

Changing the Perspective on 30 Years of Granularity with High Resolution Contaminant Distribution



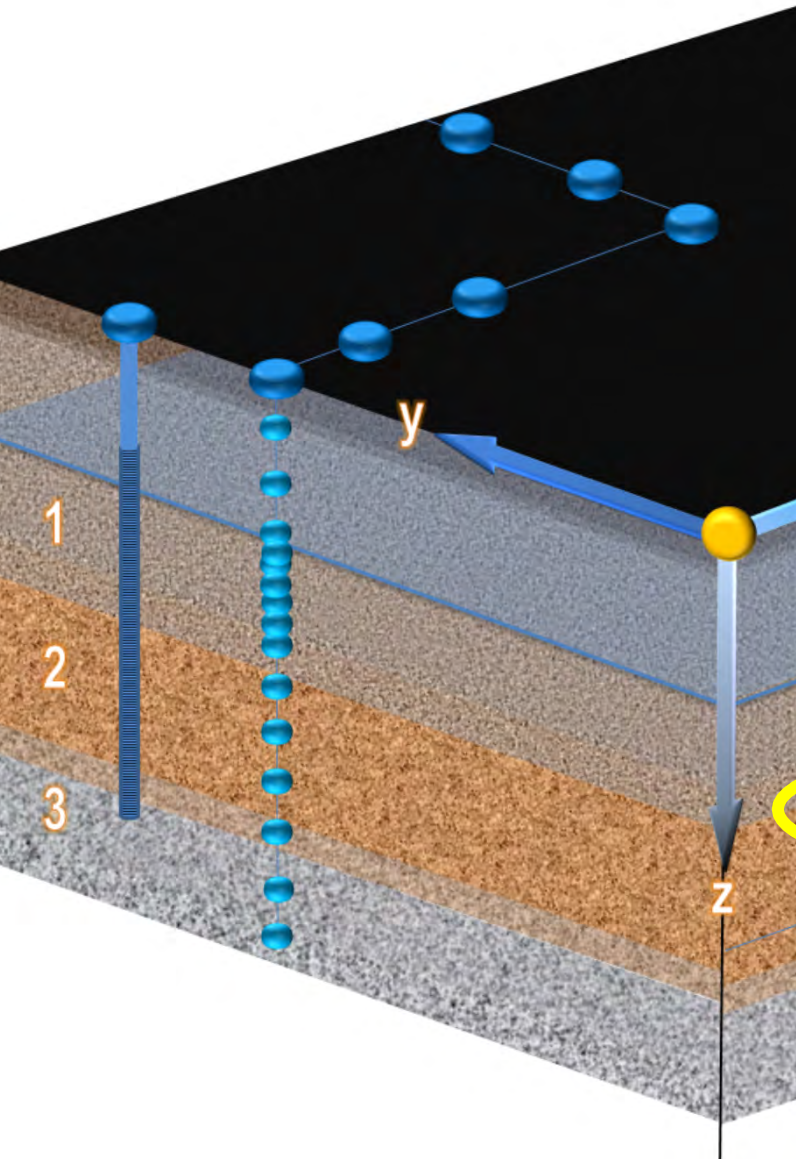
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Presentation Overview

- Recap and Context for High Resolution
 - Plume Geometry and Granularity
 - The invent of Hi-Res Contamination Distribution (HRCDD)
- What is Vertebrae™?
- How HRCDD is changing Conceptual Site Models (CSMs)
 - Site Examples
- Other Features:
 - Permanence
 - Repeatability and treatment.
 - Multipurpose – Treatment Utilities for various Technologies
- Data Gaps and How They Cause Risk

High-Resolution Review (Our Take)

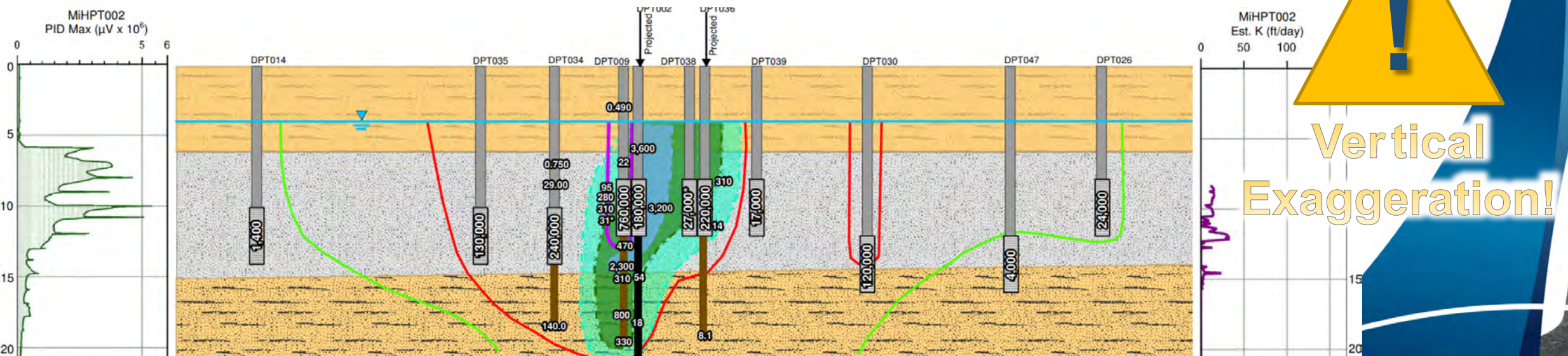


- High Resolution is better granularity than historical resolution. Enhanced Detail and Reduce Uncertainty using scale appropriate work. (CLU-IN) <https://www.clu-in.org/characterization/technologies/hrsc/hrscintro.cfm>
 - This is mostly improved vertically.
 - Horizontally, a grid or a transect approach is still applied.
- To oversimplify, with a release point in mind, vertically we are looking for when the contaminant is impeded and changing vectors, then horizontally we are looking for where it is distributed and tapered from this epicenter.
- **We are done when we can conclude that interpolation and extrapolation calculations are reasonable or correct.**

What is the General Plume Geometry?

- Typical plume geometries are more than a magnitude to larger in the horizontal plane.
 - ie. Often 10 to 100 times the length to the thickness (not depth)
- It follows that horizontal sampling resolution should be considered on these magnitudes.

