ARCADIS Design & Consultancy for natural and built assets

SMART CHARACTERIZATION – THE NEW ERA OF SITE INVESTIGATIONS

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July 19, 2016

Today's Presenters

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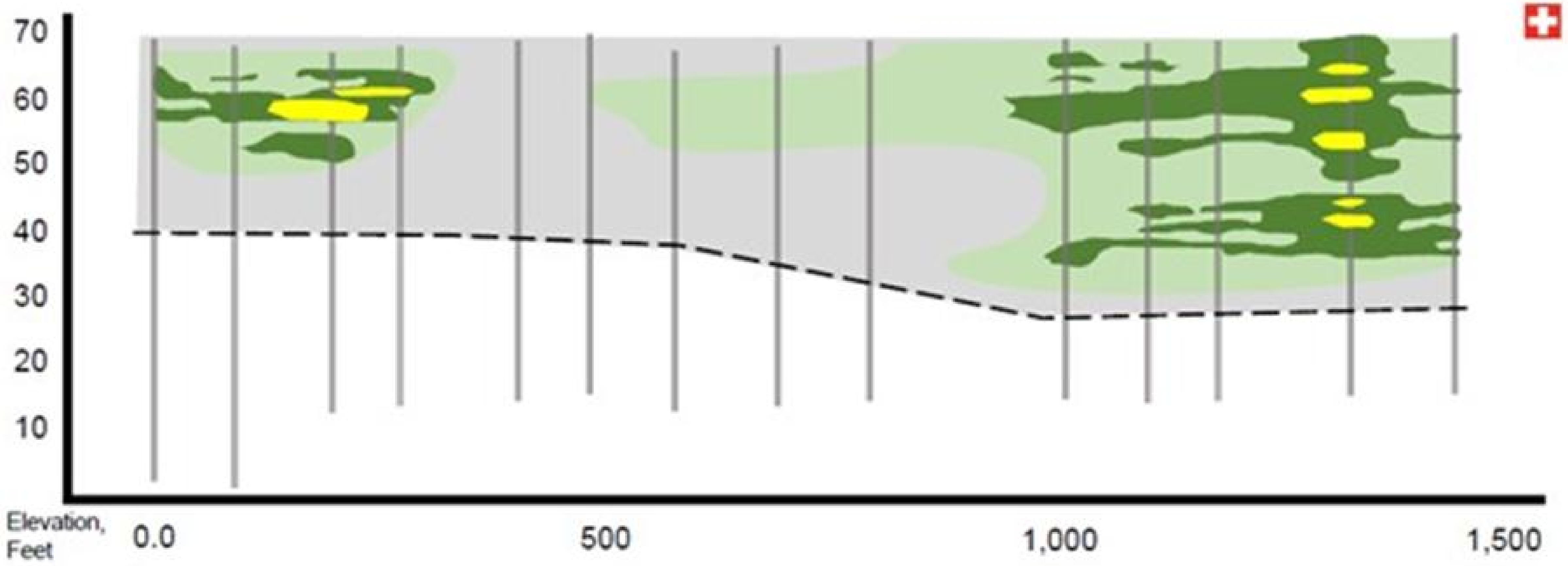
Agenda

- Return on investigation
- Why you should not use wells for site characterization
  - Break for Q&A
- Smart Characterization and mass flux
- Stratigraphic flux and NAPL flux mapping
  - Break for Q&A
- Natural source zone depletion
  - Break for Q&A

