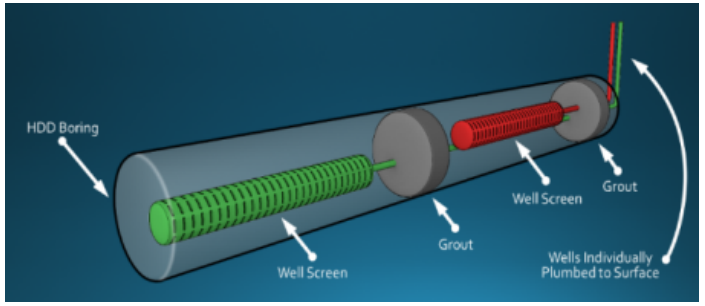
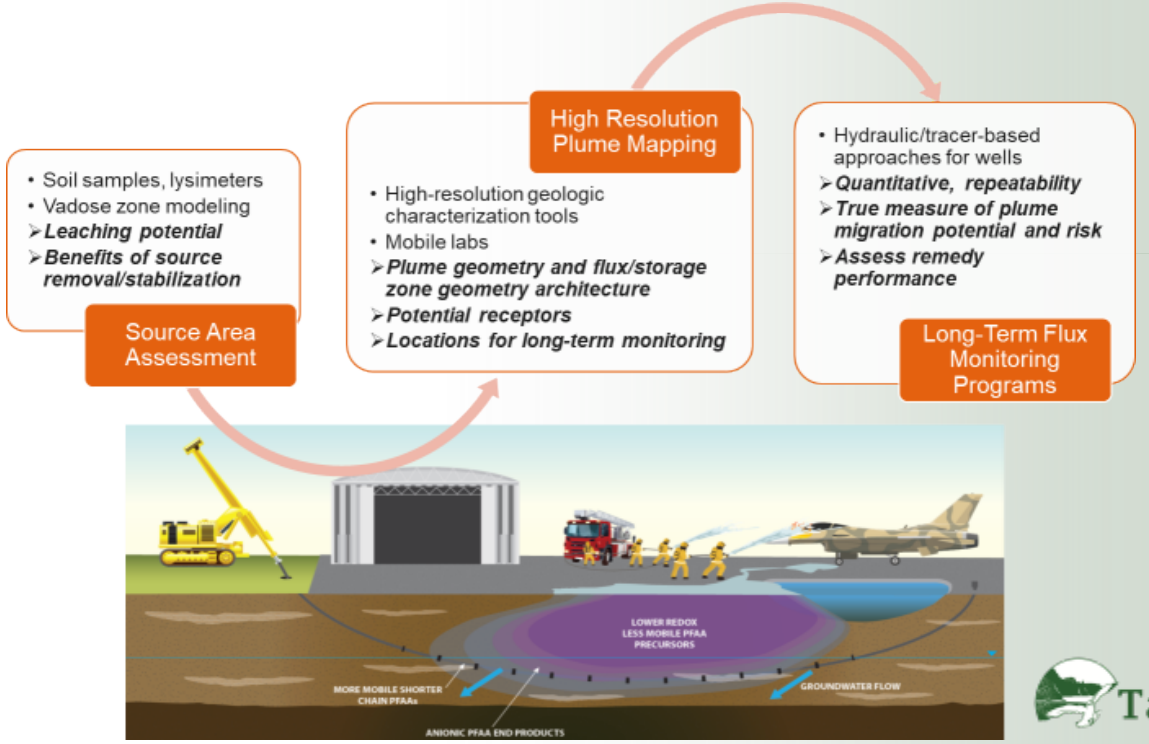
Technology Description

The Vertebrae™ system:

a segmented, nested horizontal well

- Each well screen segment isolated by a grout seal and separately plumbed to the surface
- >20 segments can be installed per system
- Well components are constructed off-site
- Cost breakpoint to vertical monitoring wells is 7-10 MWs = 1 Vertebrae system
- Provides access under active infrastructure
- Has also been used for fluid (liquid/gas) injection/extraction





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Full Scale Demonstration

Grayling Army Airfield

Vertebrae Segmented Wells

Site Description: Grayling Army Airfield

Grayling Army Airfield, Michigan

Site Conditions

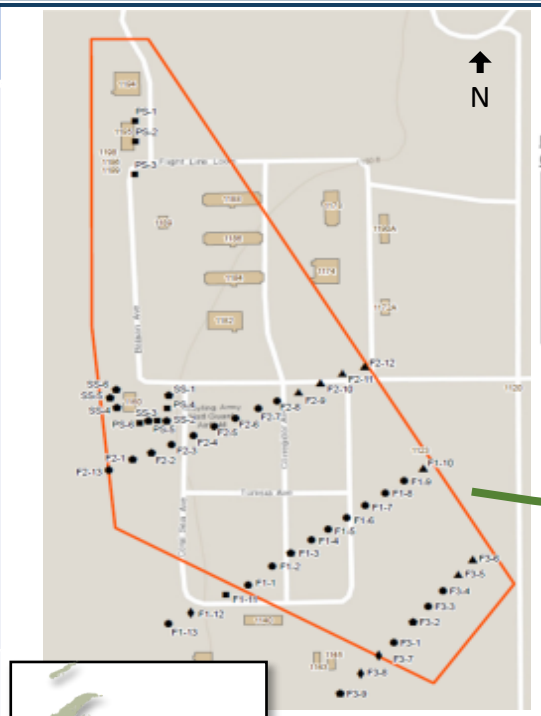
- Well characterized PFAS source and plume with HRSC data
- Total PFAS concentrations are high (>30 ug/L) and several (9) different PFAS constituents are present
- Aquifer is shallow (approx. 14 ft) and relatively permeable (approx. 75 ft/d)
- “Simple” unconsolidated geologic setting

Remedial Progress

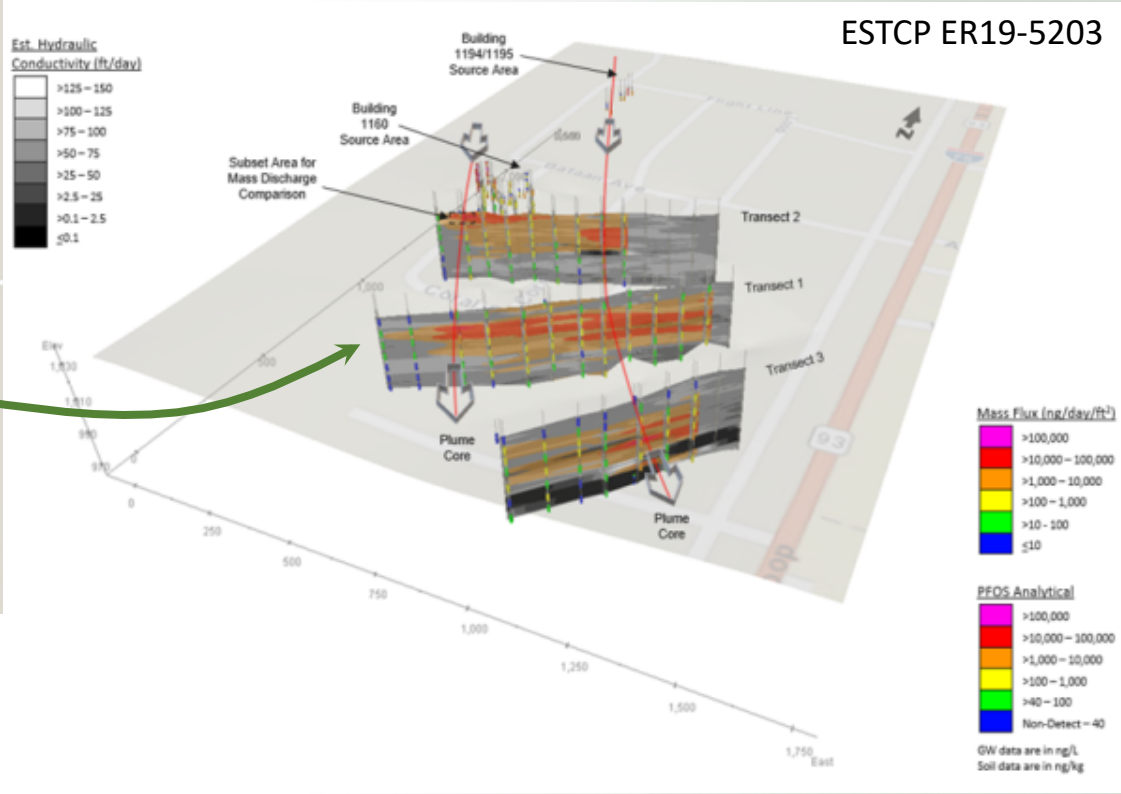
- Previous high-resolution mass flux/discharge completed via ESTCP ER19-5203
- Future mitigation actions likely

Other

- Straightforward drill rig access
- Engaged and supportive regulatory agency and stakeholders