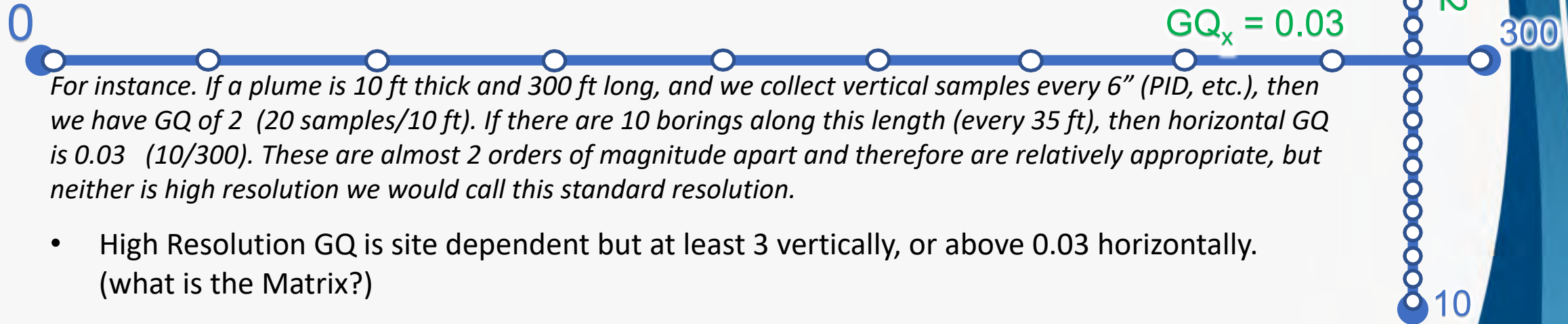
The mathematical comparisons are simple, Let's explore this.



A High-Resolution Qualifier?

- To compare these planes, we use a simple term called granularity quotient.

Samples / distance (linear ft) or samples / unit area



For instance. If a plume is 10 ft thick and 300 ft long, and we collect vertical samples every 6" (PID, etc.), then we have GQ of 2 (20 samples/10 ft). If there are 10 borings along this length (every 35 ft), then horizontal GQ is 0.03 (10/300). These are almost 2 orders of magnitude apart and therefore are relatively appropriate, but neither is high resolution we would call this standard resolution.

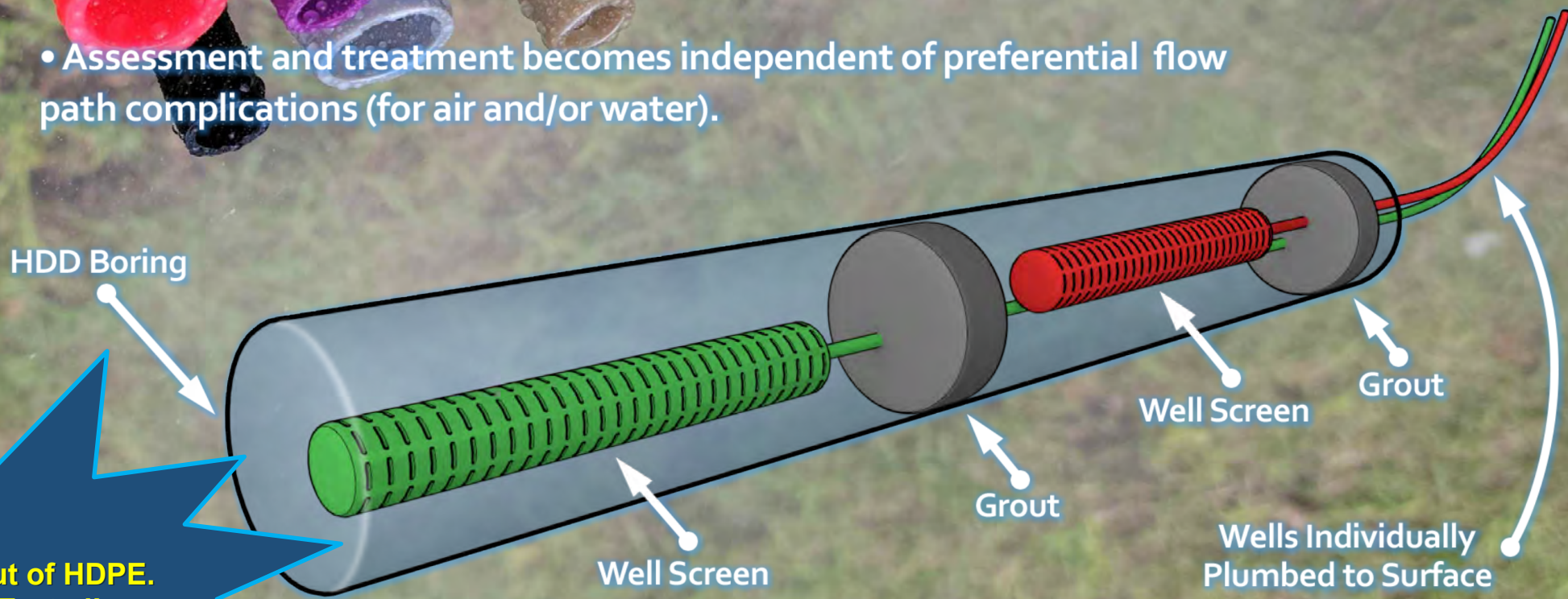
- High Resolution GQ is site dependent but at least 3 vertically, or above 0.03 horizontally. (what is the Matrix?)
- The higher the GQ the less likely the possibility of missing a more intense finding or transport zone.

By noting these differences, we show a distinctly different GQ with different utility and thus a subgroup of tools capable of cost effective horizontal sampling can provide –

High Resolution Contaminant Distribution (HRCD)

What is Vertebrae?