Introduction

Full slurry wall → Smart characterization → Focused pumping

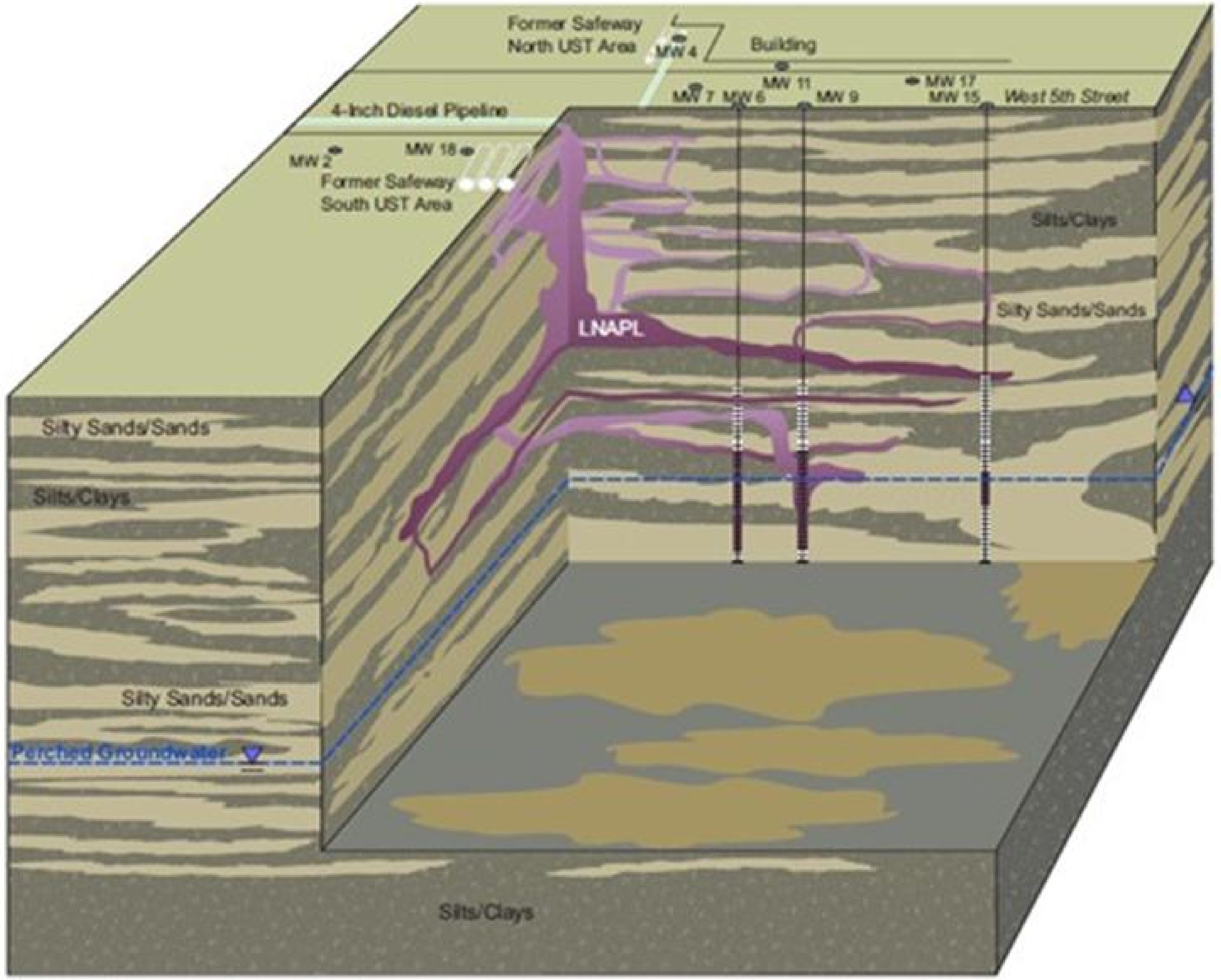
90% of relative flux in 10% of cross-section