ESTCP ER19-5203



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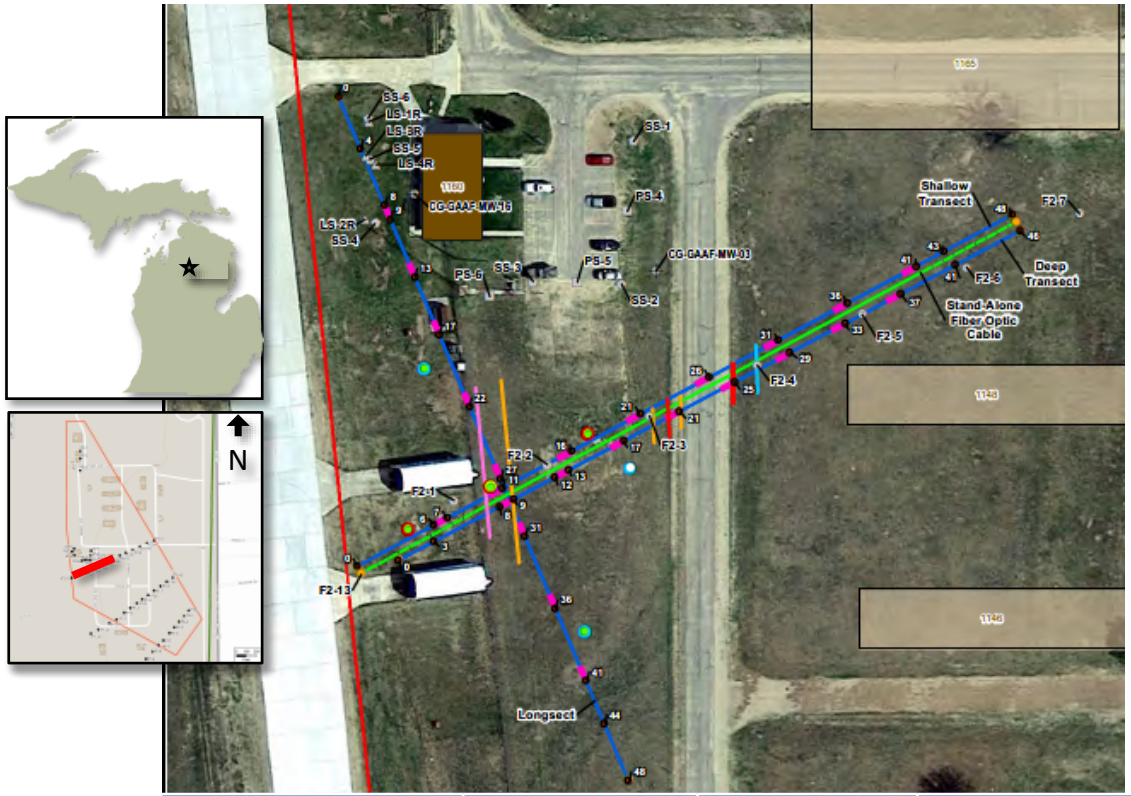
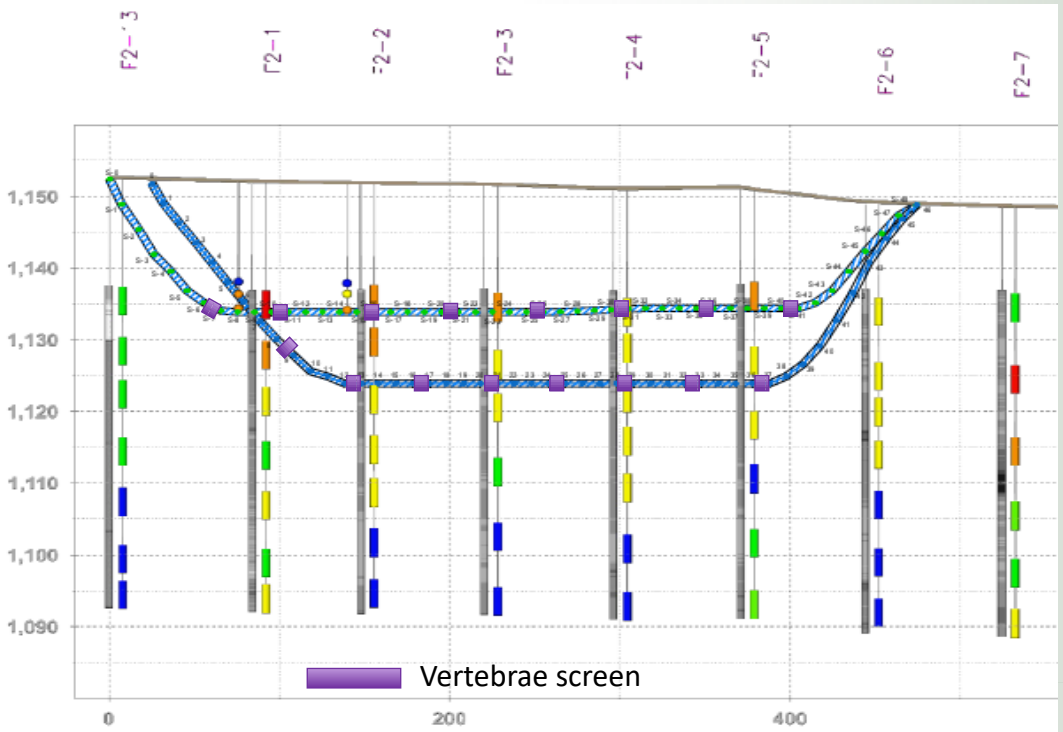
Demonstration Plan Layout – Vertebrae Segmented Horizontal Wells



East-West Transects



Well ID	Horizontal length (ft)	Maximum Depth (ft)	Screen Segments	Well Construction	Other Details
Shallow transect	487	18	8	•4-in 13.5 SDR HDPE conduit sleeve •10' long x 1" OD HDPE screen with 88-micron geotextile wrap •0.75 in OD HDPE risers •0.5 in OD HDPE Grout lines	Tracer line - full length Fiber optic cable - full length
Deep transect	457	28	8		Tracer line - full length
Longsect	477	22	8		Tracer line - full length
Stand alone Fiber optic Cable	477	19	--	3/4-in 13.5 SDR HDPE conduit sleeve	Fiber optic cable only

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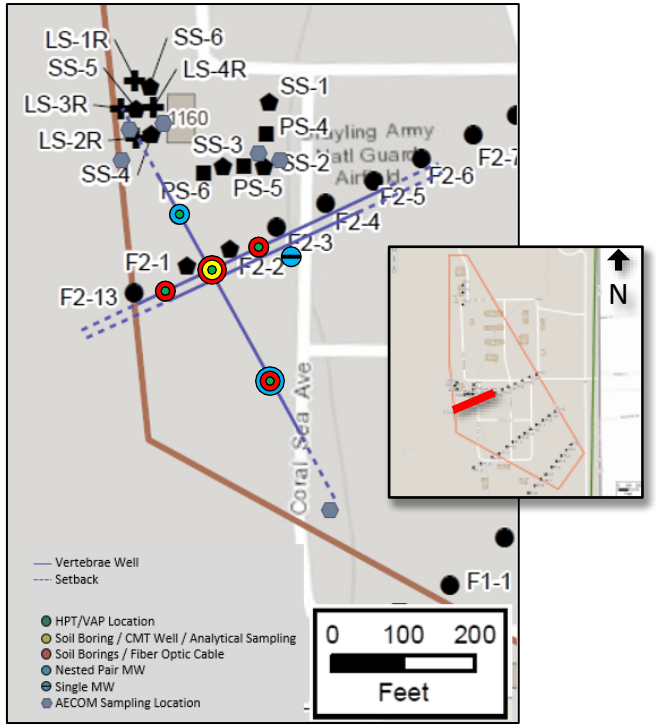
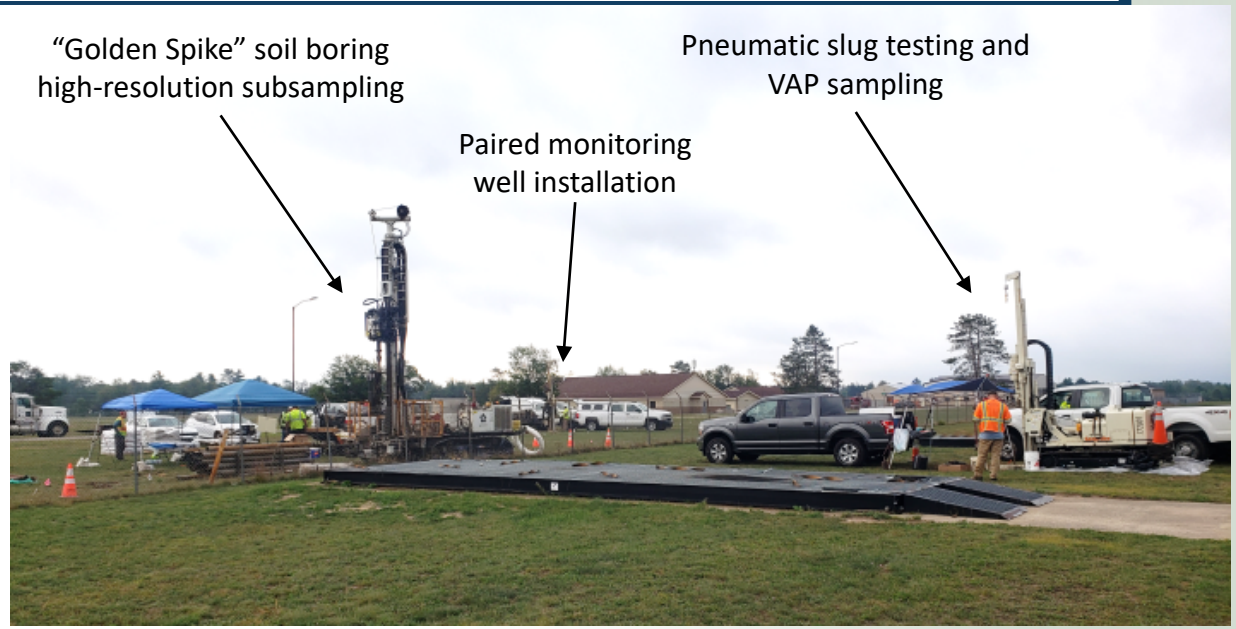
Predesign Vertical Characterization



Drivepoint FO assembly; knockout tip fitted to Geoprobe rods



CMT Port construction and multiport access

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Vertebrae™ System Installation

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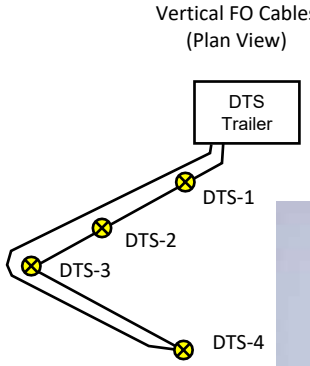
Performance Monitoring

- Quarterly groundwater sampling
  - All locations for PFAS (EPA 537M), select locations for TOP Assay, TOC
  - Shallow, Deep, and Longsect Vertebrae transects
  - CMT multilevel well
  - Shallow and deep monitoring wells
    - Pressure transducers in shallow wells for continuous water level monitoring