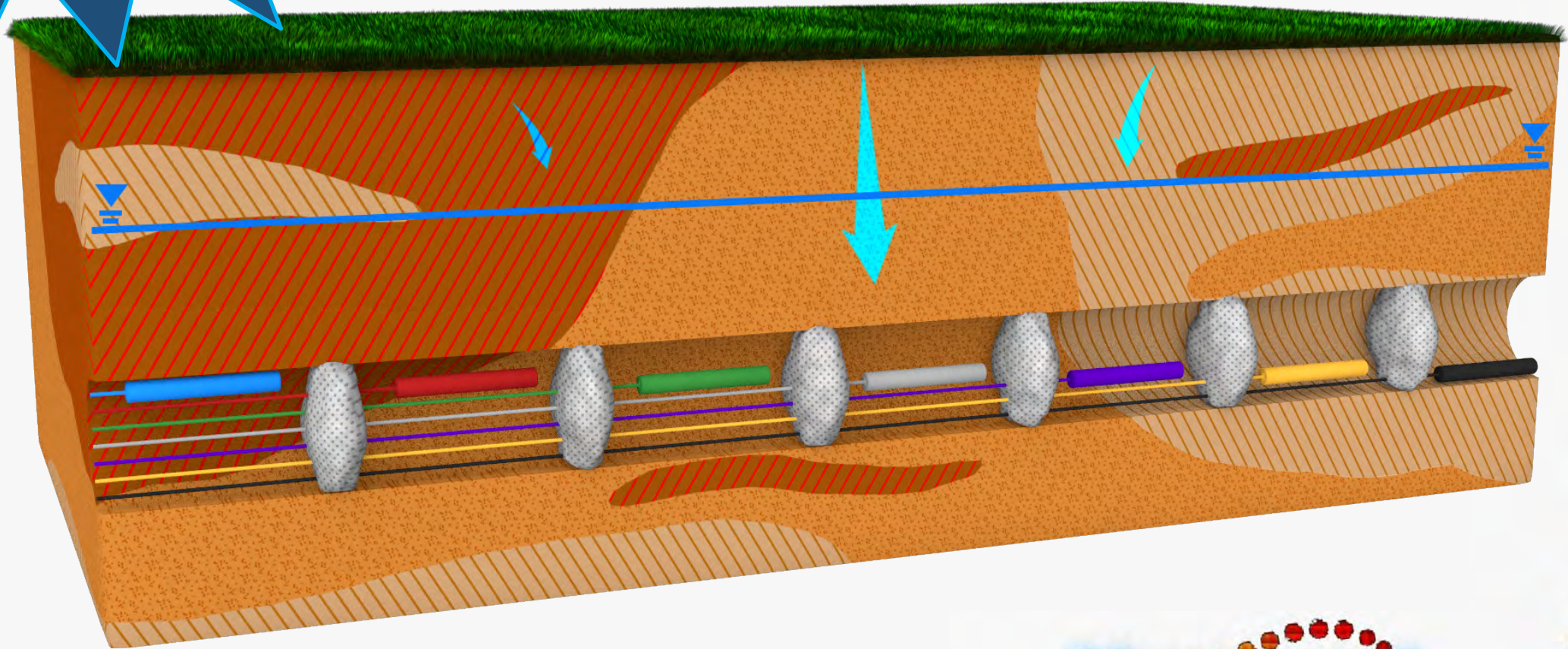
- Nested wells are discrete, using grout-based isolation, but still communicate individually to the surface.
- Assessment and treatment becomes independent of preferential flow path complications (for air and/or water).



Constructed out of HDPE.
PFAS Free Tested!

For sampling and treatment!

Increasing the Granularity!



 Sand  Silty Sand  Clay  Grout



Traditional Soil Tools allow cost efficient means to increase density in the Z direction, especially with High Resolution Site Characterization tools.

Traditional Soil Tools and monitoring well layout can be costly to increase density in the X and Y directions.

Vertebrae increased density is more compressed than monitoring well layouts with customized screen ranges from 2 to 35 feet and customized spacing lengths.



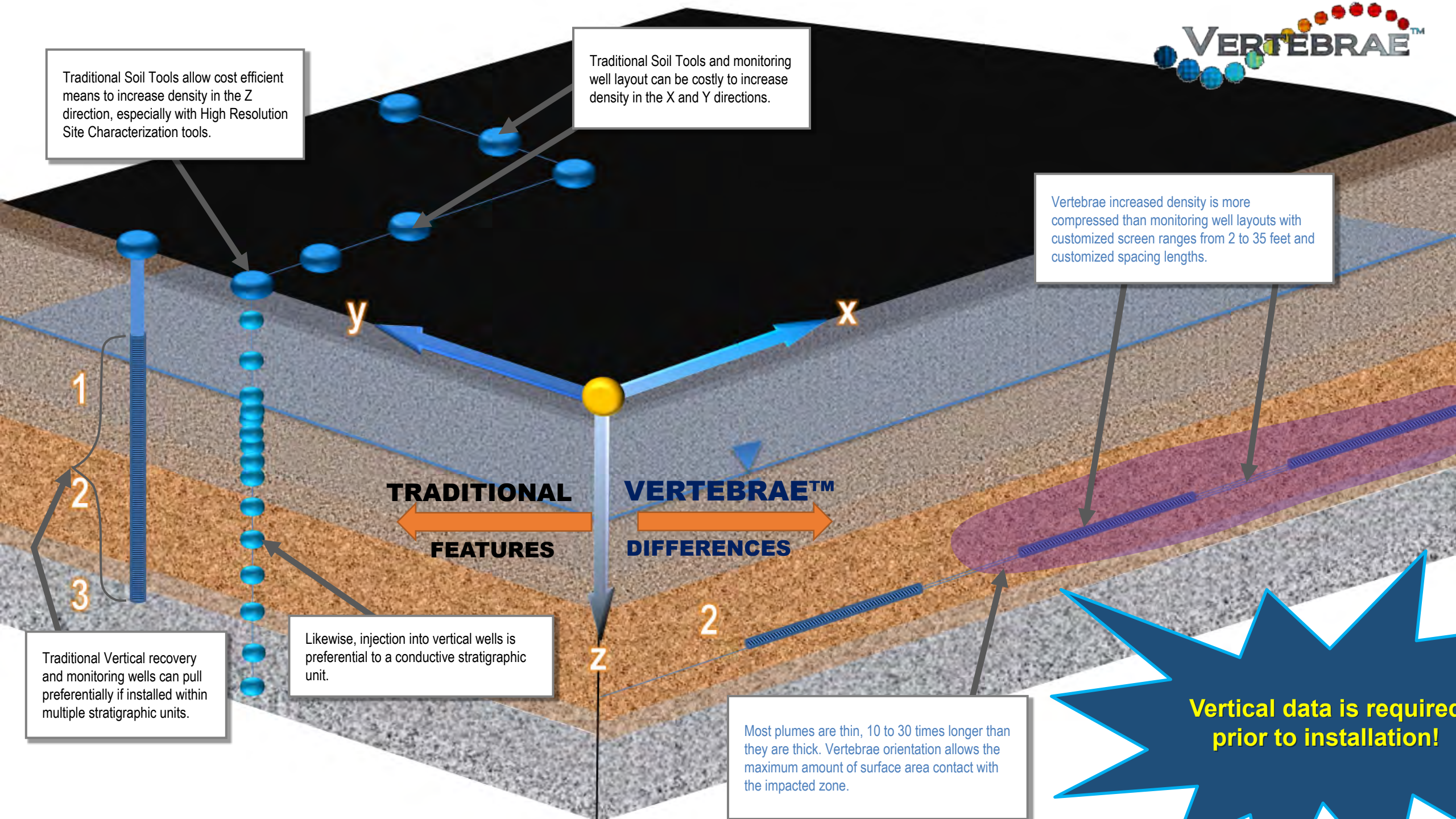
Traditional Vertical recovery and monitoring wells can pull preferentially if installed within multiple stratigraphic units.

