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Application of Analytical Element Model to Bioventing

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Today's Discussion

- ✓ Site Description
- Discuss basis for estimating biodegradation rates for bioventing or aerobic respiration
- Introduce Analytical Element Approach Applied to Bioventing
- Provide Results & Discussion

Site Setting

Former Refinery overlying a sand aquifer

Aquifer is heavily influenced by

- Seasonal fluctuations in adjacent river resulting in groundwater flow direction reversals with various river stages
- Local industrial groundwater extraction

Historic LNAPL recovery and natural processes result in remaining impacts dominated by immobile residual LNAPL, a source of dissolved phase impacts

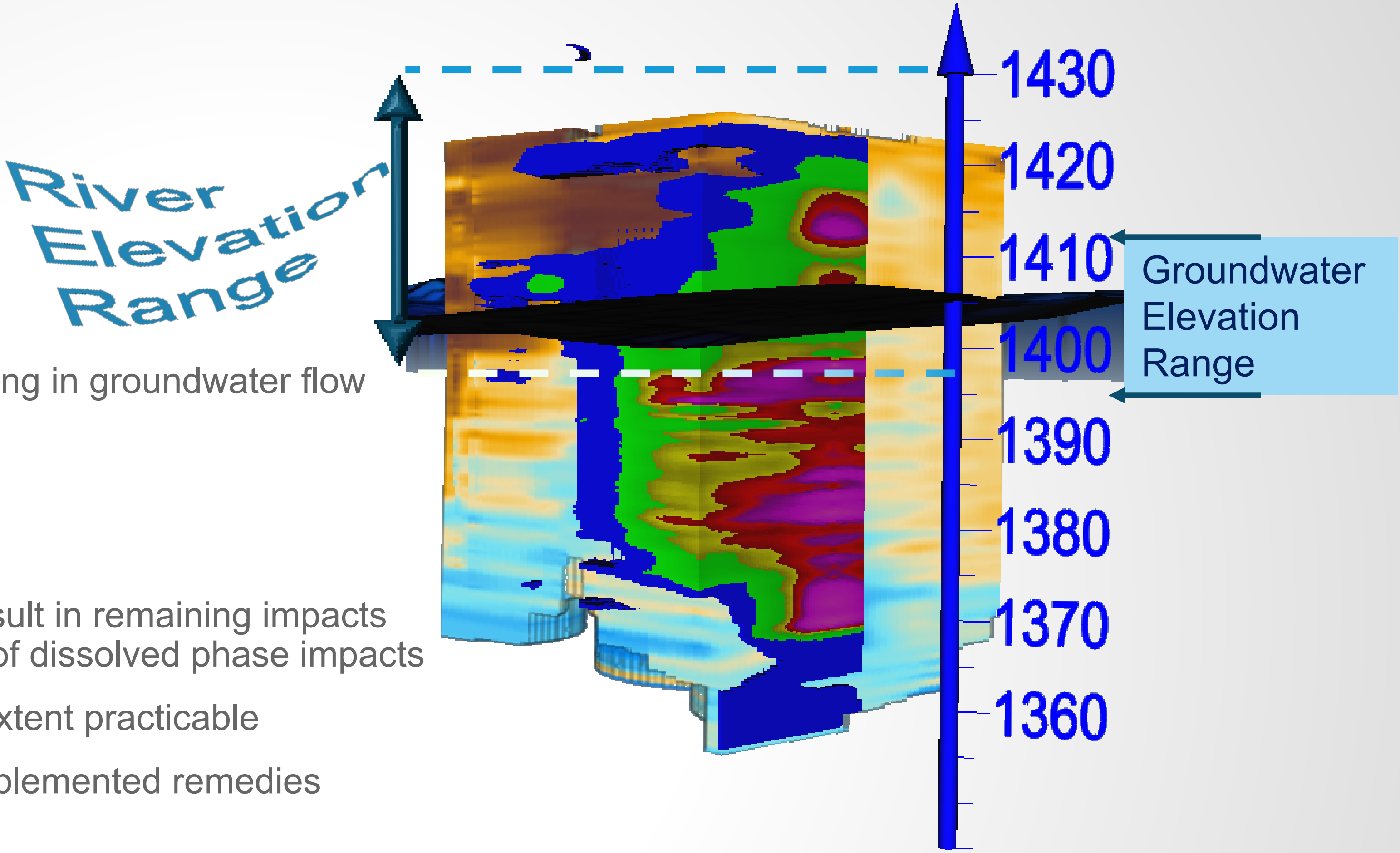
Regulatory framework does not define maximum extent practicable

Work to define remedial transition/endpoints for implemented remedies acceptable to all stakeholders

Site Approach (Simplified)

LNAPL Recovery will be performed for LNAPL transmissivity values >2 ft^2/day as measured at seasonal low water-table

Enhance biodegradation to progress dissolved phase remedial objective and represent alternative to the historical perspective of recovery to zero thickness



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Standard Respiration Testing

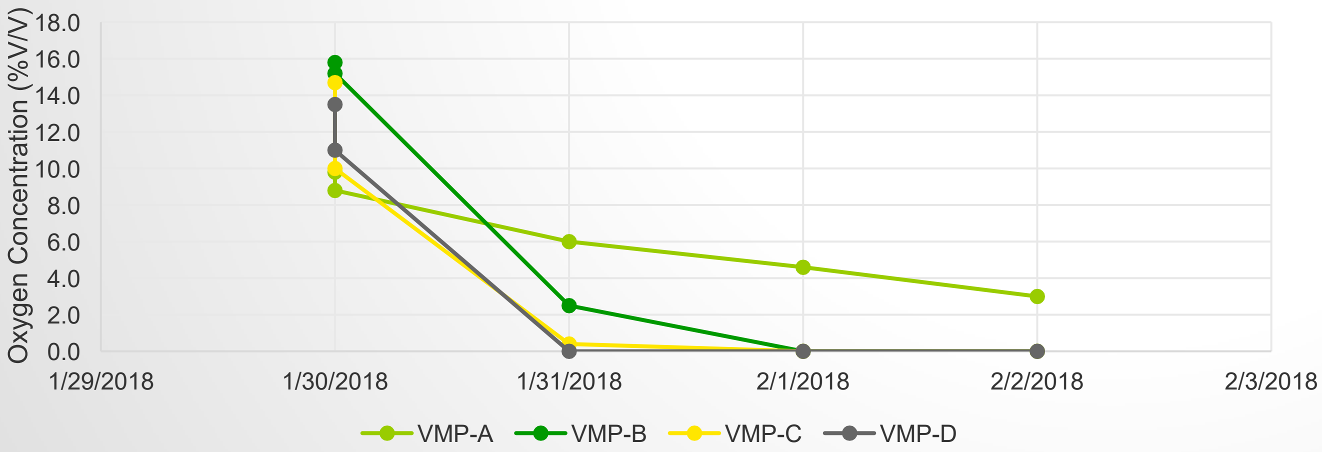
Run System → then Shutoff after a sufficient operation period

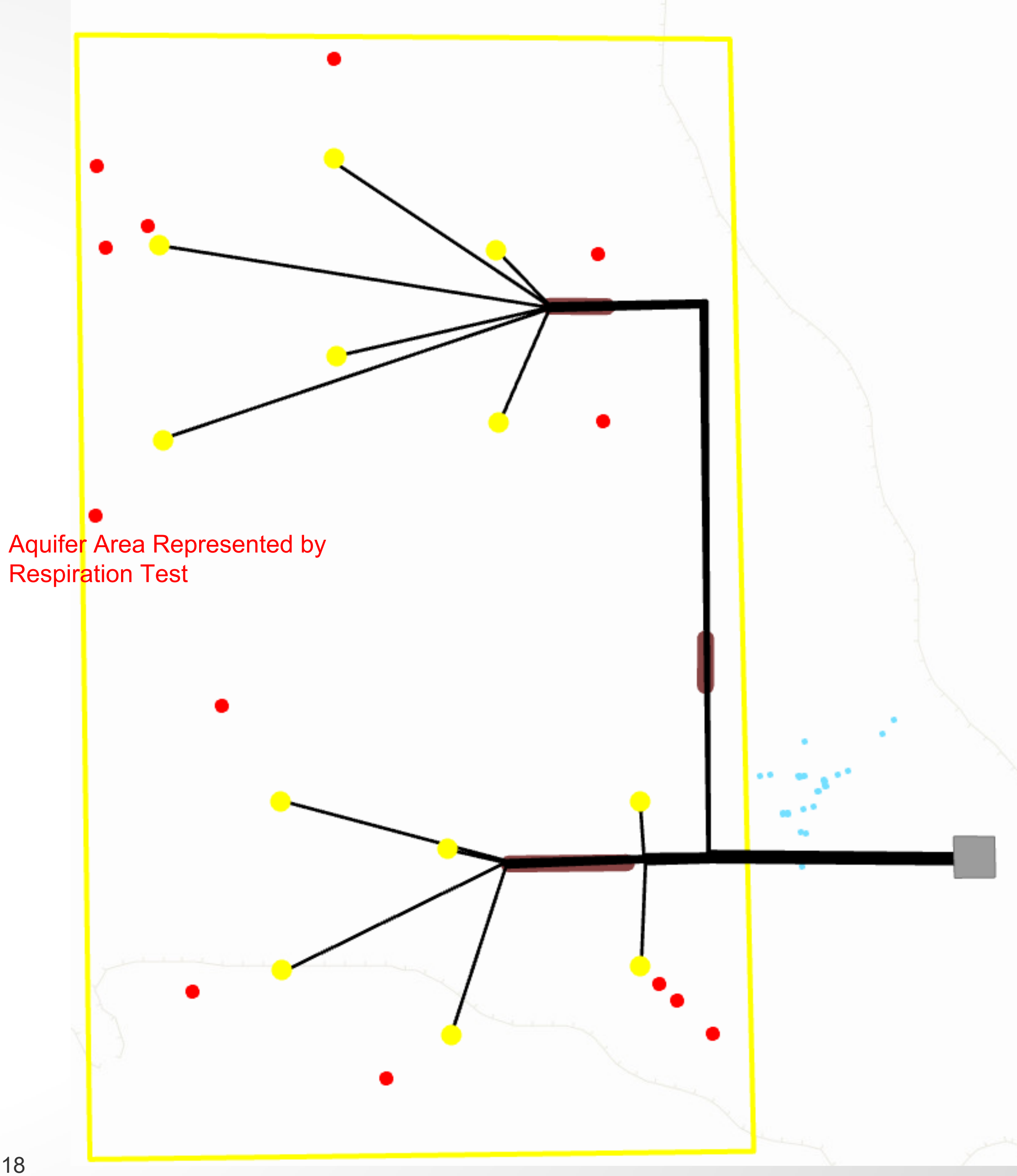
Measure change in oxygen over time at a given vapor monitoring point