- A-DTS Testing
  - Shallow transect
  - Standalone cable
  - Vertical FO cables



Select events included hydraulic & tracer testing

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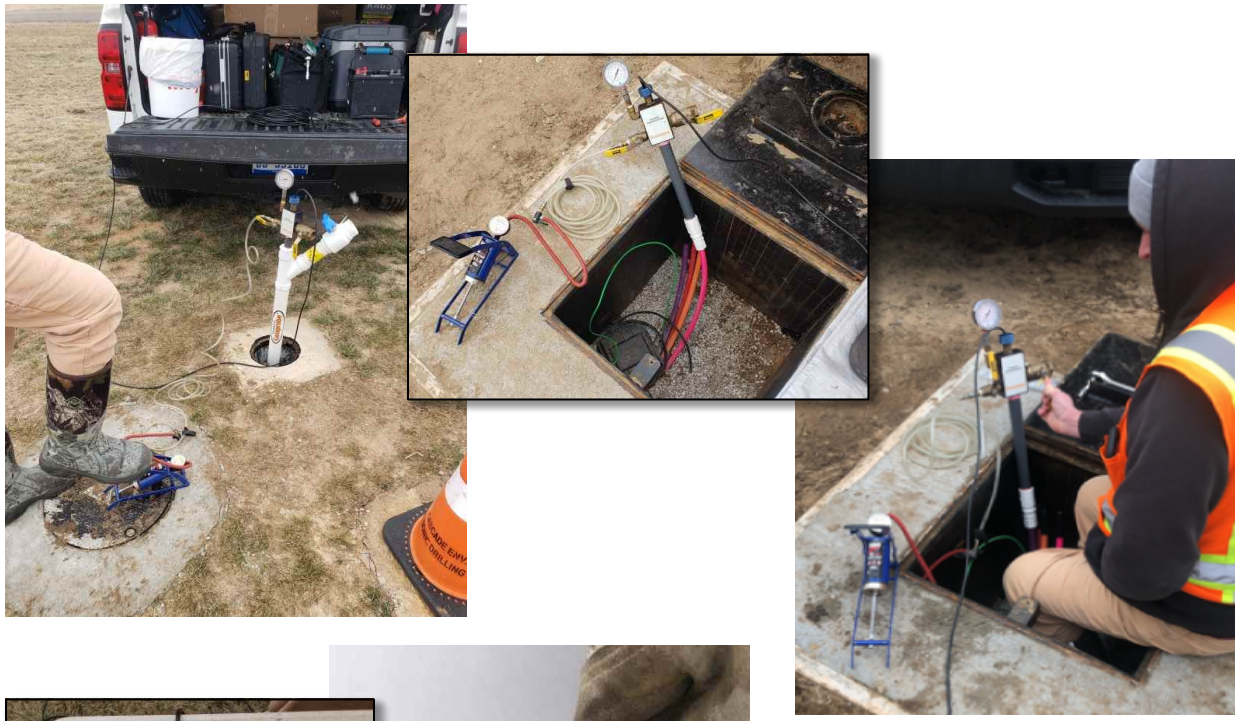
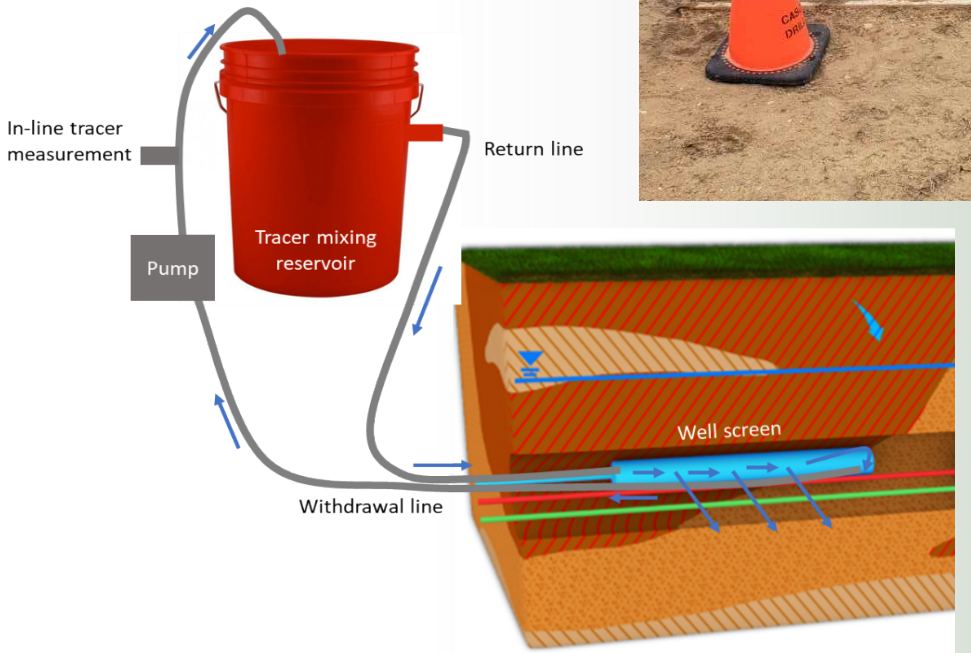
Hydraulic Testing



Pneumatic slug testing for vertical monitoring wells and Vertebrae wells with Geoprobe PST kit including small diameter pressure transducer

Single well tracer tests for vertical monitoring wells and Vertebrae wells with salt tracer



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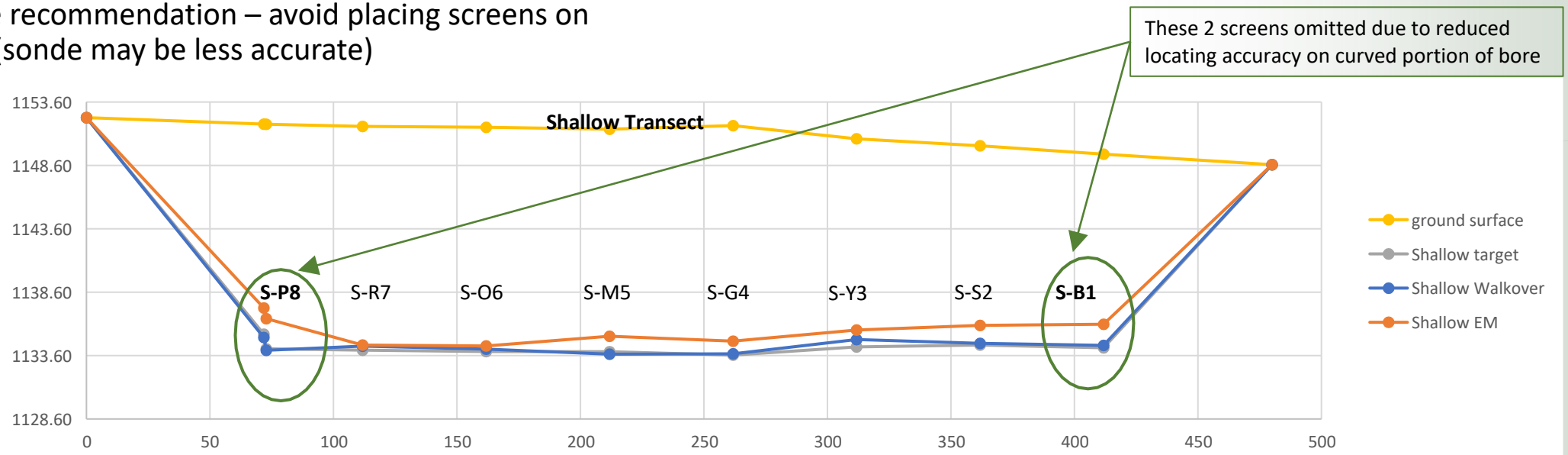
Results

Vertebrae As-Built Locations

- Three sets of coordinates
  - Target bore profile
  - Method 1: Navigation data during drilling
  - Method 2: RF line tracing after installation
- Target tolerance limit of +/- 1.5 vertical feet
  - 0.5 ft (accuracy during drilling) + 1.0 ft (goal) = 1.5 vertical feet
- Screens installed on the slopes omitted due to lower accuracy
- Future recommendation – avoid placing screens on slope (sonde may be less accurate)

Screen ID	Difference between Navigation & target (ft)	Difference between Navigation & EM Line tracing (ft)
S-R7	0.32	0.08
S-O6	0.19	0.25
S-M5	0.20	1.42
S-G4	0.10	1.00
S-Y3	0.58	0.75
S-S2	0.13	1.42
% Agreement (<1.5 ft)	**100% (6 of 6)**	**100% (6 of 6)**

6 of 6 screens along horizontal section were within 1.5 vertical feet



Performance Objective: Accurate and reliable placement of screens in subsurface

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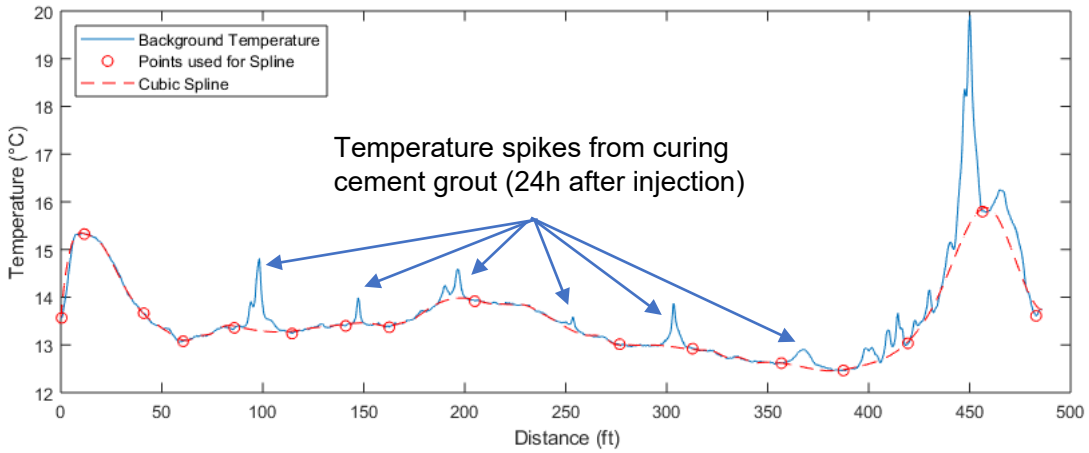
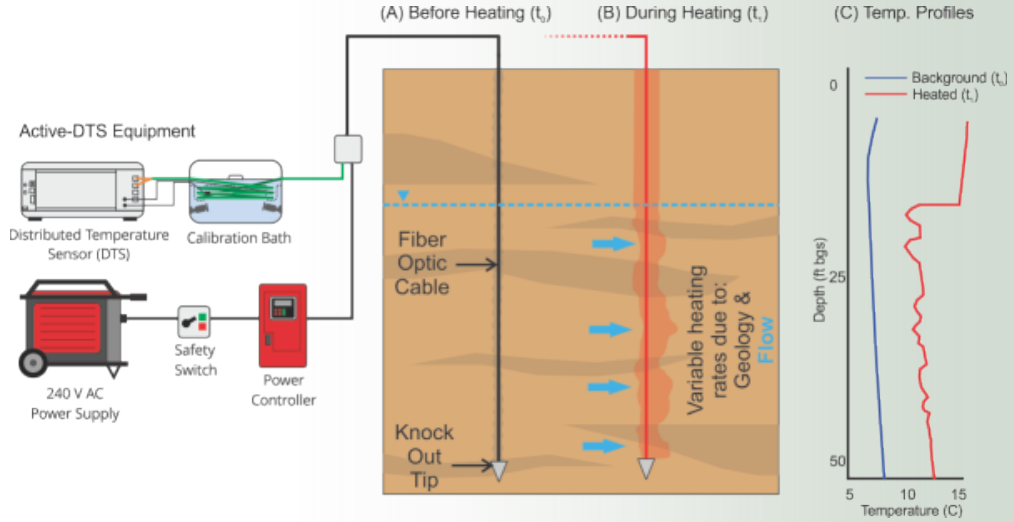
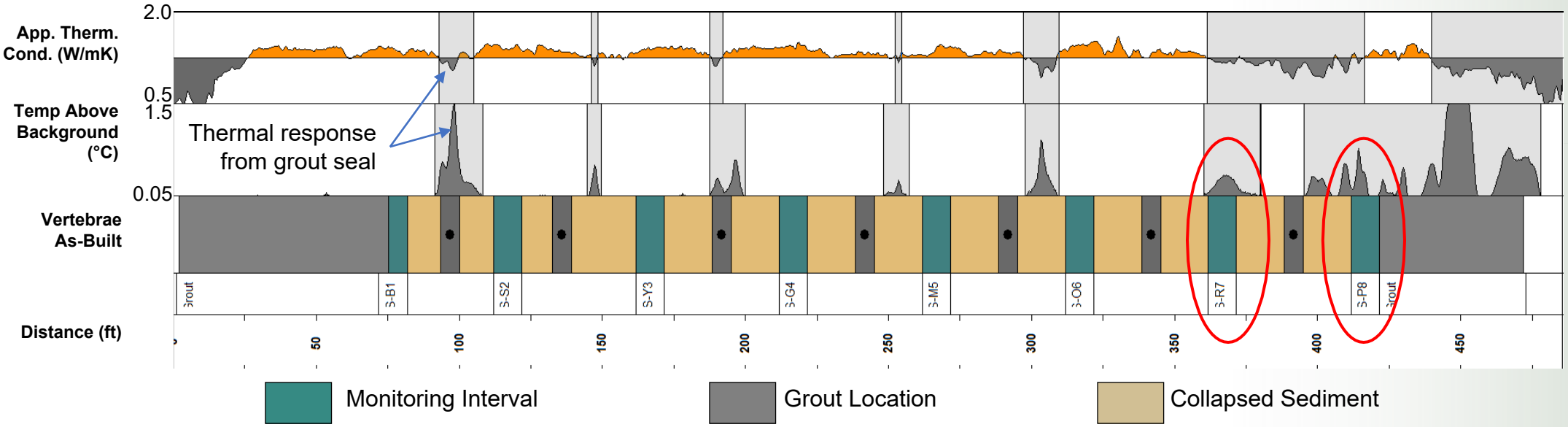
A-DTS & Vertebrae Seal Placement