Likewise, injection into vertical wells is preferential to a conductive stratigraphic unit.

TRADITIONAL FEATURES **VERTEBRAE™ DIFFERENCES**

Most plumes are thin, 10 to 30 times longer than they are thick. Vertebrae orientation allows the maximum amount of surface area contact with the impacted zone.

Vertical data is required prior to installation!



Case Study 1: Industrial Site

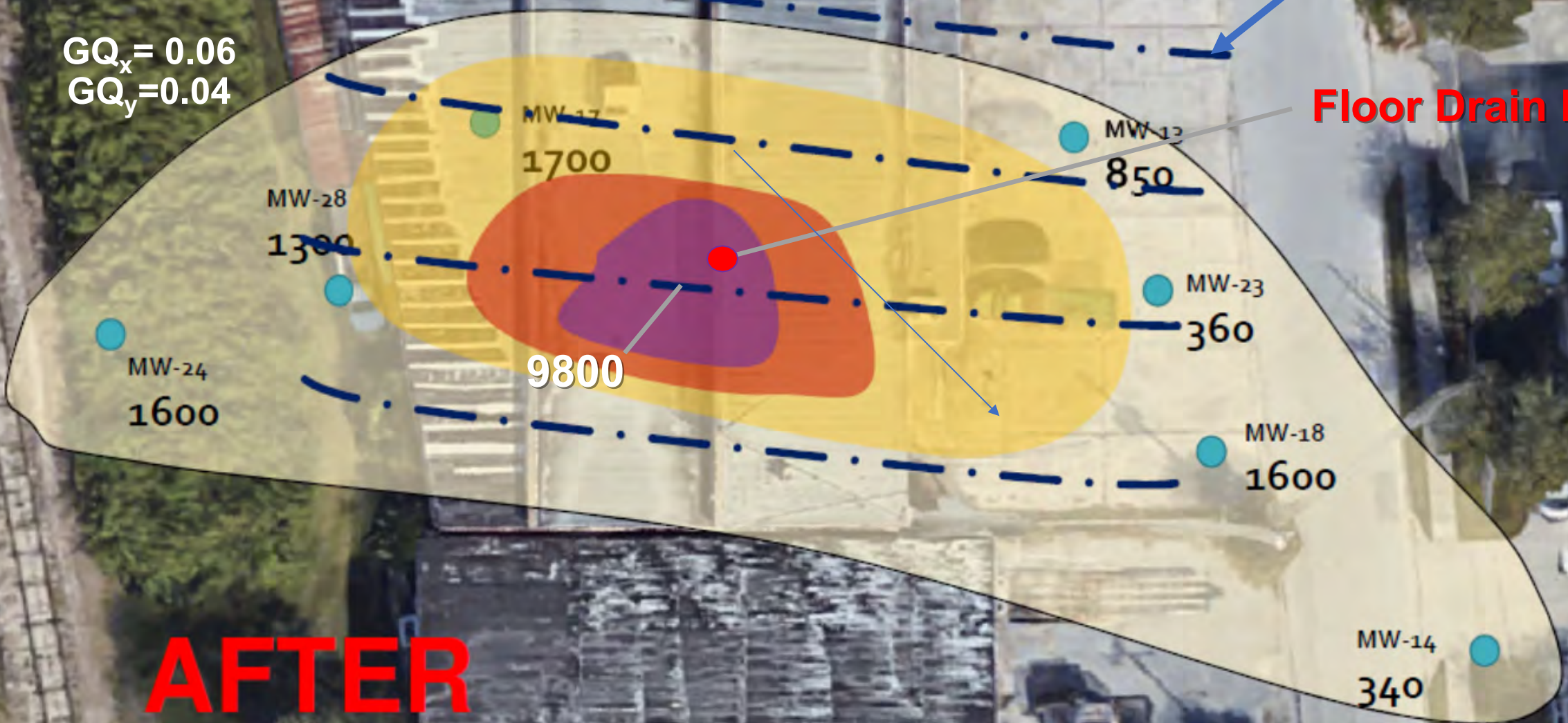


Results - 1,2 DCE in ppb

Vertebrae Screens

$GQ_x = 0.06$
 $GQ_y = 0.04$

Floor Drain Leak



AFTER

Sampling nested wells identified 400% more contamination.