Select appropriate trend and fit a line to oxygen over time

- Data needs to be filtered for time, soil gas values that result in the ~maximum rate of O_2 utilization linear behavior
- Linear behavior often does not occur at start or end of the test
- Coding data point selection for trend analysis is challenging
- Linear trends are fit manually

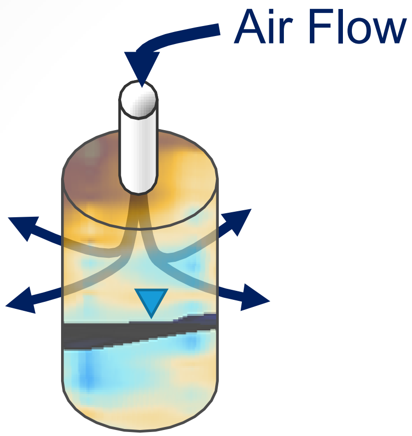
Example Respiration Test Data

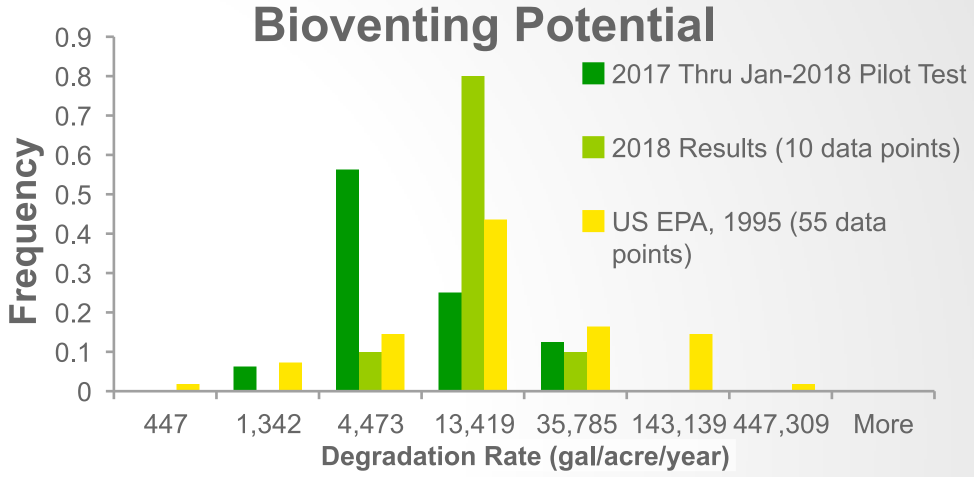




Analytical Approach

Radial Flow Solution in a Confined Vadose Zoe





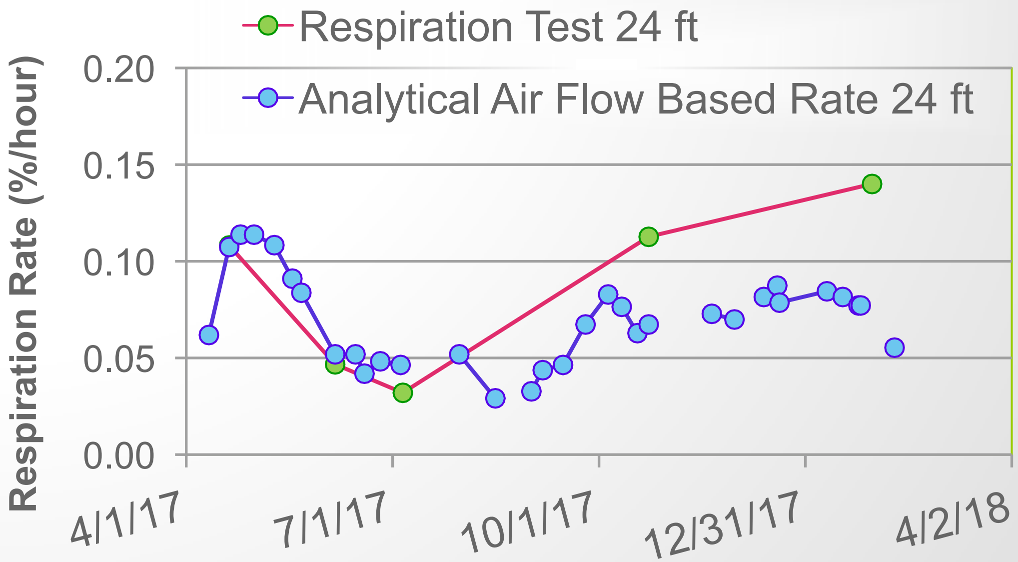
Note: US EPA Results multiplied by equivalent depth to pilot site for comparison purposes

Benefits

- Continuous measurement during operation
- Reduces Diffusion Effects?
- Can minimize effects from water-table fluctuations

Gaps

- Susceptible to permeability heterogeneity?



Multiple Wells Is More Complex

Goals of an Analytical Element Method (AEM)

- Estimate rates during operation
- Optimize data management/Analysis
- Optimization decisions based on monthly trends data rather than biannual events

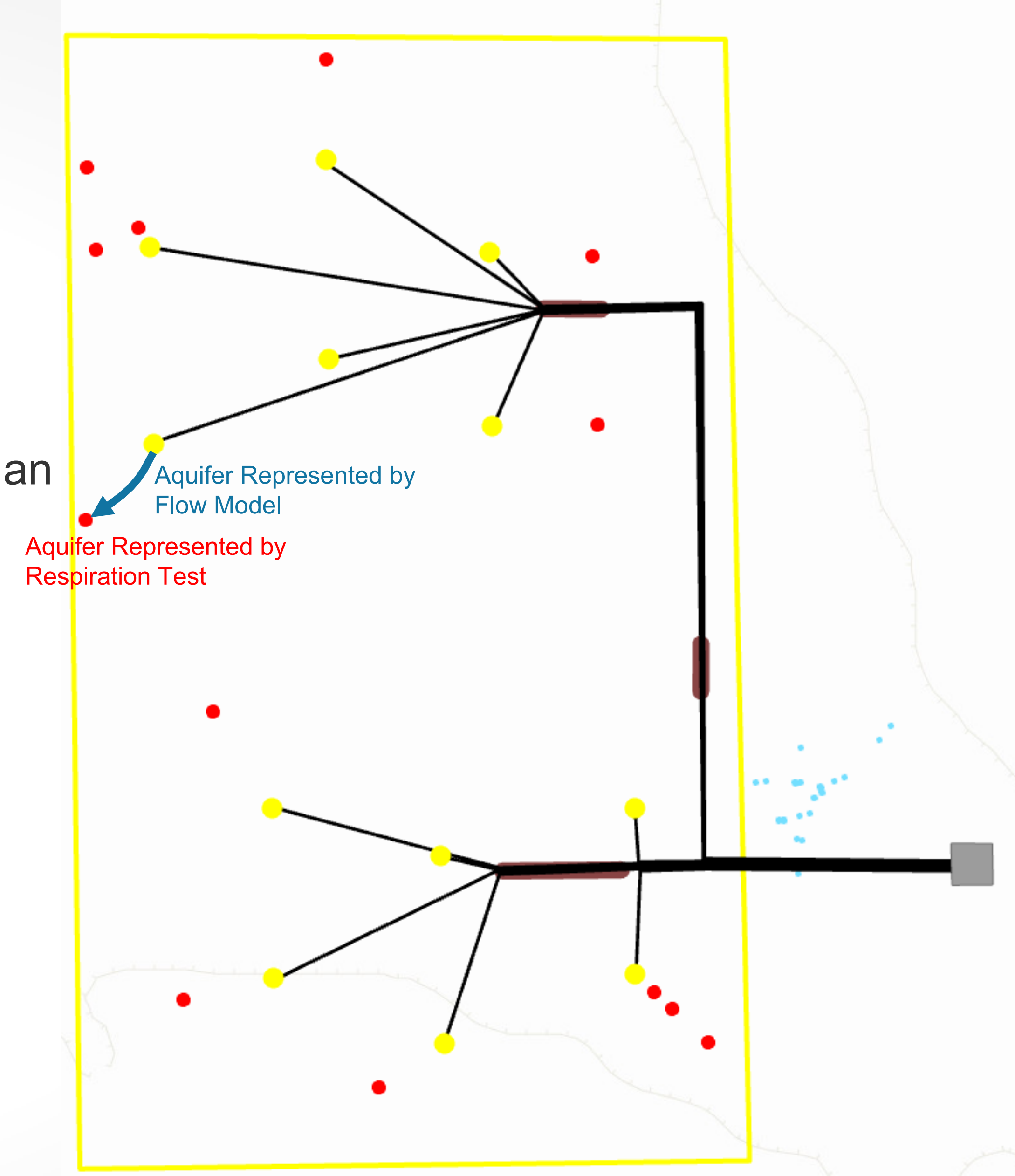
Able to account for water-table fluctuations