Monitoring Interval Grout Location Collapsed Sediment

Performance Objective: Demonstrate integrity of grout seals to isolate individual screen segments

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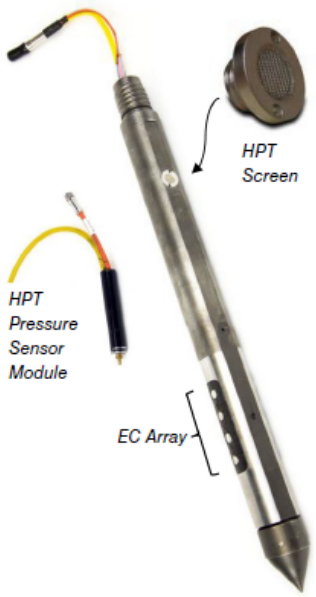
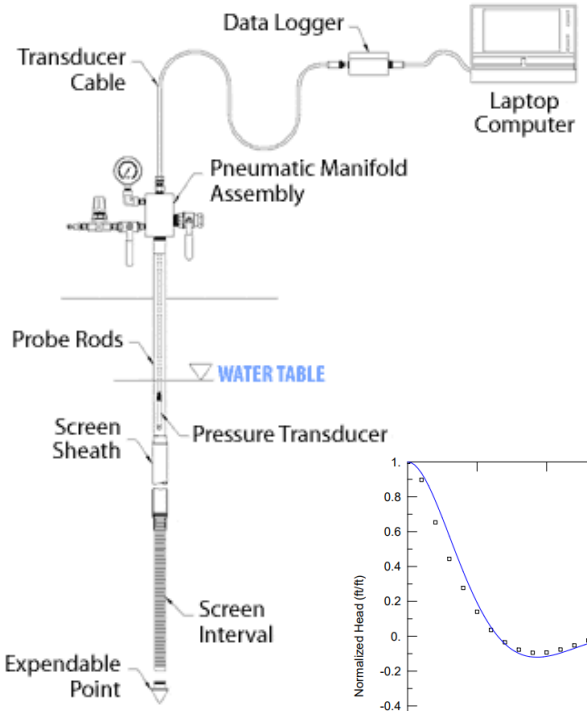
Hydraulic Profiling Tool vs. Pneumatic Slug Tests

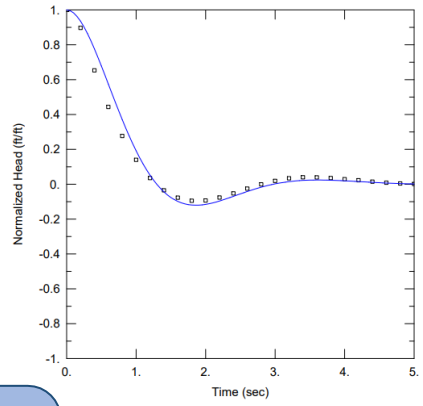
Geoprobe HPT



HPT estimated K mostly at or above upper test limit for all locations (75 ft/day ~0.0265 cm/s)

Geoprobe PST

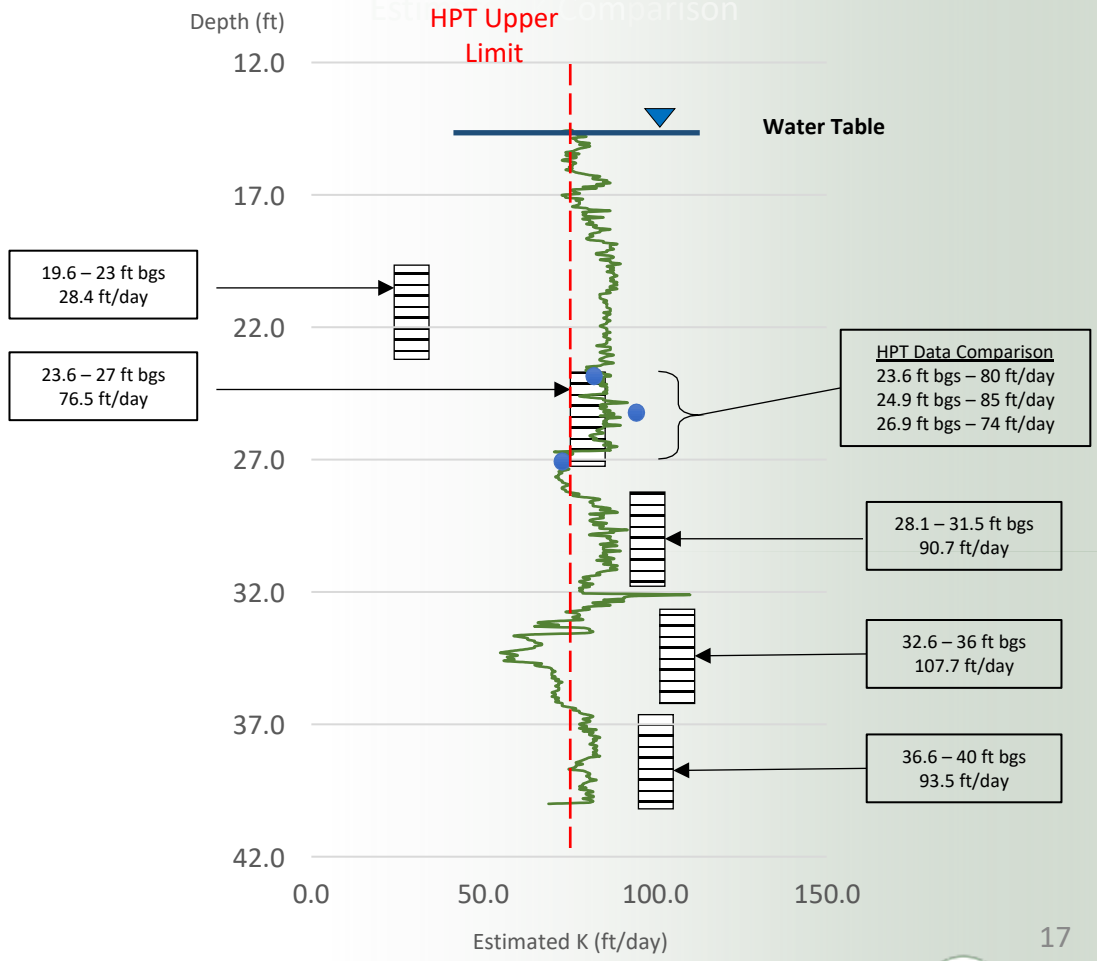




Underestimation of groundwater and PFOS mass flux / discharge

Estimated K Comparison

HPT Continuous Logging – Pneumatic Slug Test Intervals
VRTB-03



Performance Objective: Validate methods for groundwater flux measurement with Vertebrae systems

Butler, J.J., Zhan, X., 2004. Hydraulic tests in highly permeable aquifers. WRR (40). https://doi.org/10.1029/2003WR002998

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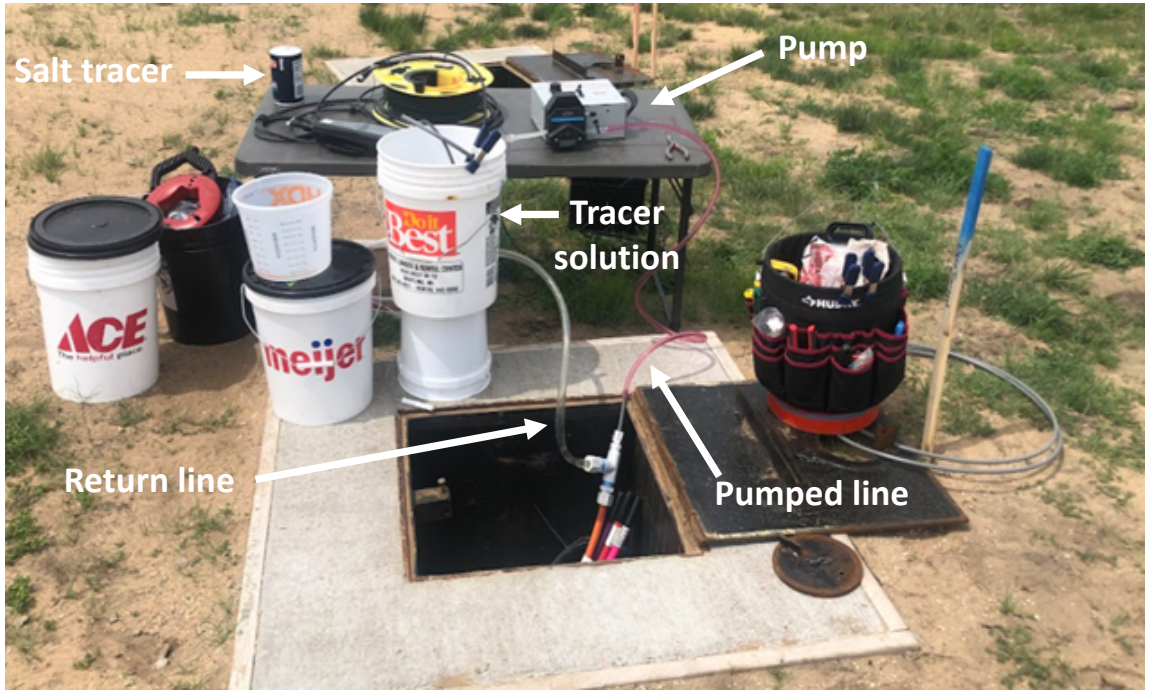
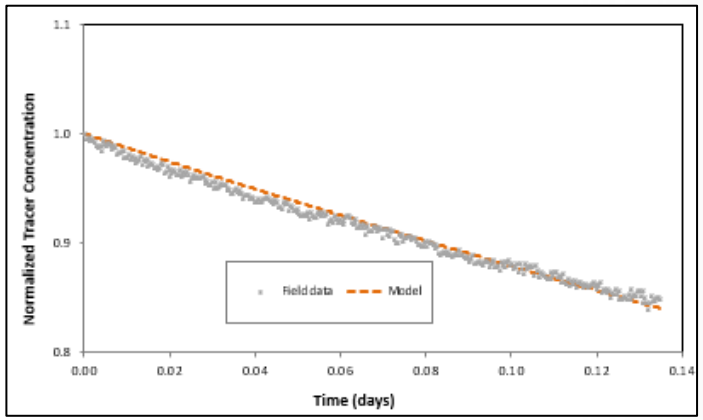
Hydraulic Testing