Results - 1,2 DCE in ppb

Case Study 2: Strip Mall Site



Groundwater Sample Location

BDL

41

BDL

6820

BDL

Total Halogenated Volatile Organic
Compounds HVOCs in ppb

Dry Cleaner Site – Orlando, FL
Shallow Zone

Data Gap Types

?
Extrapolation

?
Interpolation

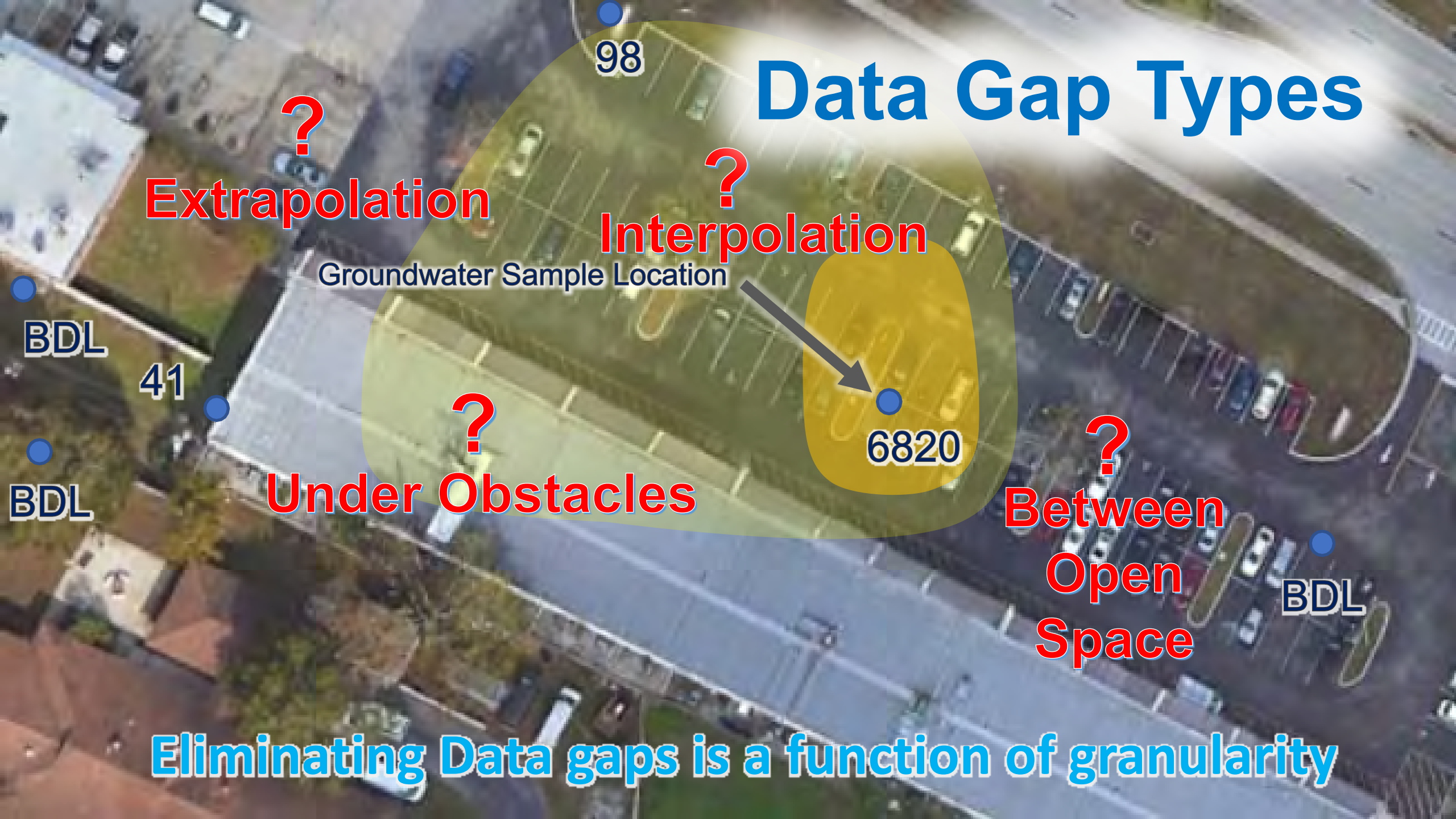
?
Under Obstacles

?
**Between
Open
Space**

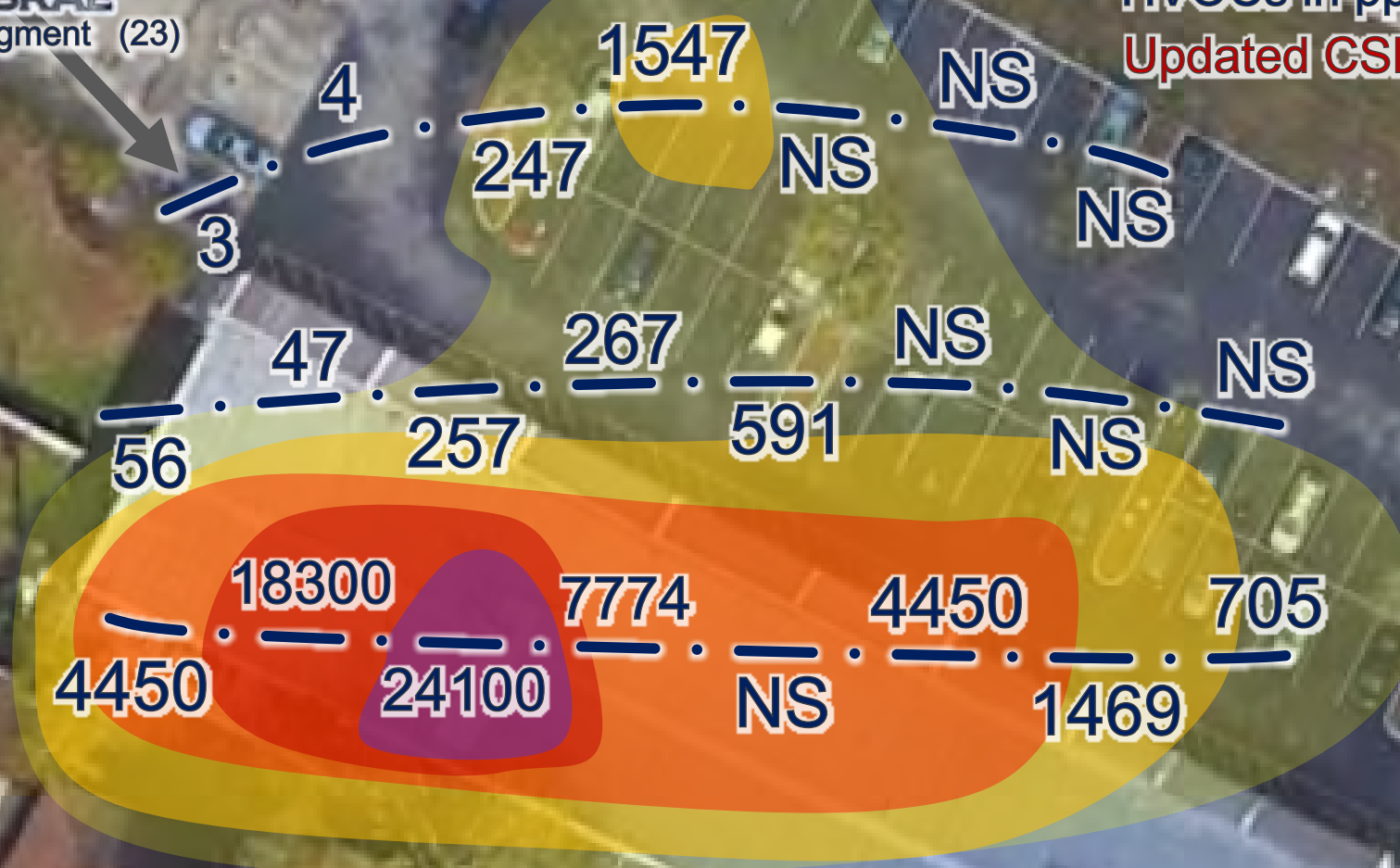
Groundwater Sample Location

6820

Eliminating Data gaps is a function of granularity



Total Halogenated Volatile Organic Compounds
 HVOCs in ppb - NS = not sampled
 Updated CSM indicated shallow mass was
 8 times greater



Dry Cleaner Site – Orlando Shallow Zone

$GQ_x = 0.06$
 $GQ_y = 0.03$



Total Halogenated Volatile Organic Compounds HVOCs in ppb

1-Year From Start of Active Remediation Using Vertebrae™ and FOCIS™
~94% reduction in mass!