Leveraged Analytical Element Method (Strack, 1989)

- Can be incorporated into Python Scripts and Automated Dashboards
- Steady State Representation
  - Calculated rates following a system startup do not reflect actual biodegradation rates
  - Treatment Area is ~400 X 700 ft
  - Would require minimum of 200 hours of operation to replace the soil gas volume

Considered MS-DOS and Mod-flow based Air3D (USEPA)

VMP's were located with this application in mind



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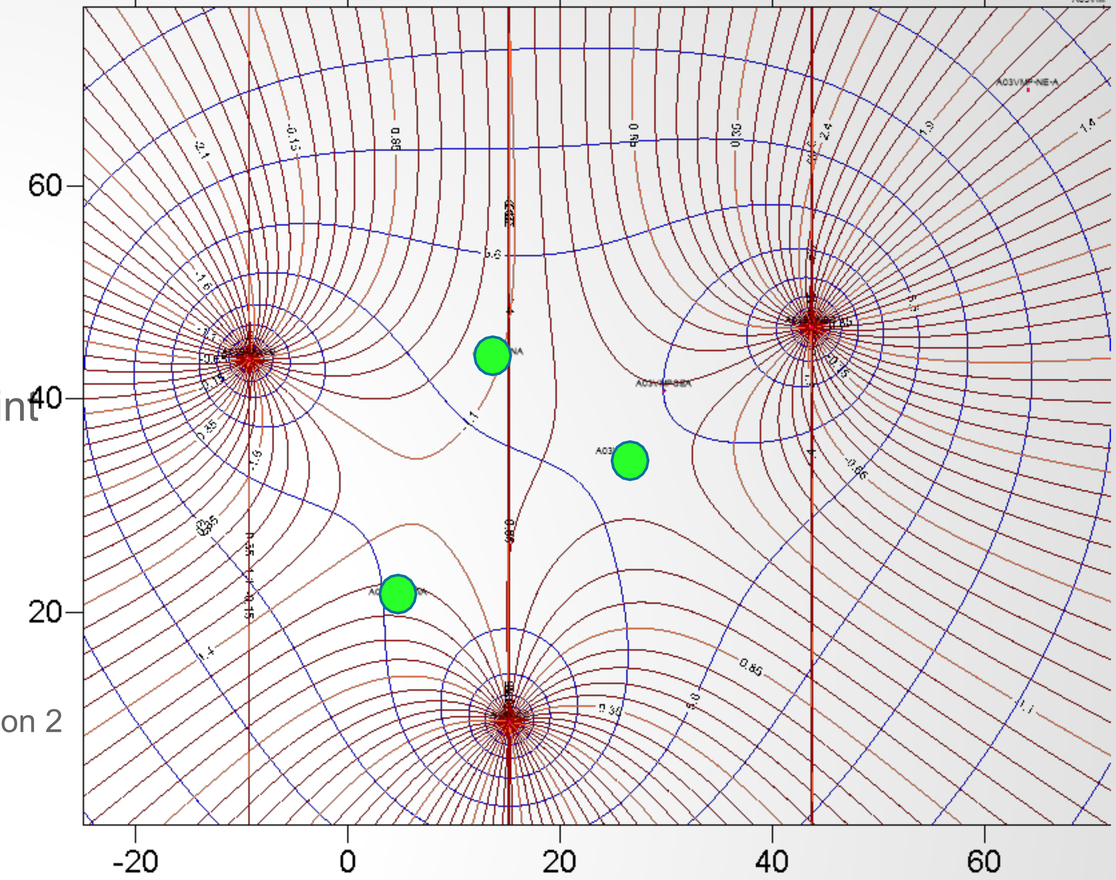
Analytical Element Method

(AEM) after Strack, 1989

Goal: Calculate the time it takes air to travel to a given vapor point

1. Calculate Stream Function (ψ) at the desired vapor monitoring point



Air Flow Head Potential

Equation 1

Equation 2

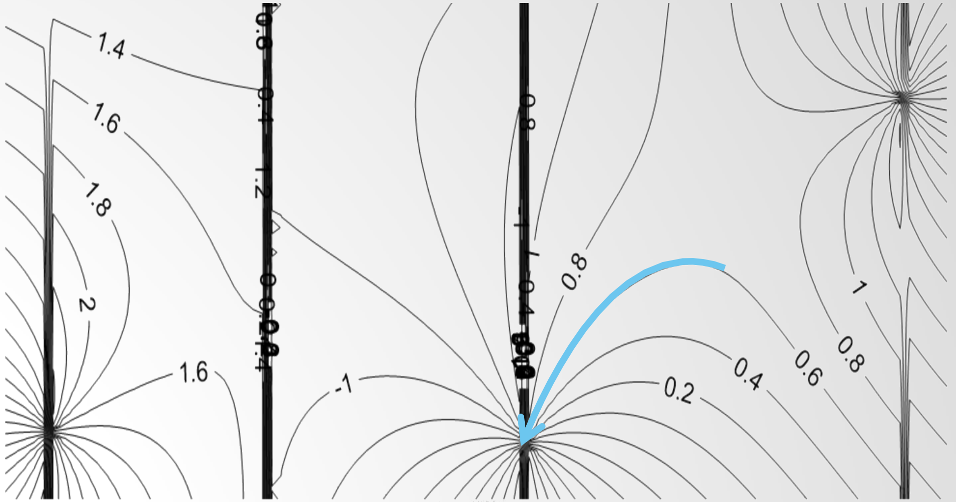
Stream Lines

$$= \frac{Q_1}{2\pi}\arctan\left(\frac{y-y_1}{x-x_1}\right) + \frac{Q_2}{2\pi}\arctan\left(\frac{y-y_2}{x-x_2}\right) + \ldots\frac{Q_n}{2\pi}\arctan\left(\frac{y-y_n}{x-x_n}\right)$$

Equation 3

AEM Process (continued)

2. Find Distance Back to original Biovent well
    1. Use Complex Coordinates for discharge vectors in x & y direction
    2. Forecast next point based on current location z plus the discharge vector
    3. Iterate using Newton-Rhapson Method to resolve z to the desired precision
    4. Log the distances along the generated path of points