"Science requires buckets"



$$C(t) = C_0 e^{-\frac{q_w t}{r}} \qquad q_w = \frac{V_w \ln(C^{-1})}{At}$$

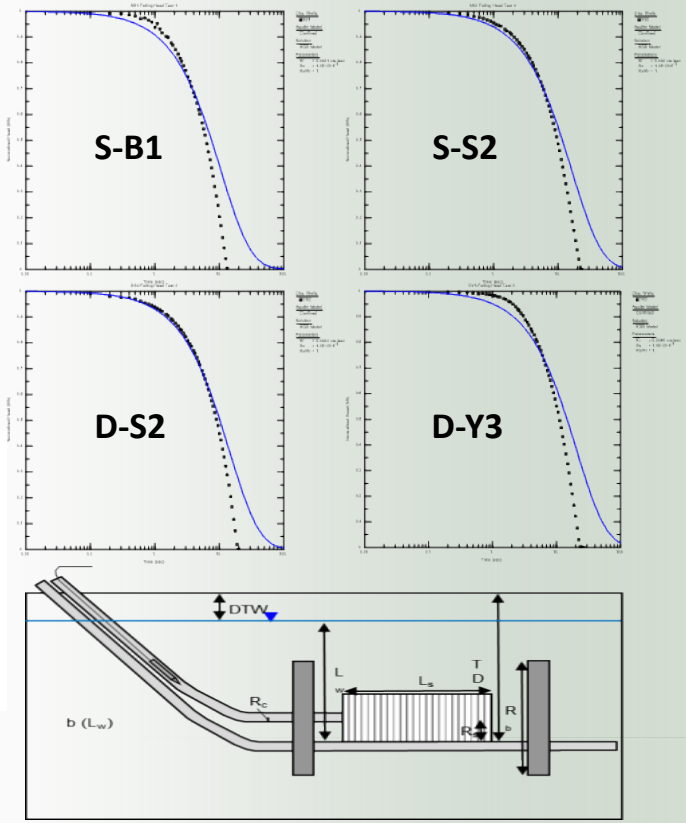
q_w is the flux through the well

A is the cross-sectional area of the well segment exposed to groundwater flow

r is the effective well radius

b is the length of the well screen

V_w is the total volume of tracer-tagged water



Vertebrae Single Well Tracer Tests

- Results within expected ranges
- Repeated tests agreed within 12%
- Data generally consistent with model
- Further optimization (volumes, duration) would likely improve test

Vertebrae Pneumatic Slug Testing

- K results lower than expected (~10x)
- Not consistent (e.g., RH tests 3-6x higher)
- Implausibly low Specific Storage
- Early- and late-time deviations from model
- Implies well skin effect

Performance Objective: Validate methods for groundwater flux measurement with Vertebrae systems

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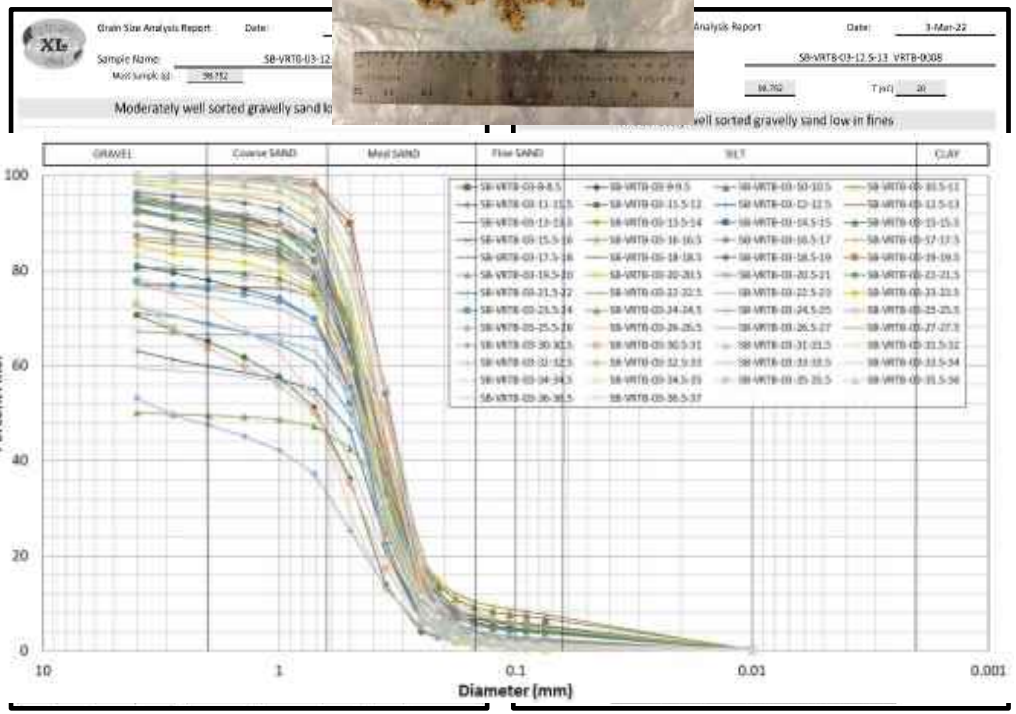
Empirical Estimates of K from Grain Size

Grain Size Re mate Report



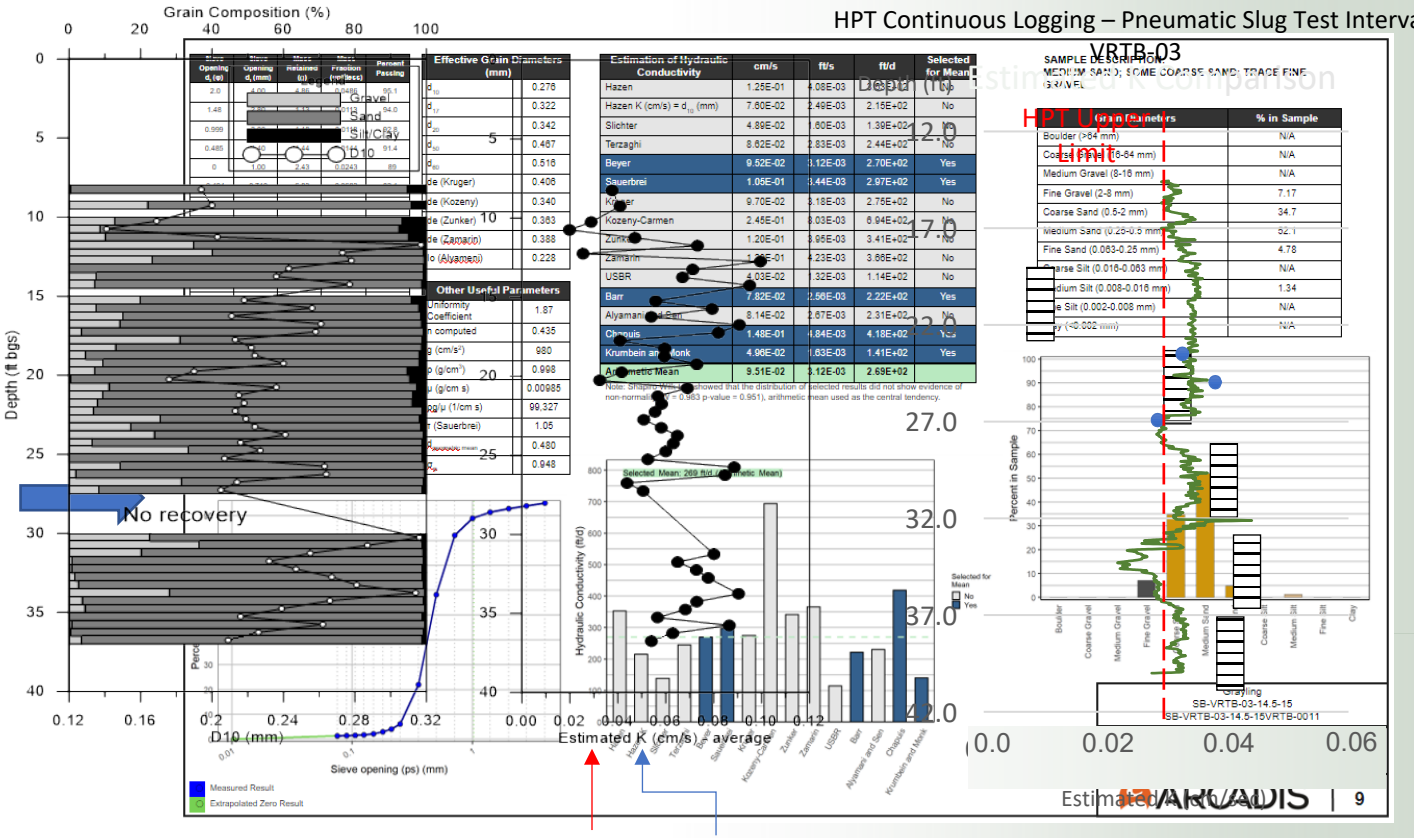
HydroGeoSieve (Devlin, 2015) http://www.people.ku.edu/~jfdevlin/Software.html

Sieve analysis by Brad Chapman, EIT

ARCADIS Updated Version (proprietary)

Estimated K Comparison

HPT Continuous Logging – Pneumatic Slug Test Intervals



HPT Upper Limit

Highest HPT K Estimates

Selects K-estimation methods most applicable for site sediments

K estimated from grain size is ~2-3x higher than K estimated from HPT

Performance Objective: Validate methods for groundwater flux measurement with Vertebrae systems