Dry Cleaner Site – Orlando Intermediate Zone

$GQ_x = 0.03$
 $GQ_y = 0.02$

Keys to Success:

Although quantifying the mass is critical,
Treating the mass at its location is more
important!



Distribution
of Mass

“Location, Location, Location”

Quantity
of Mass
(estimate)

Success

Vertebrae allows higher granularity for better Distribution understanding.

Vertebrae Wells Improved CSM!

- Most sites are currently installing Vertebrae Well Systems during the remedial phase.
- Sites where Vertebrae were used to update the CSM it has led to:
 - Higher mass estimates
Average of 4 times more!
 - Better pinpointing of the source/plume center.
Always as Density Changes!

| Sites With Vertebrae used for Assessment / Data Gaps | | | | |
|--|-----------------------------|-----------------------------|-------------|--|
| Site | Initial Mass Estimate (lbs) | Updated Mass Estimate (lbs) | Mass Change | Change In Plume Center/Mass Distribution |
| Light Industrial SW FL | 820 | 7,022 | 8.56 X | Y |
| Elegance Central FL (S) | 10 | 82 | 8.20 X | Y |
| Elegance Central FL (I) | 64 | 44 | -0.68 X | Y |
| NASA (SE US) | 3,120 | 16,290 | 5.22 X | Y |
| C-Store Pensacola, FL | 19 | 37 | 1.95 X | Y |
| C-Store Milton, FL * | 785 | 1,406 | 1.79 X | Y |

Utility of Vertebrae via Permanence

- As shown; practical to collect higher resolution planer data sets.

Also:

- Allows repeatability; attenuation or performance monitoring.
- Allow treatment through the same device, as necessary.

Additionally

- Hydraulic conductivity and flux measurements using Vertebrae have been completed successfully. Repeatably.



Strategic Environmental Research and Development Program (SERDP) and the Environmental Security Technology Certification Program (ESTCP)

Vertebrae™ Segmented Horizontal Wells for Monitoring PFAS Mass Discharge

ER20-5026

POINT OF CONTACT

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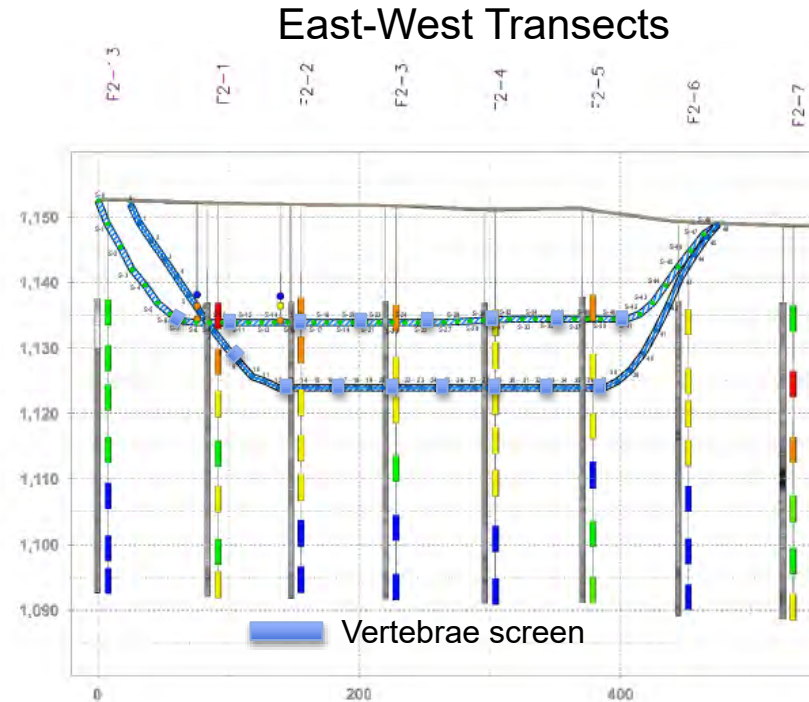
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Objective

It is increasingly apparent that contaminant mass flux/discharge provides the most representative measure of plume dynamics and risk to receptors. Consequently, remedial technologies focusing on long-term mass

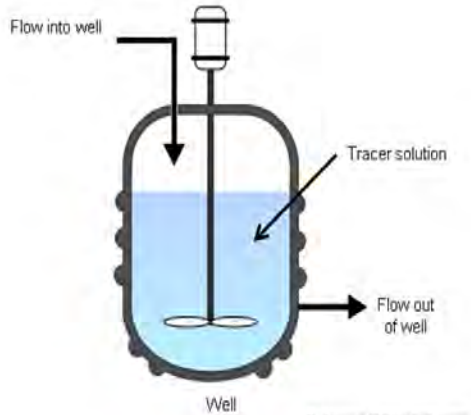
Demonstration Plan Layout – Vertebræ



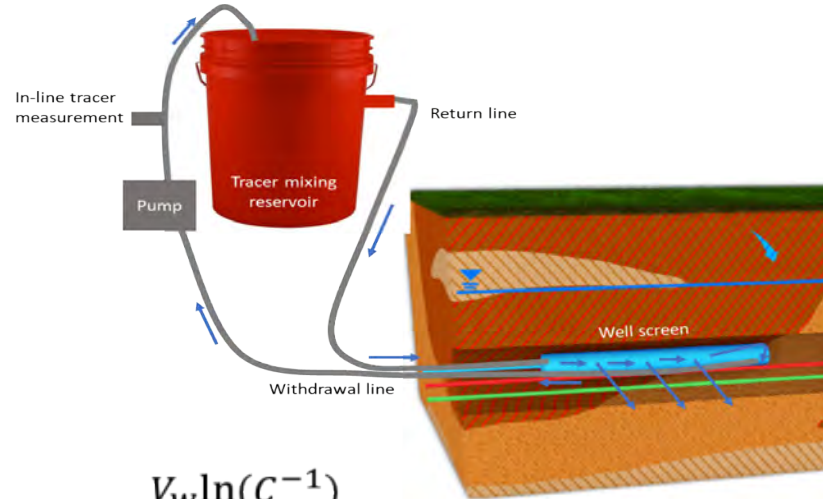
| Well ID | Horizontal length (ft) | Maximum Depth (ft) | Screen Segments | Well Construction | Other Details |
|-------------------------------|------------------------|--------------------|-----------------|--|--|
| Shallow transect | 487 | 18 | 8 | <ul style="list-style-type: none"> •4-in 13.5 SDR 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 |

Single Well Tracer Tests (SWTTs)