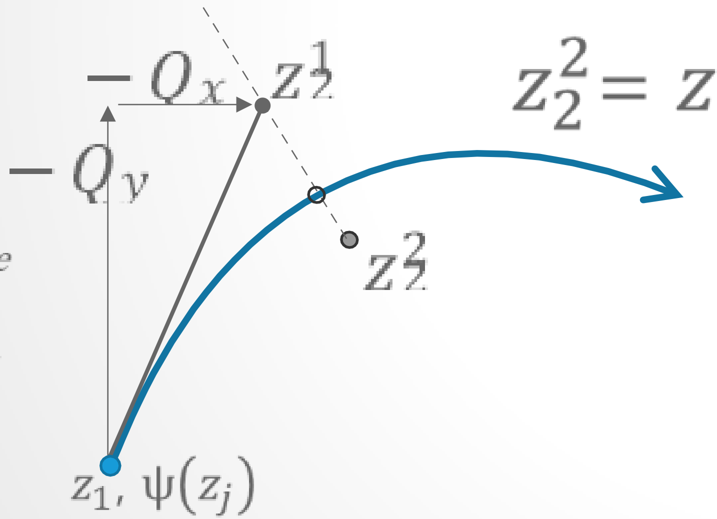
$$\bar{W} = Q_x + Q_y i$$

$$Q_x = -\frac{\delta\psi}{\delta y}$$

$$Q_y = \frac{\delta\psi}{\delta x}$$

Differentiating Equation 3

$$z_2^2 = z_2^1 + i\,\frac{\psi(z_2^1) - \psi(z_j)}{\bar{W}}$$



Complex Coordinate Plane

$\bar{z} = x + yi$

$\bar{W}$ – *discharge vector*

$$Q_x = -\frac{Q_1}{2\pi}\left(\frac{y-y_1}{(x-x_1)^2+(y-y_1)^2}\right) - \cdots \frac{Q_n}{2\pi}\left(\frac{y-y_n}{(x-x_n)^2+(y-y_n)^2}\right)$$

$$Q_y = \frac{Q_1}{2\pi}\left(\frac{x-x_1}{(x-x_1)^2+(y-y_1)^2}\right) - \cdots \frac{Q_n}{2\pi}\left(\frac{x-x_n}{(x-x_n)^2+(y-y_n)^2}\right)$$

AEM Process (continued)

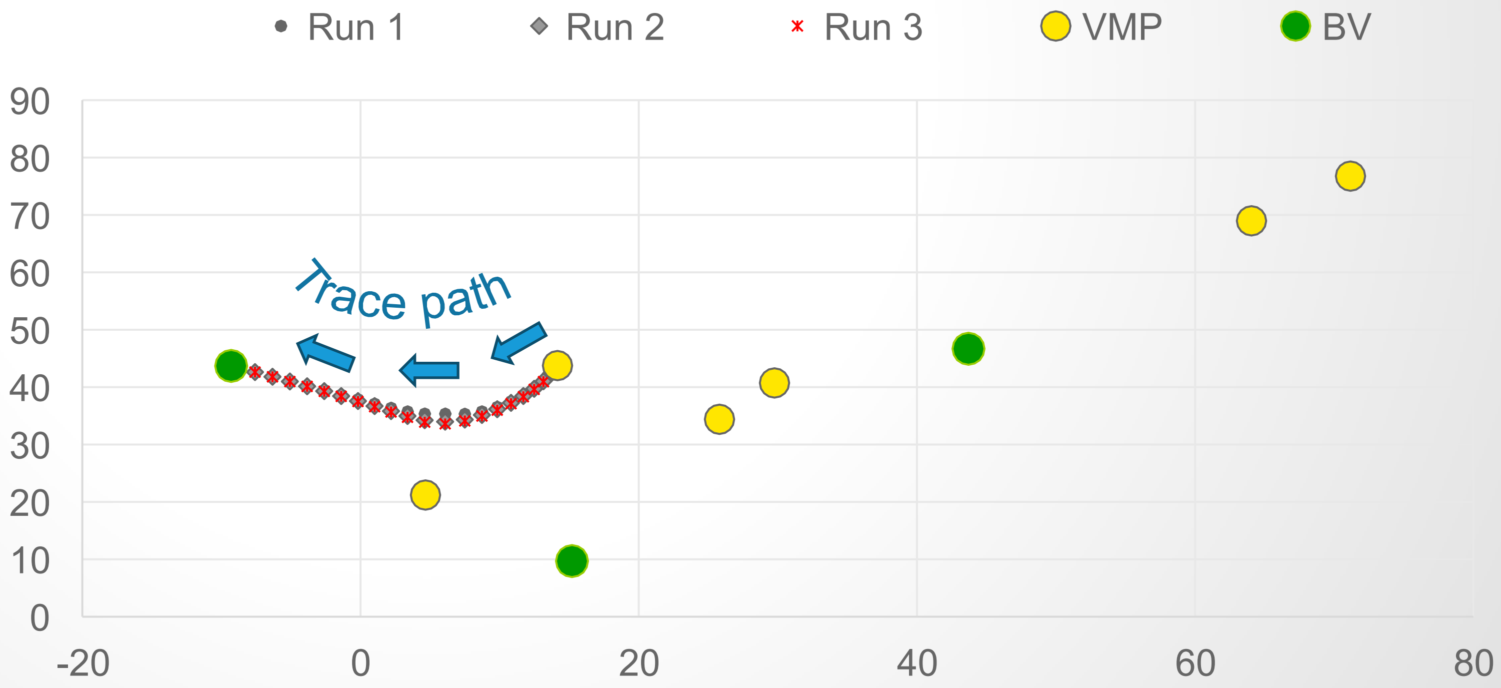
Travel time (*t*) for a given distance (*d*) segment is calculated using seepage velocity

Linear head difference used to approximate gradient

$$t = \frac{d}{v} \cong \frac{d}{\frac{k}{n}\frac{\phi_{Z_2} - \phi_{Z_1}}{d}} = \frac{d^2 n}{k\left(\phi_{Z_2} - \phi_{Z_1}\right)} = \frac{d^2 n}{\frac{Q_1}{2\pi H}\ln\left(\frac{r_{BV1\_Z_2}}{r_{BV1\_Z_1}}\right) + \cdots \frac{Q_i}{2\pi H}\ln\left(\frac{r_{BVi\_Z_2}}{r_{BVi\_Z_1}}\right)}$$

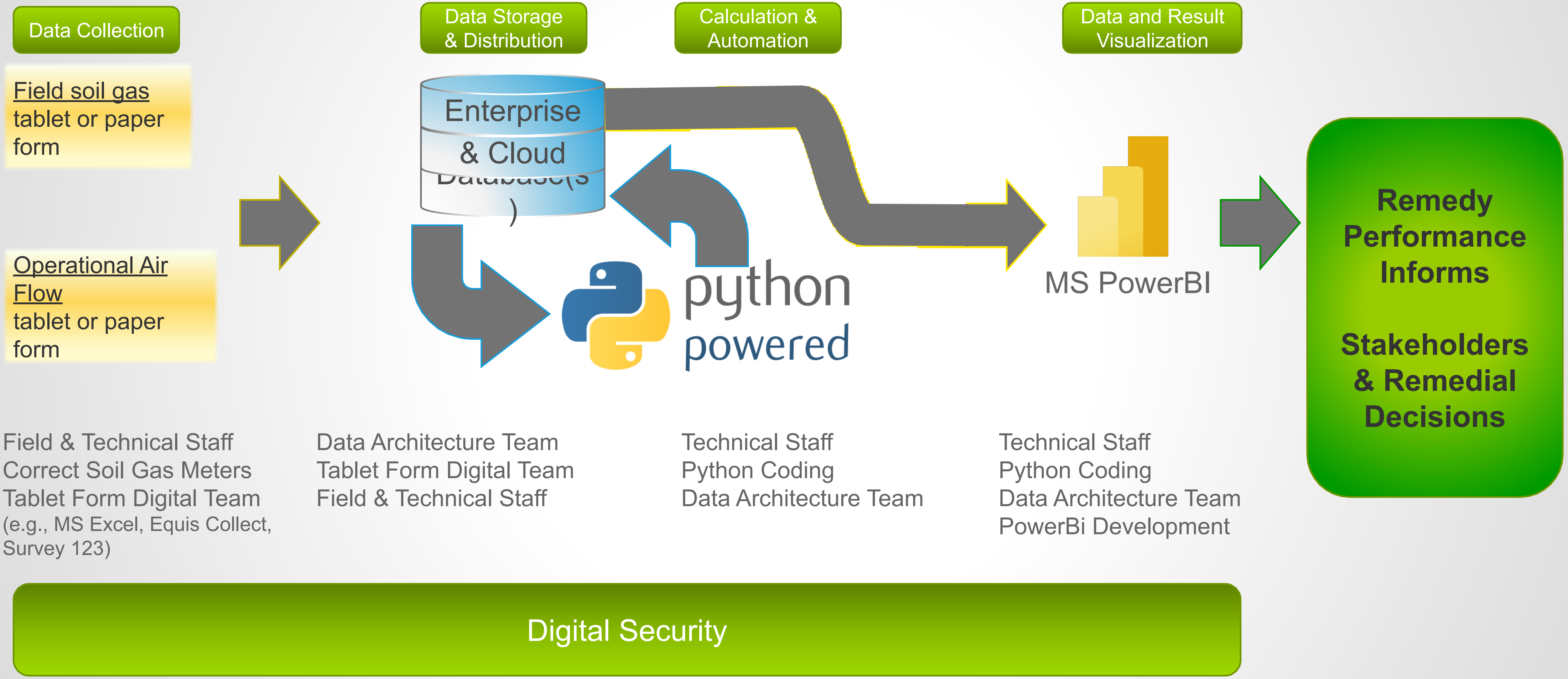
After Equation 2

Quick convergence for 3 Iterations



t – time
d – distance
n – porosity

Data Flow



Data Collection

Field soil gas
tablet or paper
form

Operational Air
Flow
tablet or paper
form

Data Storage & Distribution

Enterprise
& Cloud
Database(s
)