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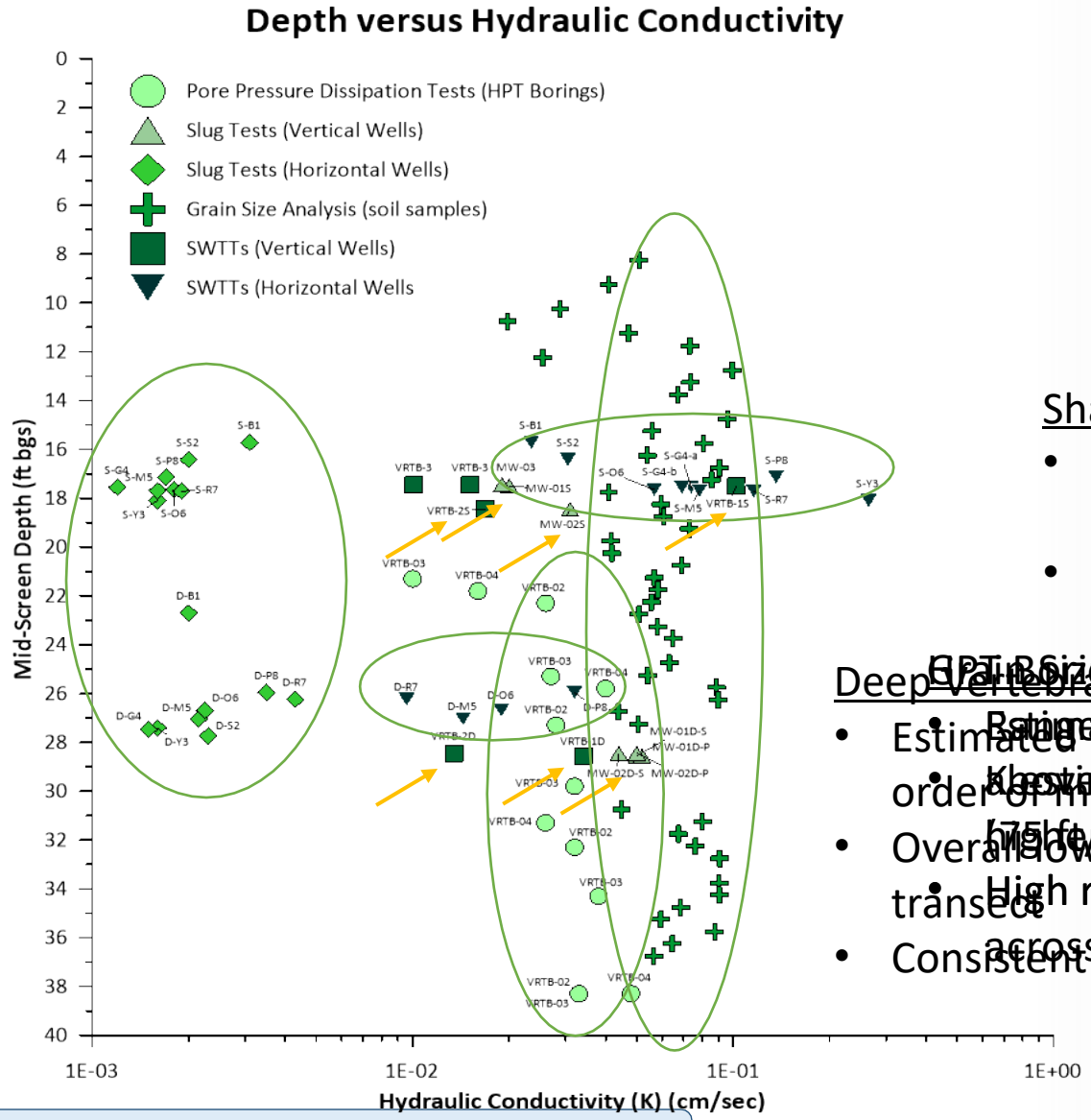
Comparison of K Methods



Vertebrae PST

- K values lower than expected
- Well skin effects
- Not consistent with VAP and MW PST

Shallow Vertebrae SWTTs

- Estimated K data varies across 2 orders of magnitude
- Similar to shallow MW SWTTs

Deep Vertebrae SWTTs

- Estimated K data varies across an order of magnitude
- Overall lower K than shallow transect
- Consistent with deep MW SWTTs

GPT Boring Analysis

- Estimate of K usually factor of 5 [illegible]
- Estimated from grain size is ~2-3x [illegible] than K estimated from HPT
- High resolution data [illegible] across the site

Performance Objective: Validate methods for groundwater flux measurement with Vertebrae systems

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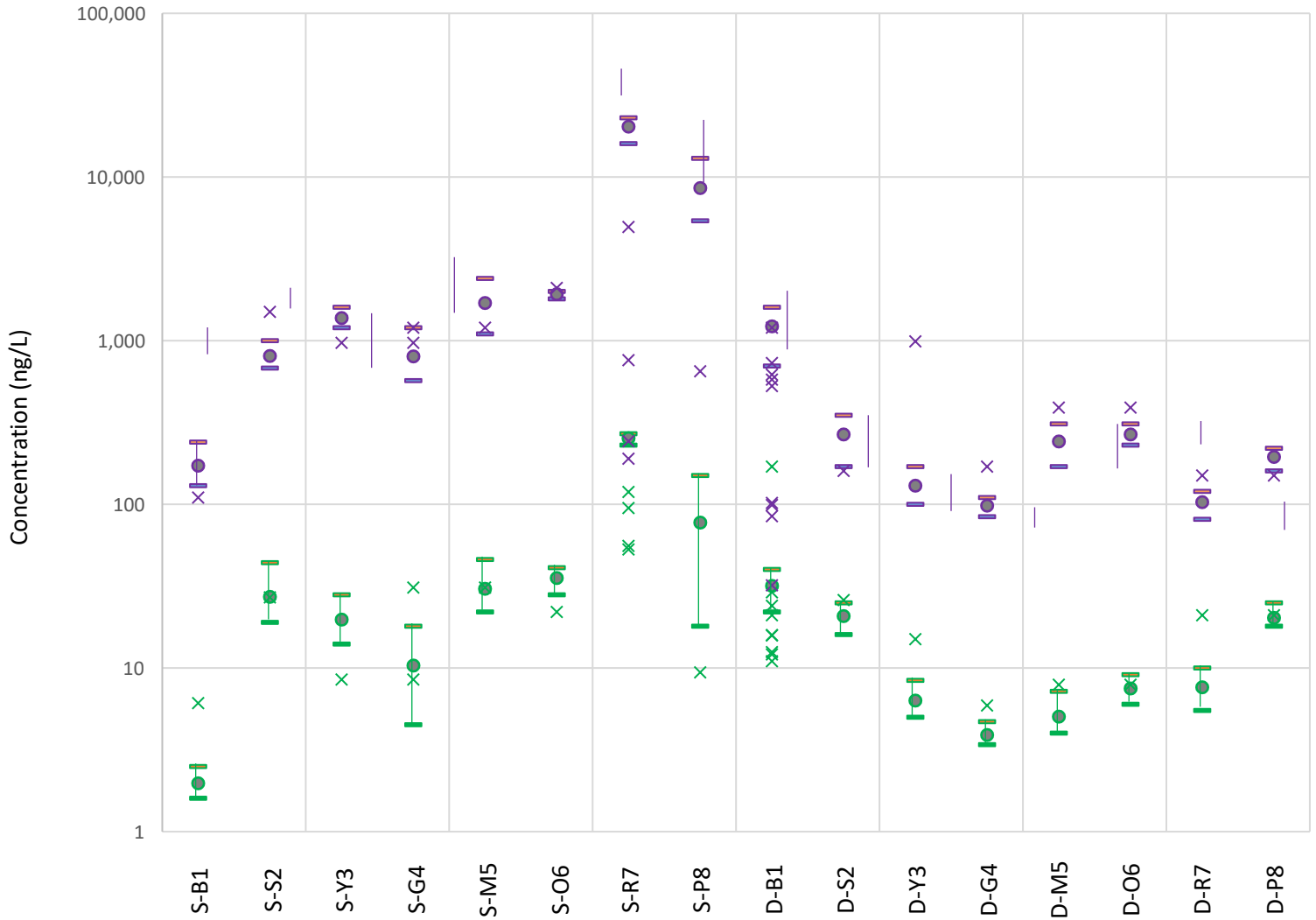
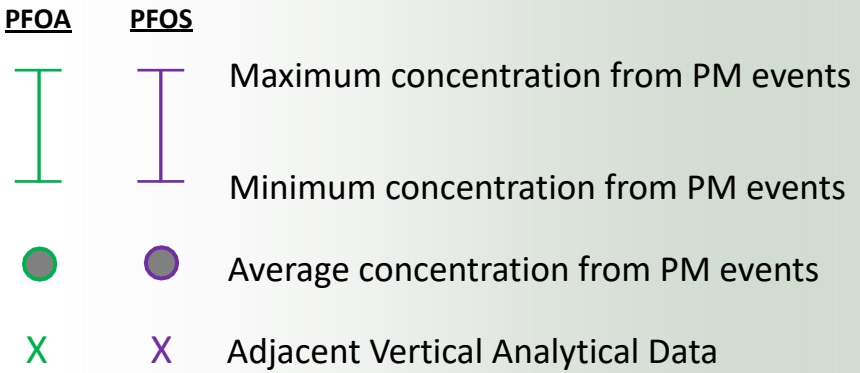
Comparison of Vertebrae to Vertical Analytical Data





Comparing PFOS analytical data from Vertebrae performance monitoring events to closest adjacent vertical analytical data

Spatial and temporal variability is apparent, but generally good agreement

Performance Objective: Assess comparability of samples from Vertebrae system screens to grab samples

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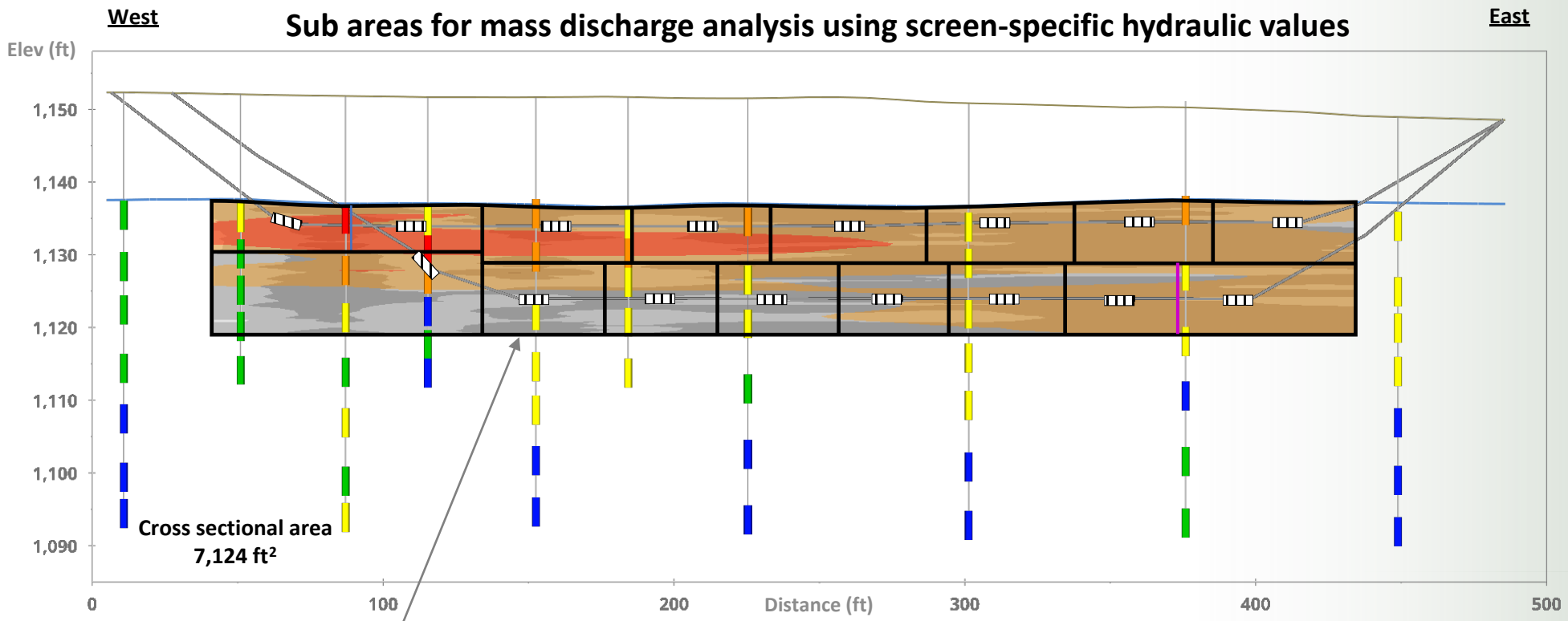
In Progress: Mass Discharge Analysis



$$M_D = \sum MM_i = C_i \cdot q_i \cdot A_i$$

- M_D: Mass Discharge
- C_i: Concentration
- q_i: Darcy flux (hydraulic conductivity x gradient)
- A_i: Area