SWTT for groundwater flux



Reference: Wikipedia Images



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

q_w is the flux through the well

A is the area of the well segment exposed to groundwater flow

r is the effective well radius

b is the length of the well screen

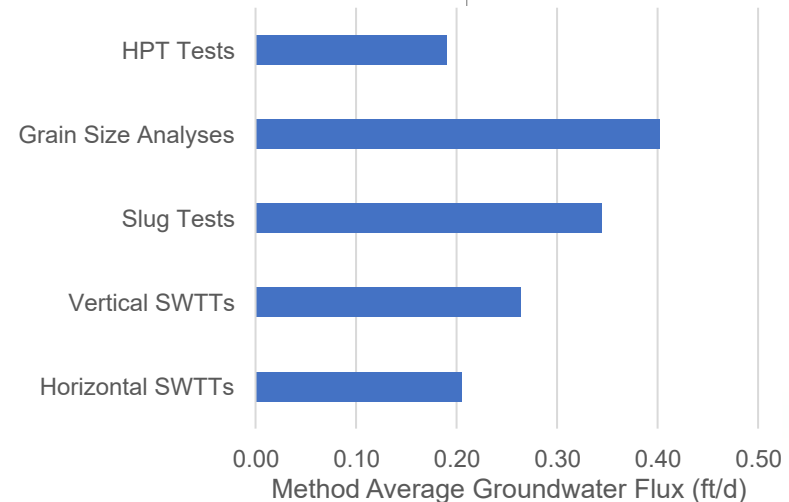
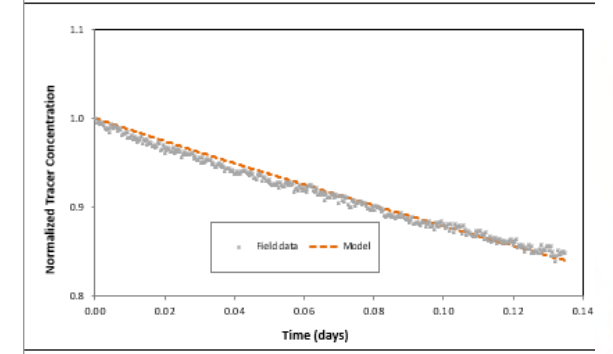
V_w is the total volume of tracer-tagged water

Vertebrae™ System Single Well Tracer Test Analysis Tool

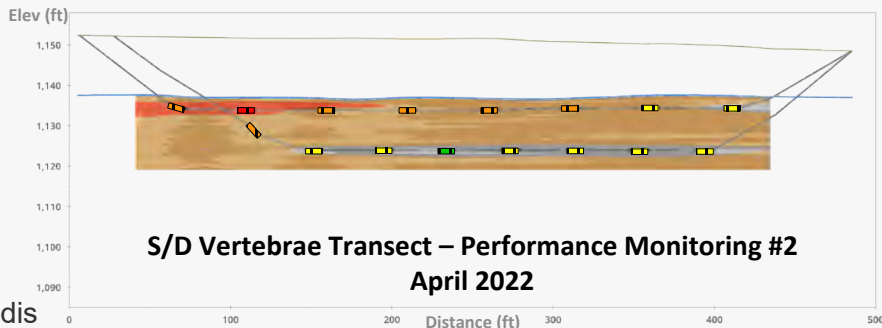
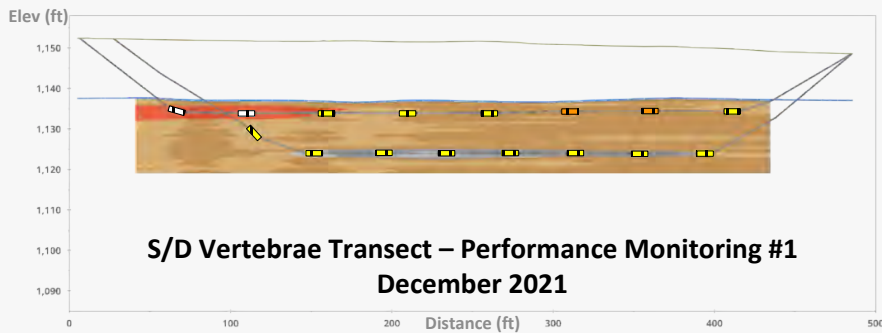
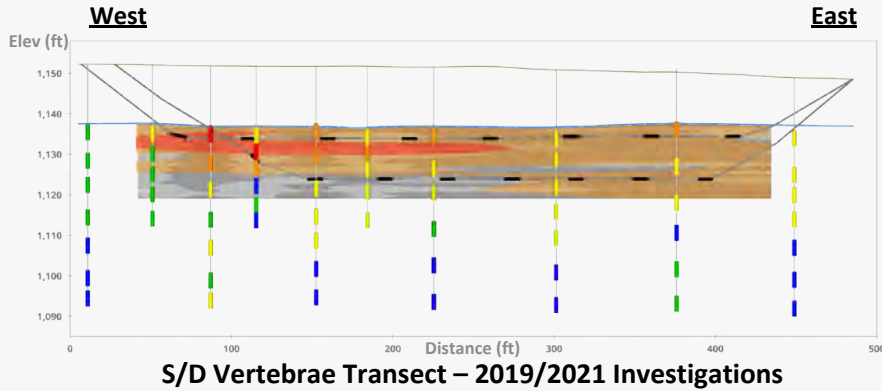
C. Divina, J. Wright, L. Robinson, Version 1.1, June 2022

Site/Project #: ST
 Analysis by/date: CED
 Vertebrae Well ID: ST
 Well Segment ID: DP8
 Tracer Used: Saline Solution

| | | |
|---------------------------------------|-----------------|---------------|
| Tracer Type Introduced | Saline Solution | Units |
| Background Tracer Concentration | 500 | uS/cm |
| Starting Tracer Concentration in Well | 985 | uS/cm |
| Tracer Test Start Date and Time | 1/7/09 2:24 | |
| Well Water Flux (q_w) | 0.48 | ft/day |
| Y-Axis Intercept | 1.00 | Dimensionless |
| Well Area/Volume | 2.68 | t^{-1} |



Mass Discharge Analysis



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

| PFOS Mass Discharge | GW Gradient | GW Discharge for Cross Sectional Area | Total Mass Discharge for Cross Sectional Area |
|--|-------------|---------------------------------------|---|
| | ft/ft | gpm | mg/day |
| 2019/2021 Investigations | 0.0023 | 6.5 | 37 |
| Vertebrae Transect PM#1 | 0.0023 | 6.5 | 31 |
| Vertebrae Transect PM#2 | 0.0018 | 5.0 | 29 |
| Cross sectional area = 7,124 ft² | | | |

$$M_D = \sum C_i \cdot (K_i \cdot i) \cdot A_i$$

Remedial Utility of Vertebrae

- Through enhancement of the CSM via HRCD, Vertebrae provides:
 - Better pinpointing of the source/plume center
 - Controlled treatment for efficient technologies
- More Efficient Remedial Technologies
 - Increased screen area and length allows for higher injection and recovery rates
 - Customized distribution of wells within a single stratigraphic unit allows for active treatment where it's needed