Calculation & Automation

Data and Result Visualization

MS PowerBI

Remedy Performance Informs

Stakeholders & Remedial Decisions

Field & Technical Staff
Correct Soil Gas Meters
Tablet Form Digital Team
(e.g., MS Excel, Equis Collect, Survey 123)

Data Architecture Team
Tablet Form Digital Team
Field & Technical Staff

Technical Staff
Python Coding
Data Architecture Team

Technical Staff
Python Coding
Data Architecture Team
PowerBi Development

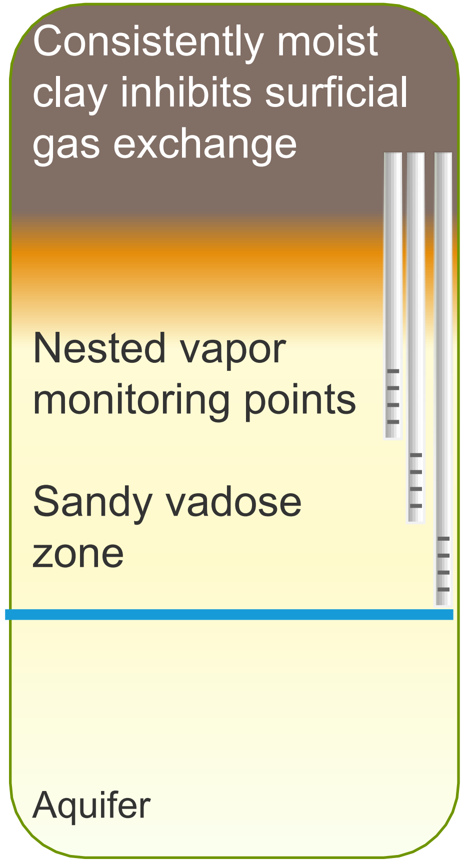
Digital Security

Soil Gas Behavior

Prior to continuous operation river induced oxygen concentration less than 2 percent

Operation of bioventing system increases oxygen concentrations above background

Groundwater elevation Induced flow not accounted for in model

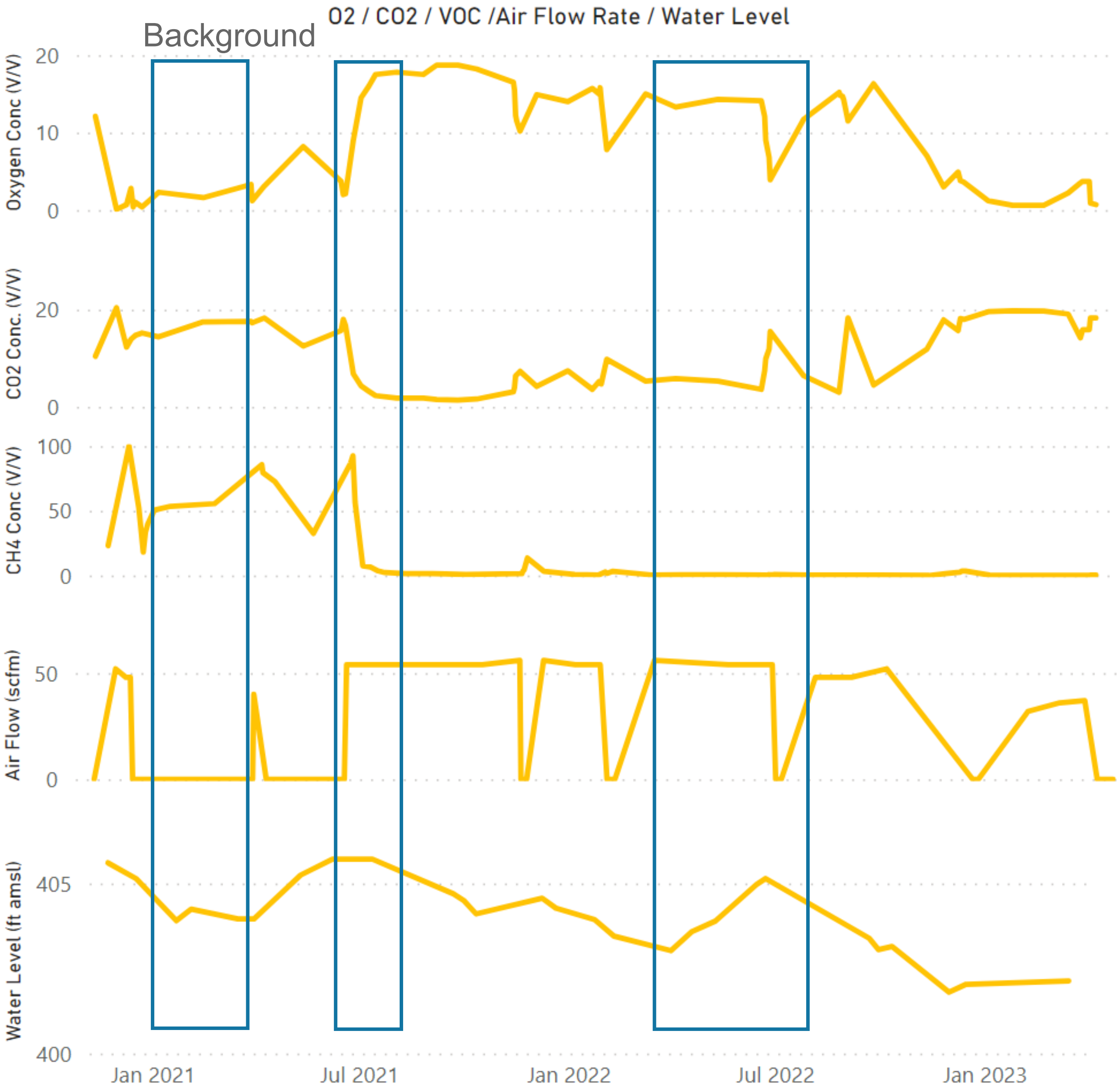


Consistently moist clay inhibits surficial gas exchange

Nested vapor monitoring points

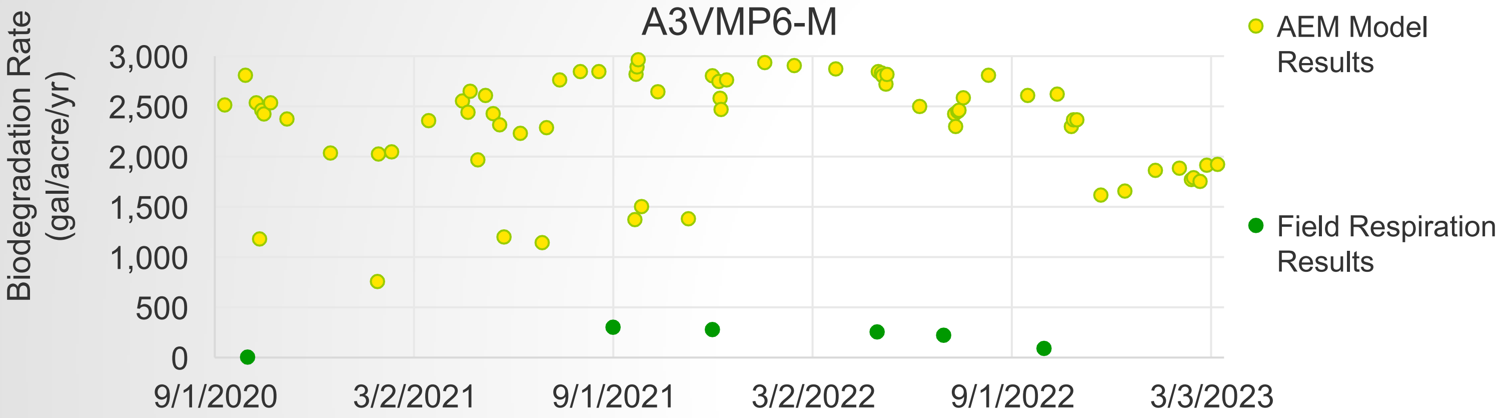
Sandy vadose zone

Aquifer

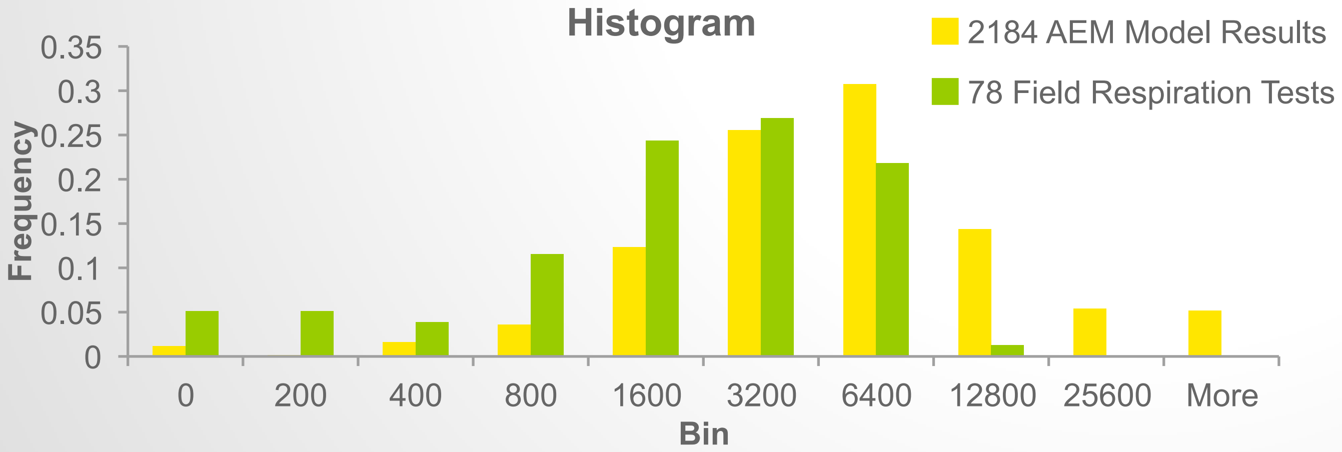


Comparison of Flow Model to Traditional Respiration Tests

- Results do not compare well at a singular location
- They do not represent the same spatial measure of space