PFOS Analytical (ng/L)
- >100,000
- >10,000 – 100,000
- >1,000 – 10,000
- >100 – 1,000
- >40 – 100
- Non-Detect – 40

Mass Flux (ng/day/ft2)
- >100,000
- >10,000 – 100,000
- >1,000 – 10,000
- >100 – 1,000
- >40 – 100
- Non-Detect – 40

Est. Hydraulic Conductivity (ft/day)
- >125 – 150
- >100 – 125
- >75 – 100
- >50 – 75
- >25 – 50
- >2.5 – 25
- >0.1 – 2.5
- ≤0.1

HPT Est. K and [PFOS] Kriged to the same grid

Performance Objective: Validate Vertebrae application for quantifying mass flux/discharge

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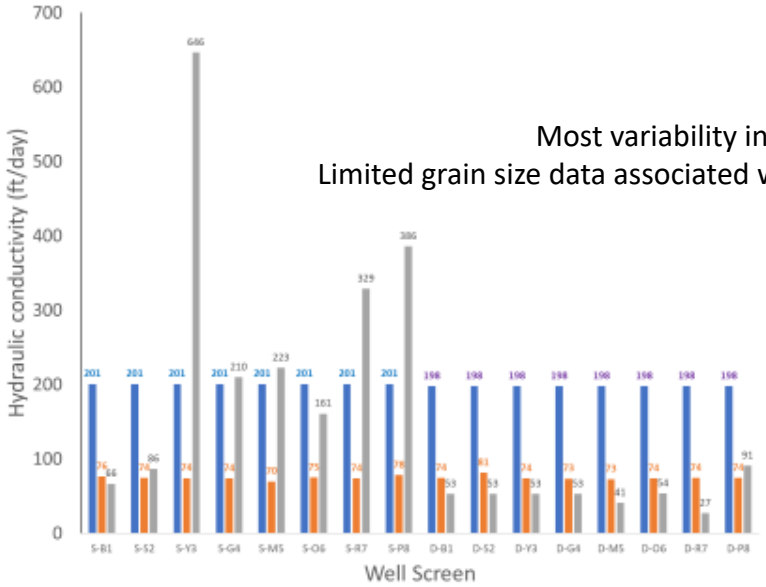
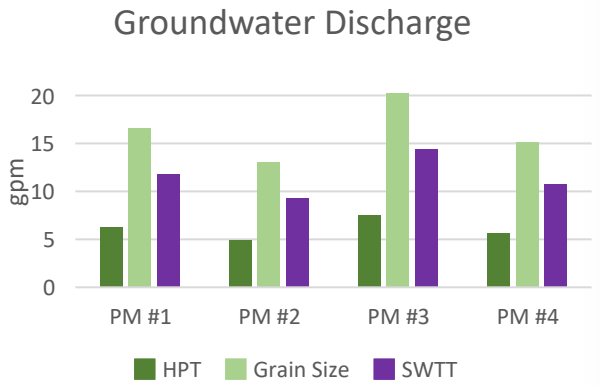
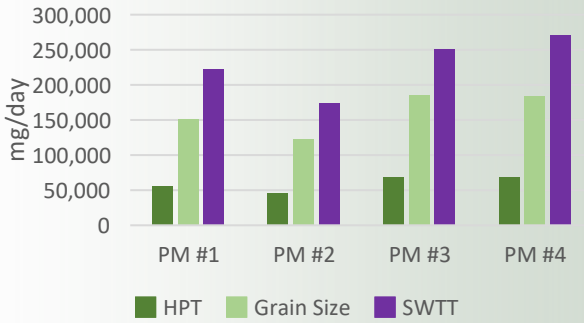
In Progress: Mass Discharge Analysis

PFOS Mass Discharge	GW Gradient	Estimated K from HPT		Estimated K from Grain Size		Estimated K from SWTT		Estimated K from DTS	
		GW Discharge	Total Mass Discharge	GW Discharge	Total Mass Discharge	GW Discharge	Total Mass Discharge	GW Discharge	Total Mass Discharge
	ft/ft	gpm	mg/day	gpm	mg/day	gpm	mg/day	gpm	mg/day
2019/2021 Investigations	0.0025	In Progress	In Progress	In Progress	In Progress	NA	NA	NA	NA
Vertebrae Transect PM#1	0.0023	6	56,000	17	151,000	12	226,200	In Progress	In Progress
Vertebrae Transect PM#2	0.0018	5	45,700	13	123,100	10	176,400	In Progress	In Progress
Vertebrae Transect PM#3	0.0028	8	69,000	20	185,300	15	254,700	In Progress	In Progress
Vertebrae Transect PM#4	0.0021	6	68,600	15	183,500	11	275,000	In Progress	In Progress
Vertebrae Average	**0.0023**	**6**	**59,825**	**16**	**160,725**	**12**	**233,075**	In Progress	In Progress



Most variability in SWTT
Limited grain size data associated with Vertebrae intervals





Performance Objective: Validate Vertebrae application for quantifying mass flux/discharge

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Key Points

- Vertebrae wells were easily installed, and as-built boring is within +/- 1.5 ft of target elevations for most locations
- A-DTS was able to determine the position and extend of grout seals between monitoring intervals. Seals appear to function; however, there is evidence of grout penetration in some screens
- Multiple groundwater flux estimation methods have been adapted to the Vertebrae system and appear to yield reasonable and consistent darcy flux values; however, pneumatic slug test results are biased low, likely due to well skin effects.
- PFAS concentrations from Vertebrae wells are consistent with previous data and some data show significant spatial variability
- Groundwater dynamics at this site are significant and are associated with large concentration variations near the capillary fringe
- PFAS mass flux analyses are underway and preliminary results indicate good comparability between Vertebrae and HRSC-type methods

Acknowledgements

Environmental Security Technology Certification Program (ESTCP ER20-5026)

Grayling Army Airfield, Grayling, Michigan

The Grayling Army Airfield Demonstration was successful as a result of support from ESTCP and contribution from many. Specific acknowledgement is extended to:

- **Camp Grayling**: Patricia Lyman, Jonathan Edgerly, and Bonnie Packer
- **Arcadis**: Craig Divine, Jesse Wright, Patrick Curry, Austin Westhuis, Madison Olender, Kara Donahue, and Kevin Toth
- **EN Rx**: Lance Robinson, Wes Wiley, and James Laymon
- **University of Guelph Morwick G360 Institute**: Beth Parker, Steven Chapman, Jonathan Munn, and Carlos Maldaner
- **Cascade Drilling**
- **Pace Analytical**

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Questions? Contact Us

Additional Information

Next Steps

SERDP Proposal

Groundwater Dynamics and PFAS at the Capillary Fringe

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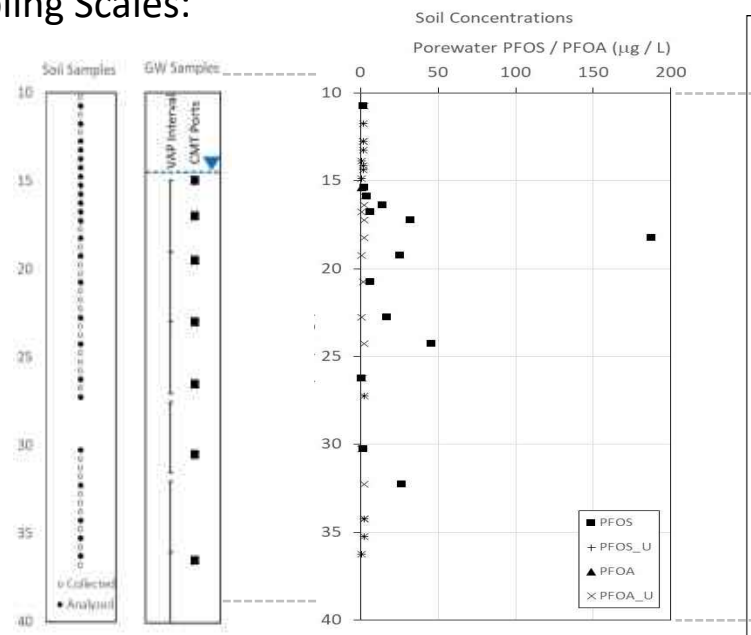
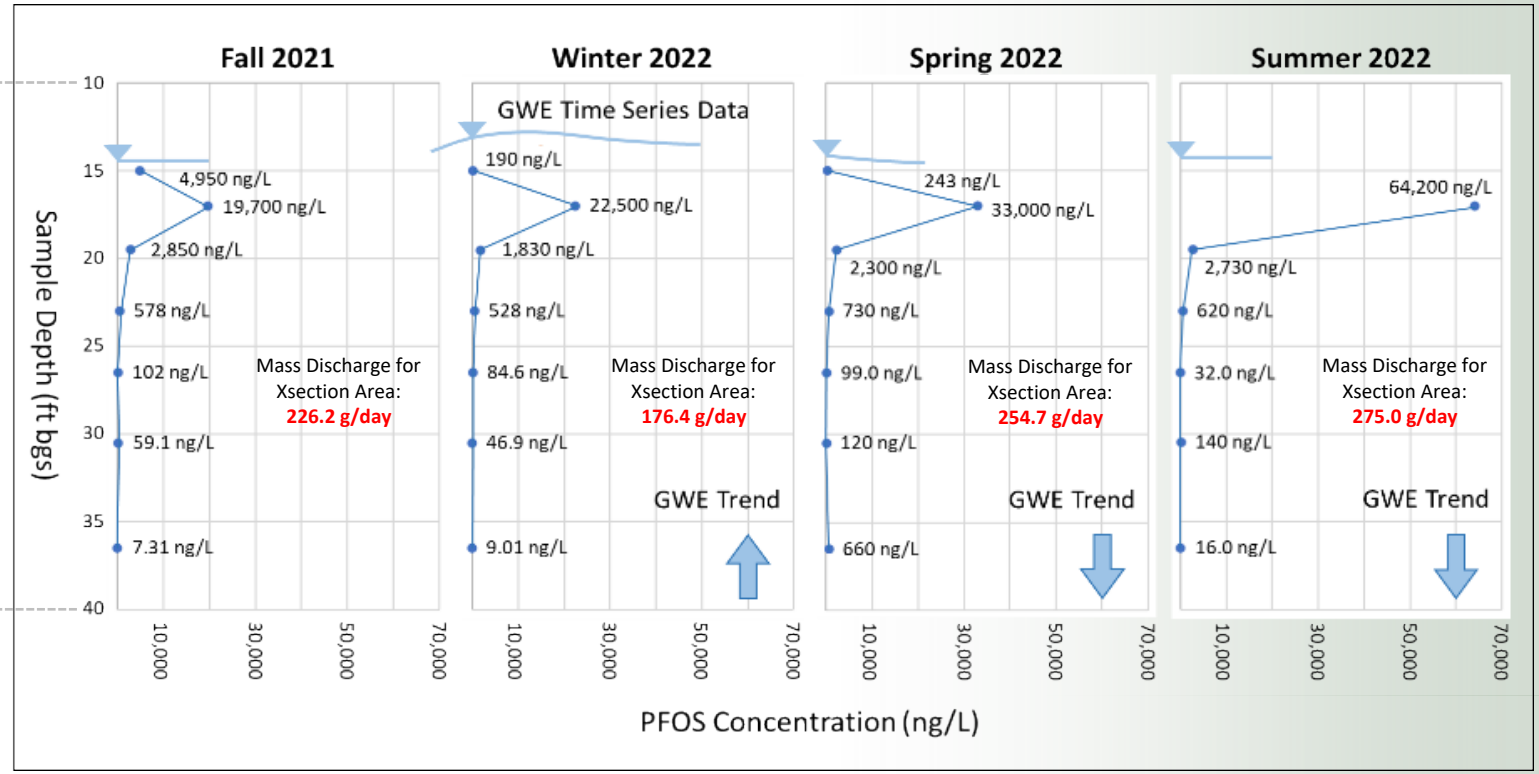
Groundwater Dynamics and PFAS at the Capillary Fringe