Deployed Types of Vertebrae

| Technology | State | Risers | Design Spec | Screen Length | System Length | Well Systems | Total Screens | Screen depth |
|------------------|-------|---------------|--------------|---------------|---------------|--------------|---------------|--------------|
| AS Curtain | MT | 1.25" | 260 cfm | 20' | 200' | 1 | 7 | 30' |
| Bio Sparge | FL | 0.75" | 0.1 cfm /ft | 15' | 900' | 1 | 12 | 61' |
| AS/SVE | CO | 0.75" / 1.25" | 435 cfm | 15' | 600' | 5/5 | 29/19 | 15'/30' |
| SVE (only) | TX | 1.5" | 400+ cfm | 20' | 200' | 7 | 22 | 8' |
| Ozone | FL | 0.5" | 0.5 cfm / ft | 15' | 150' | 1 | 7 | 35' |
| AOP (HP portion) | FL | 0.375" | 0.25 gpm | 2' | 400' | 3 | 42 | 41' |
| ISCO | AZ | 0.5" | 11 gpm | 10' | 200' | 1 | 11 | 21' |
| Vapor Mitigation | CA | 1.25" | 510 cfm | 20' | 550' | 6 | 17 | 20' |
| Recirculation | NY | 0.75" | 21 gpm | 10' | 400' | 5 | 28 | 12'/20' |
| Bio Amendment | PA | 0.75" | 14 gpm | 10' | 400' | 1 | 8 | 14' |
| PFAS Flux | MI | 0.75" | sensors | 15' | 460' | 3 | 24 | 18'-28' |

It's Risky Business

Horizontal Tools to explore data gaps is a must to reduce risk!

- Obstacle Gaps and Open Spacing Gaps Produce Risk:

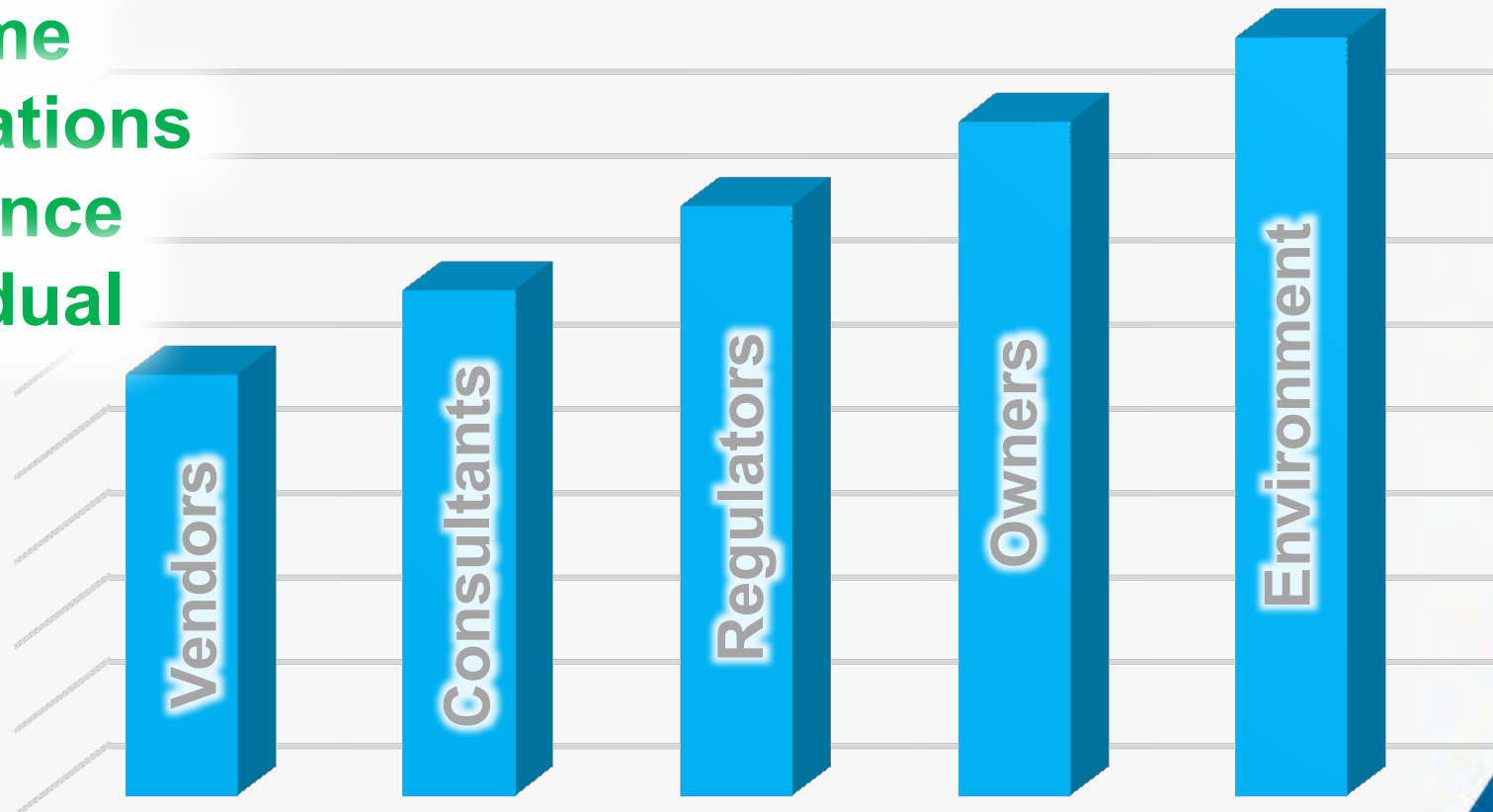
Increased Costs

Increased Time

Damaged Reputations

Poor Performance

Harmed Individual



Changing The Paradigm!

- Data gaps are no longer an excuse!
 - Formerly exploring these gaps was both difficult and costly
Now it is cost effective and practical in most cases!
 - HRCDD takes away gaps in open areas, increasing granularity.
 - Granularity Quotient is practical calculation to see when Assessment has minimized risk.
- Vertebrae is useful and can be critical in both assessment and remedial applications
Life Cycle Reduction is the key in both phases!

We are seeing the shift from installing Vertebrae for Remediation to installing them for Characterization prior to FS/RI design



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Excellence Expertise Integrity

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