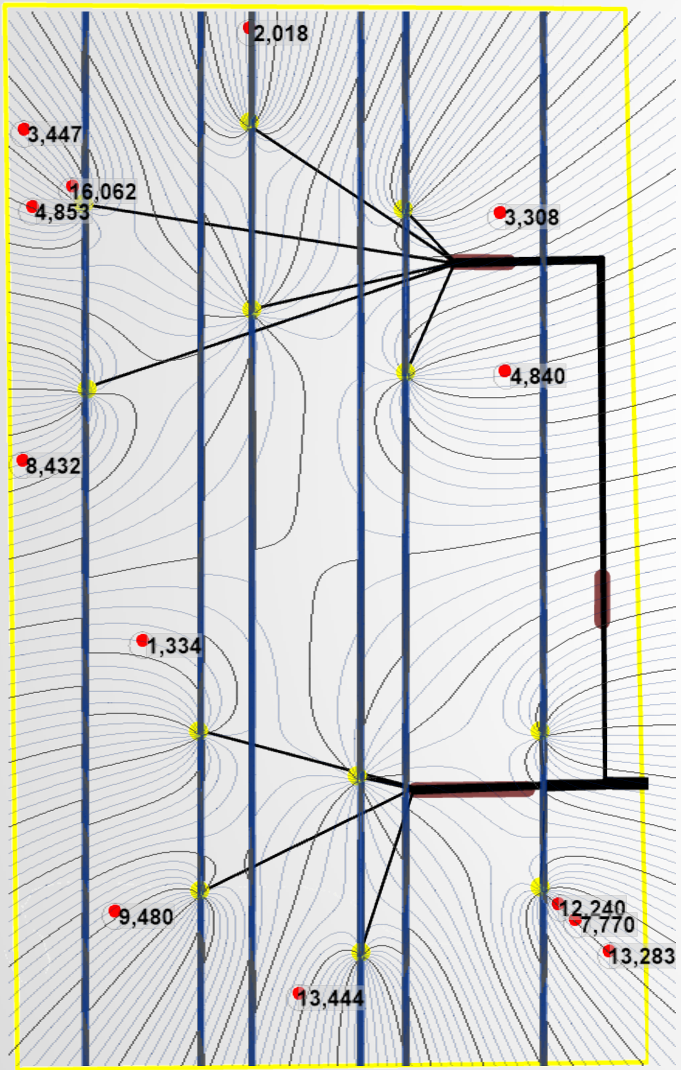
- Comparison of all locations may have room for optimism



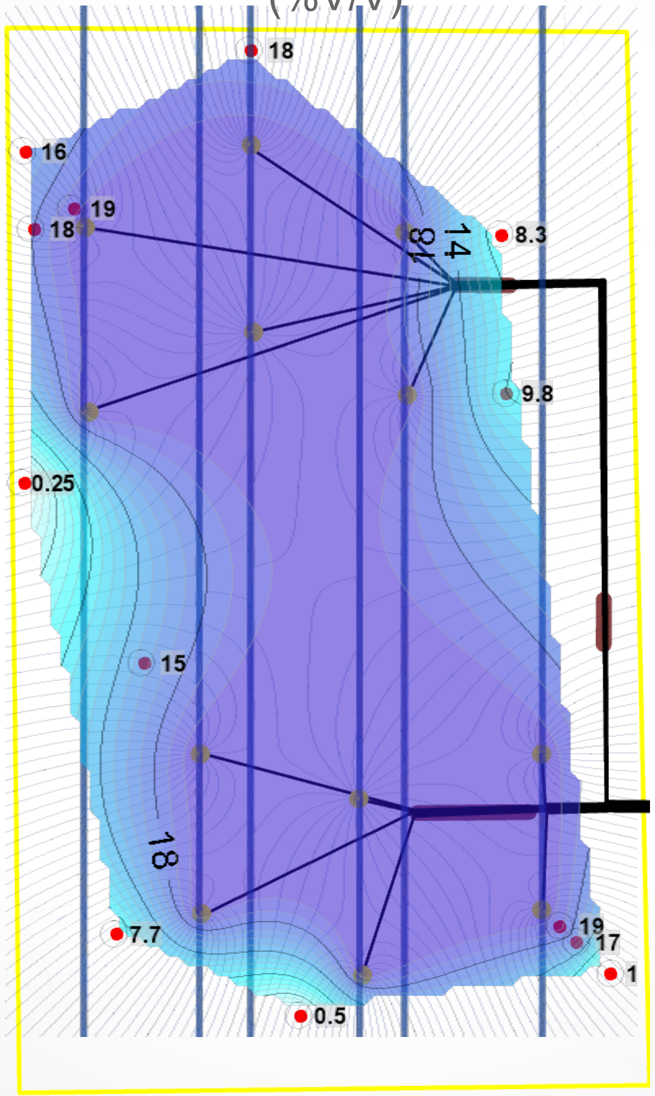
Monitoring Point (Depth)	Vertical Extent BV Influence (feet)	October-20		September-21		December-21		May-22		July-22		October-22	
		gal-NAPL/ acre/ year		gal-NAPL/ acre/ year		gal-NAPL/ acre/ year		gal-NAPL/ acre/ year		gal-NAPL/ acre/ year		gal-NAPL/ acre/ year	
A3VMP1 (17)	5.00	2,939	5,061	609	1,341	700	1,516	310	4,000	477	881	1,689	5,216
A3VMP1 (22)	5.00	2,122		732		816		1,066		404		1,733	
A3VMP1 (27)	5.00	--		--		--		2,624		--		1,794	
A3VMP2 (17)	5.00	1,866	3,918	1,982	4,478	1,143	2,939	958	7,187	657	1,838	799	1,879
A3VMP2 (22)	5.00	2,052		2,495		1,796		1,564		1,182		641	
A3VMP2 (27)	5.00	--		--		--		4,664		--		440	
A3VMP3 (17)	5.00	233	233	1,563	2,589	1,283	2,542	1,263	2,486	461	911	437	922
A3VMP3 (22)	5.00	0		1,026		1,259		1,223		450		242	
A3VMP3 (27)	5.00	--		--		--		--		--		242	
A3VMP4 (17)	5.00	1,329	4,501	2,006	3,848	1,189	3,312	1,445	3,320	451	1,851	2,511	5,216
A3VMP4 (22)	5.00	3,172		1,842		910		1,356		455		1,876	
A3VMP4 (27)	5.00	--		--		1,213		519		945		829	
A3VMP5 (17)	5.00	1,796	4,618	3,522	6,297	980	3,452	1,403	3,030	2,408	3,970	1,565	3,370
A3VMP5 (22)	5.00	2,822		2,775		1,936		307		832		782	
A3VMP5 (27)	5.00	--		--		536		1,320		730		1,023	
A3VMP6 (17)	5.00	1,399	1,702	886	1,166	886	1,399	--	0	342	564	320	412
A3VMP6 (22)	5.00	303		280		257		--		223		91	
A3VMP6 (27)	5.00	--		--		257		--		--		0	
A3VMP7 (17)	5.00	513	1,959	886	1,563	420	1,049	56	420	316	481	69	1,210
A3VMP7 (22)	5.00	1,446		676		630		201		165		424	
A3VMP7 (27)	5.00	--		--		--		163		--		717	
A3VMP8 (17)	5.00	303	1,633	1,259	2,379	1,073	2,892	660	1,140	624	1,746	1,017	3,180
A3VMP8 (22)	5.00	1,329		1,119		770		451		672		1,191	
A3VMP8 (27)	5.00	--		--		1,049		29		450		972	
A3VMP9 (17)	5.00	210	1,772	1,073	2,262	840	2,635	480	2,524	997	1,878	0	0
A3VMP19 (22)	5.00	1,563		1,189		816		1,152		416		0	
A3VMP9 (27)	5.00	--		--		980		892		465		0	
A3VMP10 (17)	5.00	420	956	117	233	396	840	--	0	193	392	24	98
A3VMP10 (22)	5.00	536		117		420		--		148		66	
A3VMP10 (27)	5.00	--		--		23		--		51		8	
A3VMP11 (17)	5.00	1,842	3,662	2,006	4,454	956	1,959	206	474	546	1,101	335	811
A3VMP11 (22)	5.00	1,819		2,449		1,003		75		556		225	
A3VMP11 (27)	5.00	--		--		--		193		--		251	
A3VMP12 (17)	5.00	327	583	396	840	513	1,119	610	1,559	136	155	211	874
A3VMP12 (22)	5.00	257		443		606		687		19		141	
A3VMP12 (27)	5.00	--		--		--		263		--		521	
A3VMP13 (17)	5.00	163	443	320	709	280	630	--	0	101	167	0	36
A3VMP13 (22)	5.00	280		389		350		--		66		0	
A3VMP13 (27)	5.00	--		--		--		--		--		36	
			2,388		**2,474**		**2,022**		**2,011**		**1,226**		**1,786**
			AVERAGE TOTAL		**AVERAGE TOTAL**		**AVERAGE TOTAL**		**AVERAGE TOTAL**		**AVERAGE TOTAL**		**AVERAGE TOTAL**