Sampling Scales:



Note: soil concentrations converted to porewater values using assumed ϕ, ρ_b and assuming no sorption.



- Site is homogeneous and high K ("Borden of the South")
- Notable groundwater dynamics
  - Fast recharge
  - Gradient magnitude varies >50%
  - Flow direction ranges ~30 degrees
- CMT data shows high variability in concentrations at capillary fringe
- Large variability in mass flux/discharge

SERDP preproposal submitted (ER24-C5-4228) to collect additional high-resolution data in capillary fringe (core sampling and ongoing monthly monitoring including additional CMT wells, lysimeters, and Vertebrae system sampling)

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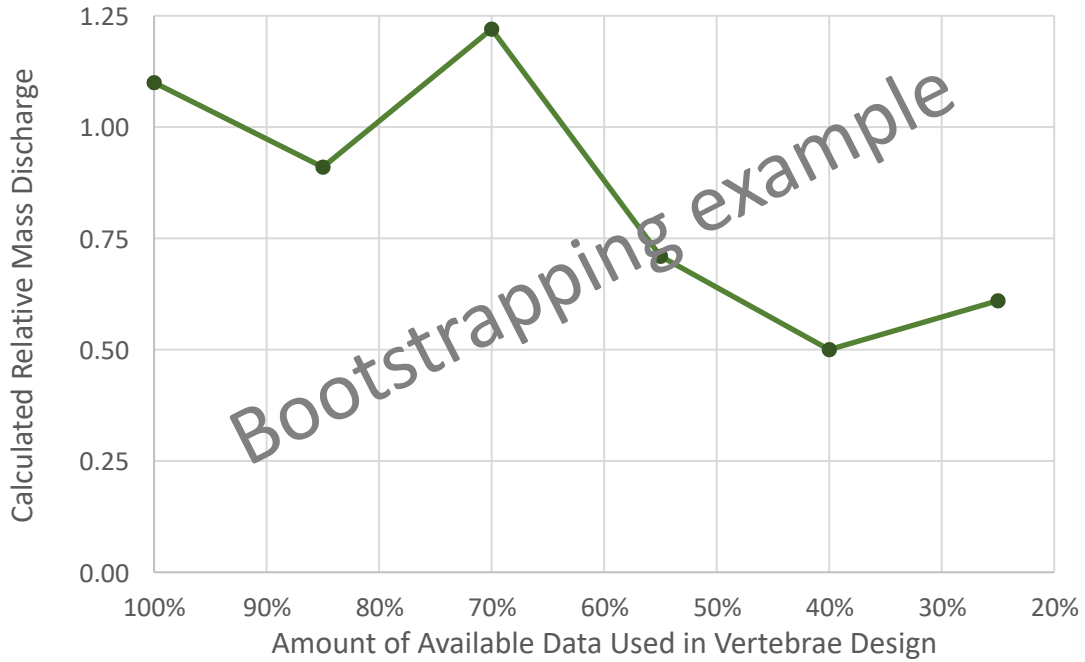
In Progress: Design Data Requirements



Performance Objective: Demonstrate method to identify appropriate mass flux zones to target Vertebrae placement

Success will be achieved if a relationship between pre-design data availability and the predicted mass discharge measured from the resulting Vertebrae system designs can be developed, and if this relationship indicated the Vertebrae design will yield a mass discharge estimate within ±25% of the estimated derived from other data.

Related guidance for design of Vertebrae system from site data will be developed

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Assessment of Accuracy of Mass Discharge Estimates

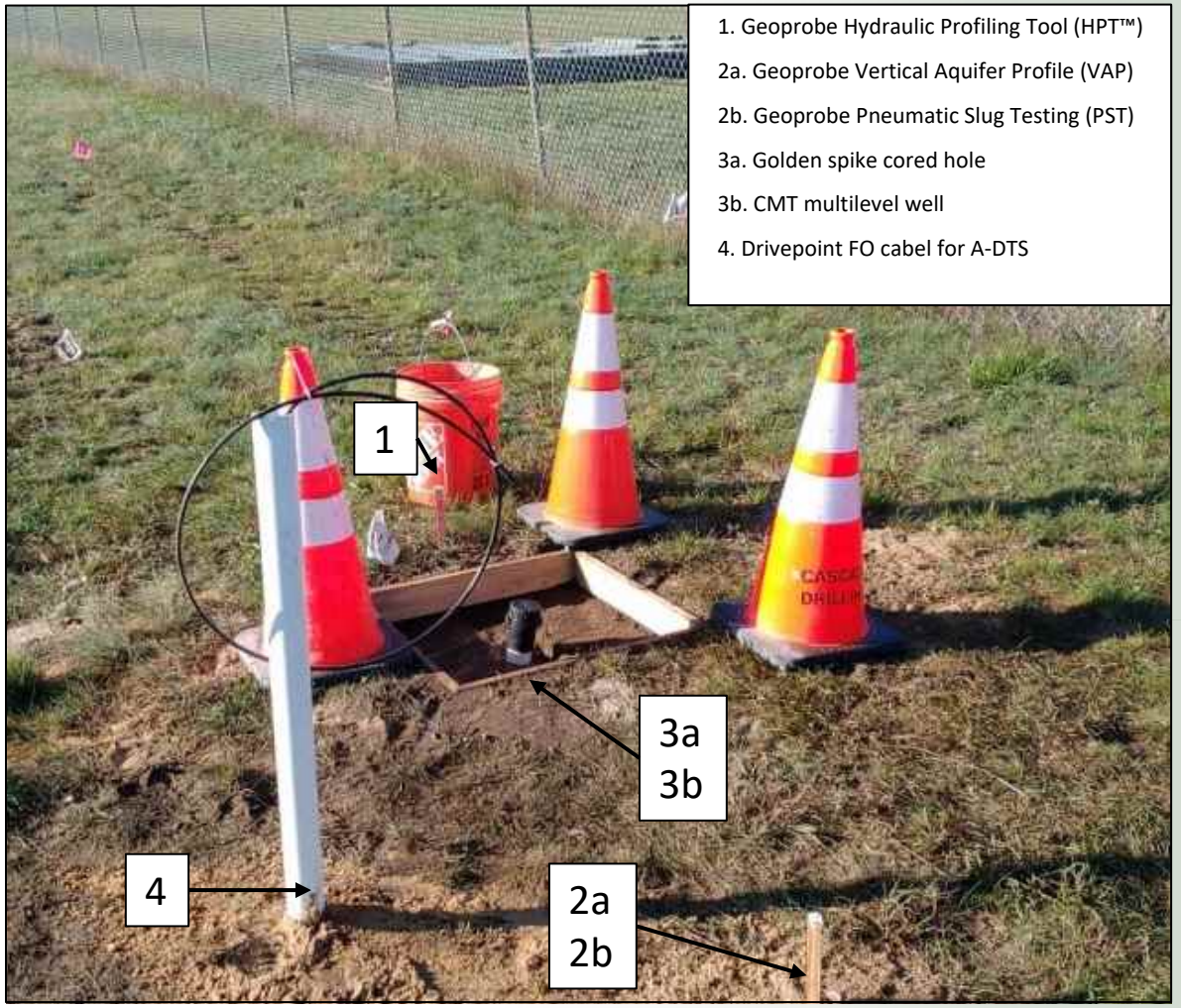
Paired Location Comparisons

Focus on:

- K derived from Geoprobe HPT™
- PFOS concentration variability

Paired locations with…

- K / GW flux comparisons:
  - Geoprobe HPT™
  - Pneumatic slug testing in Geoprobe screen point sampler
  - Continuous cores – K from grain size estimates
  - A-DTS in drivepoint fiber optic point installations
- PFOS concentration variability
  - Geoprobe screen point groundwater sampling
  - CMT multilevel well – 7 discrete ports
  - High-resolution core subsampling



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Lessons Learned & Technology Robustness

- Avoid installing screens at an angle
- Limit entry/exit angles to prevent tight bends in Vertebrae system
- Irresolvable uncertainty in confirming as-built vertical borehole location results in a minimum target thickness of 1.5 feet
- Well materials/construction significantly affect some hydraulic test results
- Grout delivery methods and options
- Challenges on feeding sampling tubed; dedicated tubing is recommended
- Well materials are non-detect for PFAS
- Large box vaults are rugged and recommended
- Total Vertebrae wells installed to-date: >200

Performance Objective: Identify challenges and limitations of the Vertebrae wells

Challenges and limitations are understood and can be readily mitigated

Performance Objective: Assess robustness of the technology

No fundamental design flaws/limitations and no systemic problems experienced

Performance Objective: Verify materials compatibility with PFAS

Rinsate blank samples are free of PFAS

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