Degradation, Travel Time and Oxygen Concentrations

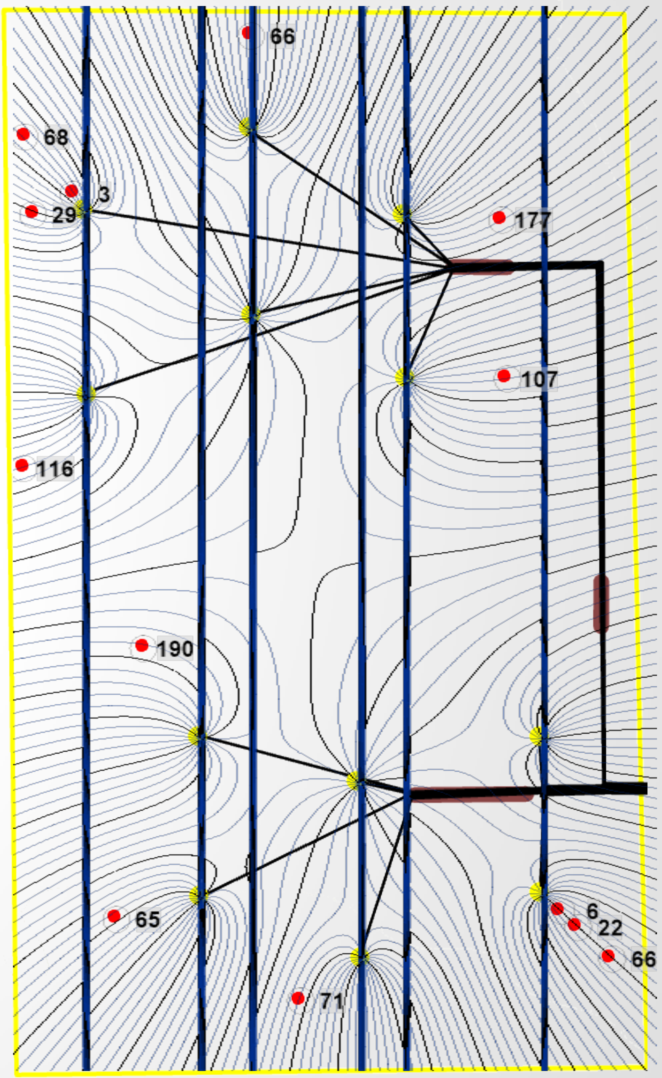
Biodegradation Rate
(gal/acre/yr)



Oxygen Concentration
(%V/V)



Travel Time



Comparison of Biodegradation Rates Needs to Consider What each Measure Represents

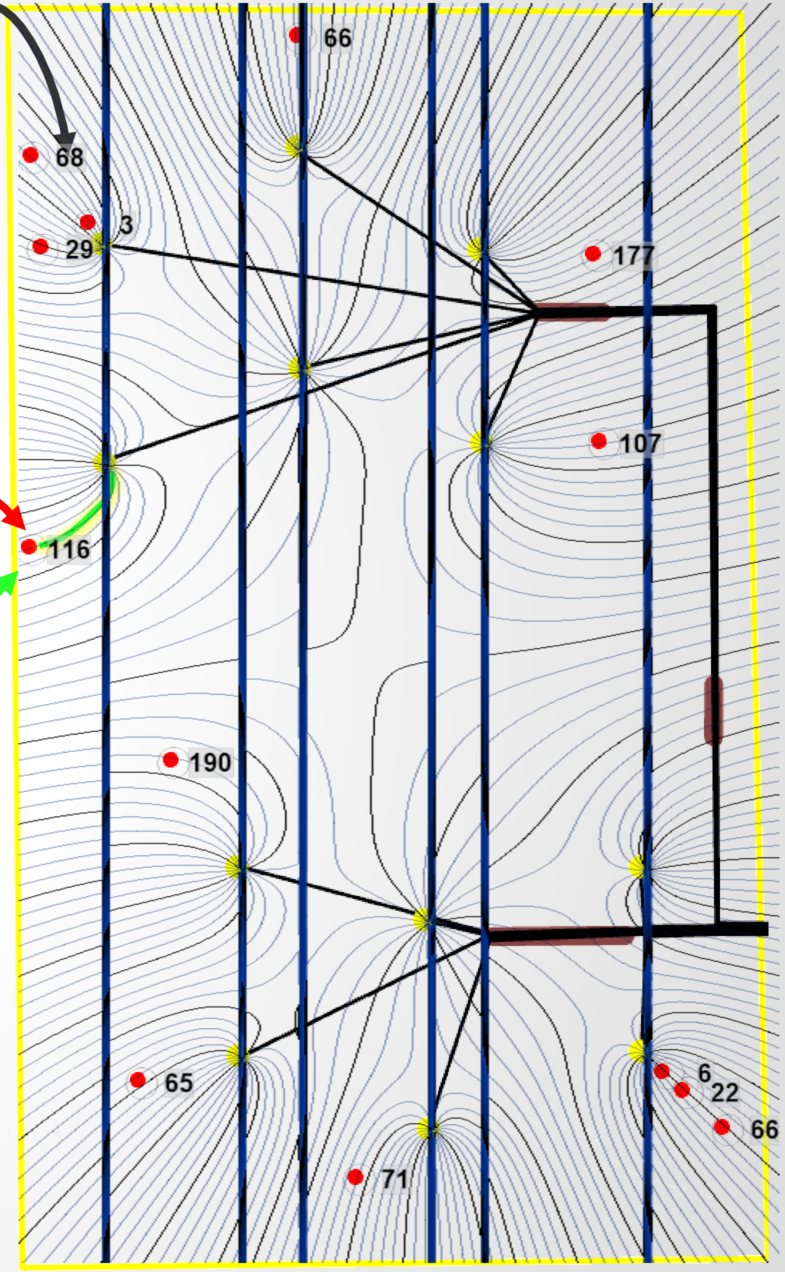
Respiration Field Tests – point Measure

- 14 points 2-3 depths and 6 events provide a reasonable space time average
- **Average Degradation across the design 6 acres → 12k gal/yr**

AEM Results represent the oxygen depletion that occurs from the biovent well out to the vapor monitoring point along a particle path

- Larger portion of aquifer represented
- Vapor Monitoring points were placed on the edge of remedial area to support evaluation of larger extent of remediation
- Earlier pilot started with vapor points interior and had to expand outward during the test
- **Average degradation across 6 acres → 23K gal/yr**

Actual oxygen volume injected should have degraded 21K gal/yr



Travel Time in Hours for 54 SCFM distributed across all wells

Formation Area Represented by Respiration Test

Formation Area Represented by Flow Model

Where to Go From Here

Both Respiration methods result in same conclusions in terms of rates as well as optimization recommendations

AEM flow models could optimize traditional respiration testing method (Leeson and Hinchee, 1995)

- Similar data collection – Smaller events but more frequent, more confidence
- Automated calculations
- No need to shut system down
- Provides an advective regime which could help sites that can not achieve diffusion during shutdown for standard testing method
- Standard respiration test or helium injection could help calibrate porosity or thickness in the AEM
- Even if absolute values are off, the time trends of soil gas levels at individual location will help estimate trends in rates

Outcome depends on monitoring network design and ability to model flow regime

AEM has potential to be applied to unconfined vadose zones with constant head leaky layer elements

Same method has been applied to carbon dioxide and methane readings in wells

- Methane - represents NSZD rate in vadose zone or perhaps from below the water-table
- Carbon Dioxide
    - Good because CO_2 is produced from organic reactions and isn't produced when inorganics are oxidized such as iron sulfides
    - Caution as CO_2 can be buffered by carbonates or calcium oxides

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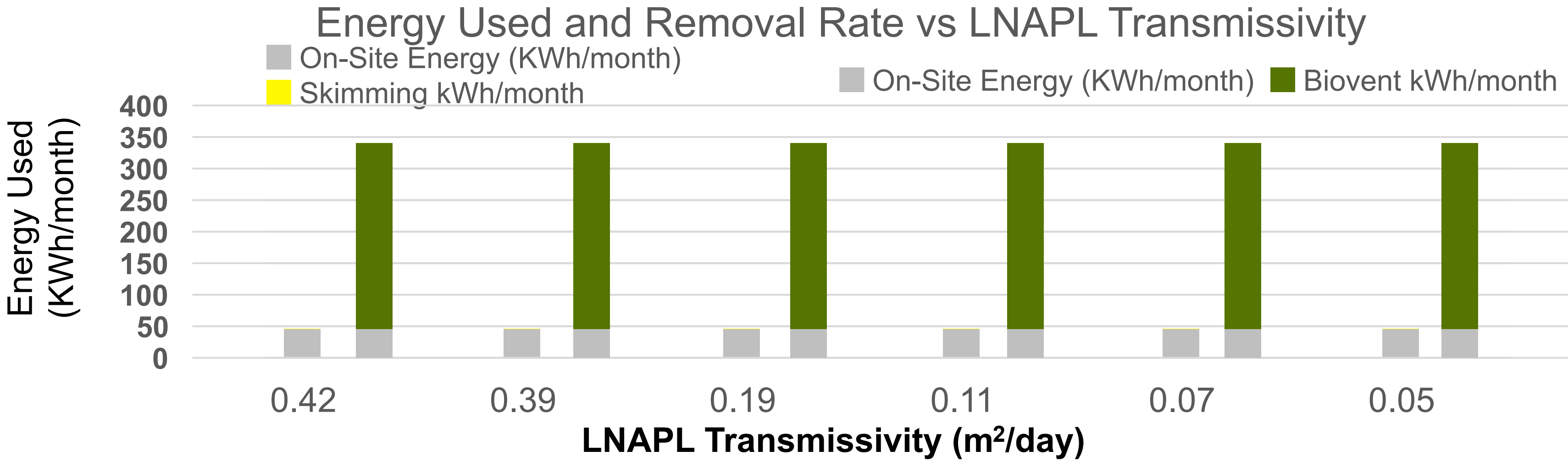
References

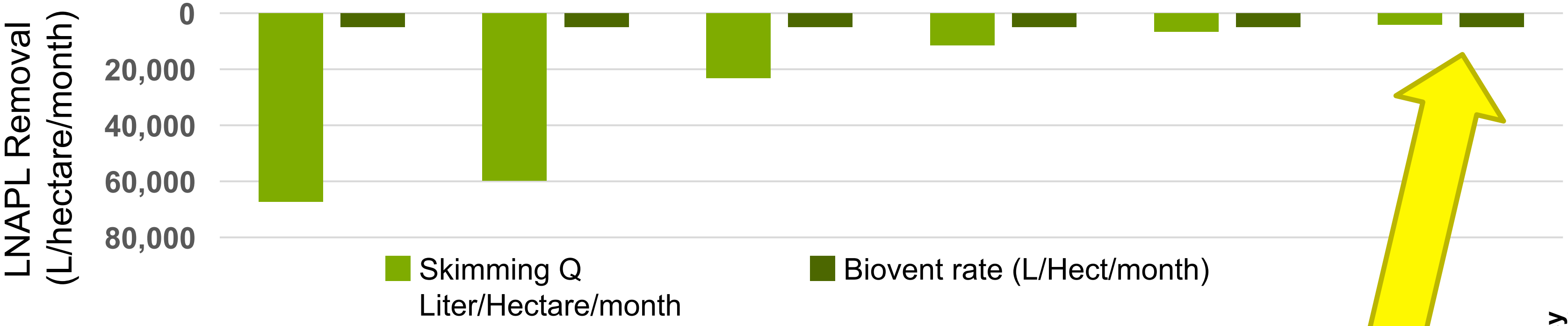
Leeson and Hinchee, *Bioventing Principles and Practice,* United States Environmental Protection Agency, EPA/540/R-95/534a, 1995.

Strack, O.D.L., *Groundwater Mechanics,* Prentice Hall Englewood Cliffs, NJ 07632, 1989

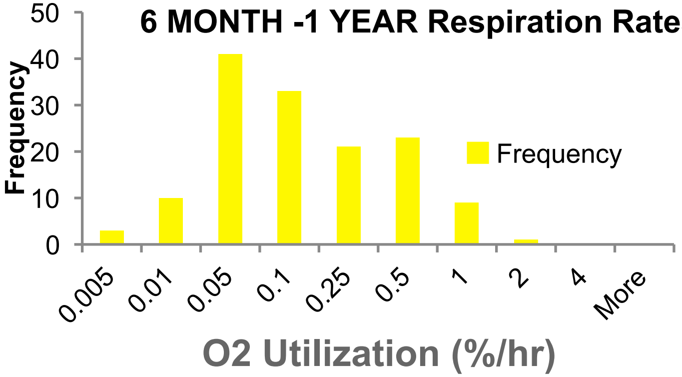
Extras

Energy Used Evaluation For a 3 m/day Sand



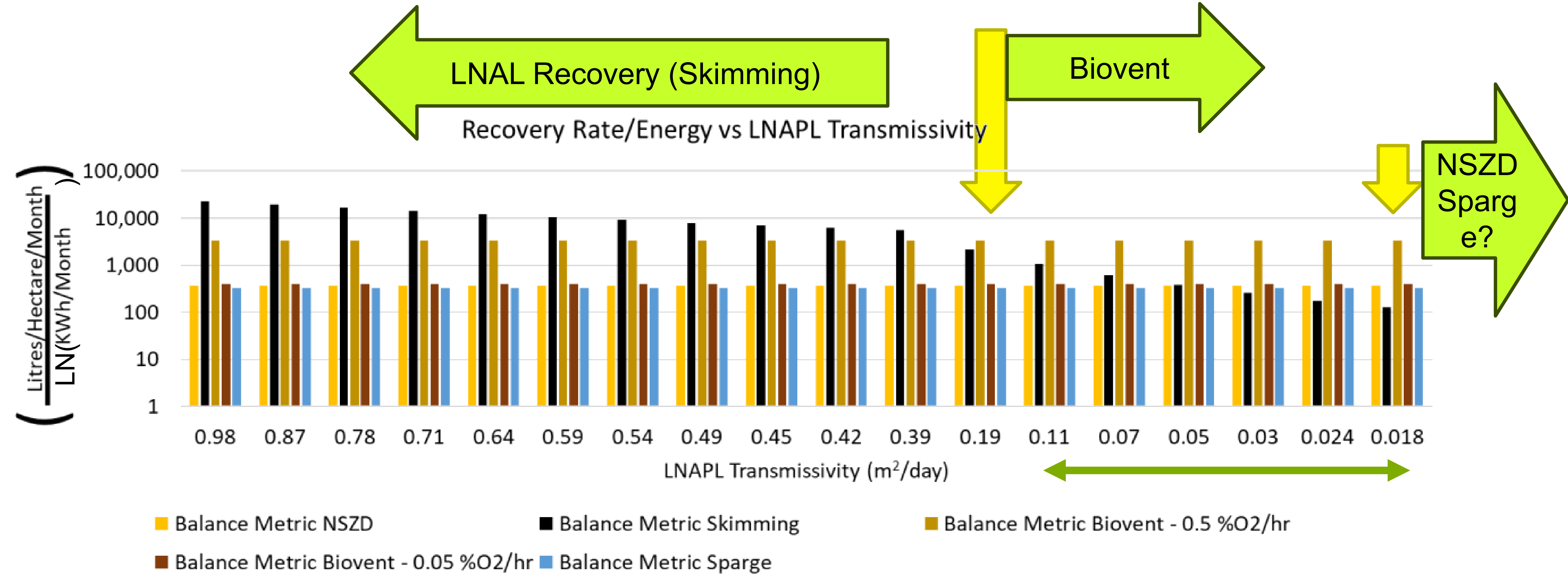


- Air – 50*Less viscous than water (Higher conductivity in soil than water)
- 2,000L air to treat 1L of LNAPL
- Bioventing Air Injection Rate 40 SCFM/ hectare is equivalent to
  - ~0.05%O_2/hr respiration or;
  - 4950 L/hectare/yr
- Actual biodegradation rate could be 10X higher
- Less Permeable Soils Proportionally more Energy, Higher Permeability Soils Proportionally less energy for Bioventing



Skimming 14% Energy & Equivalent Recovery rate

Revised Metric with LN(Energy)



LNAL Recovery (Skimming)

Biovent

NSZD
Sparg
e?

Sparging likely requires an alternate driver to mass removal for implementation