Return on Investigation

Client avoided spending > $5M on slurry wall

LNAPL Recovery (10 ft LNAPL) → Smart characterization → Bioventing



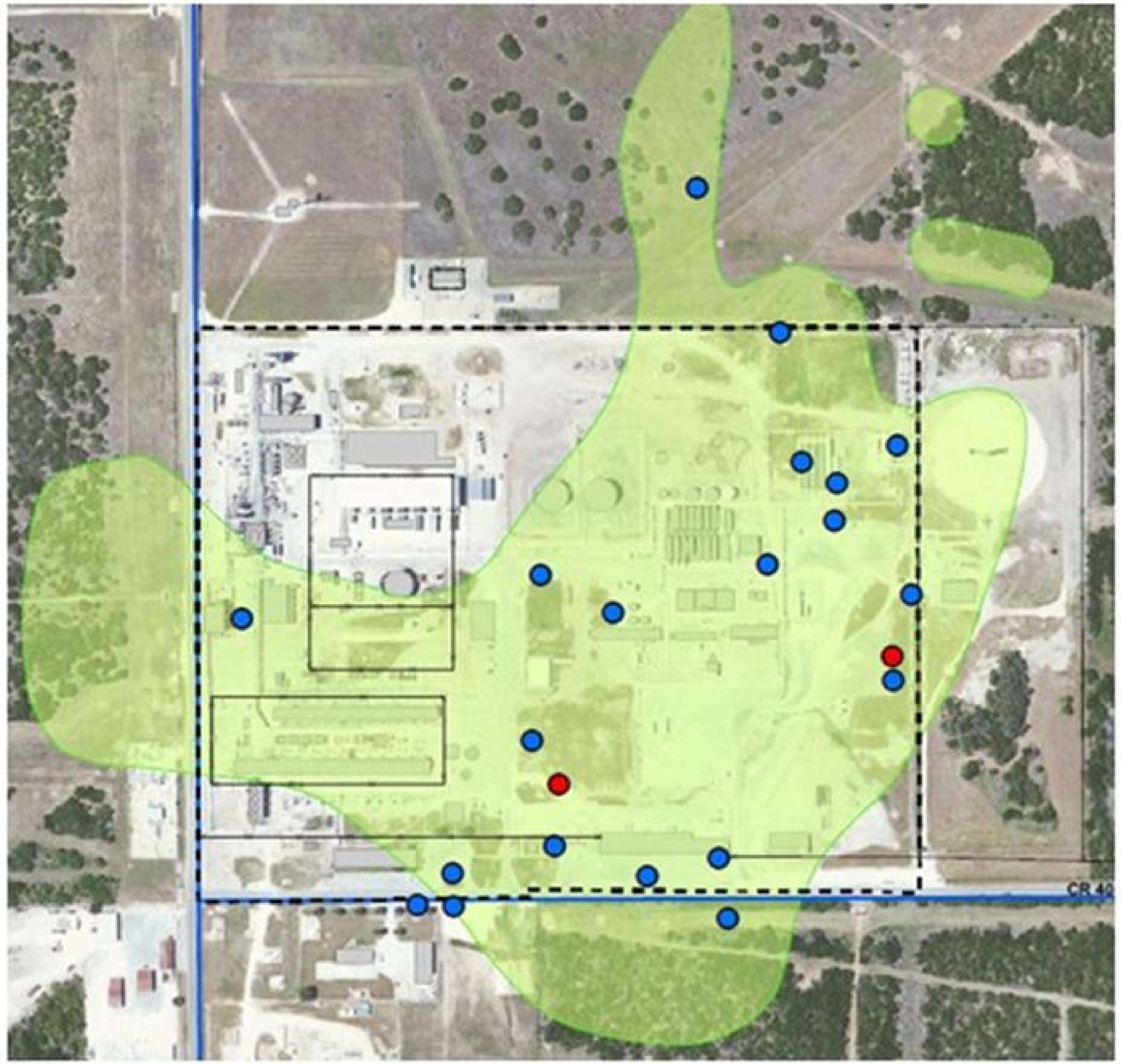
Return on Investigation

Client avoided spending ~$3M on MPE system

LNAPL recovery (> 25 acres)

Smart characterization

Natural Source Zone Depletion



Return on Investigation

Client avoided spending $4 - $5M on active LNAPL recovery

40 years of LNAPL recovery

Smart characterization

Natural Source Zone Depletion

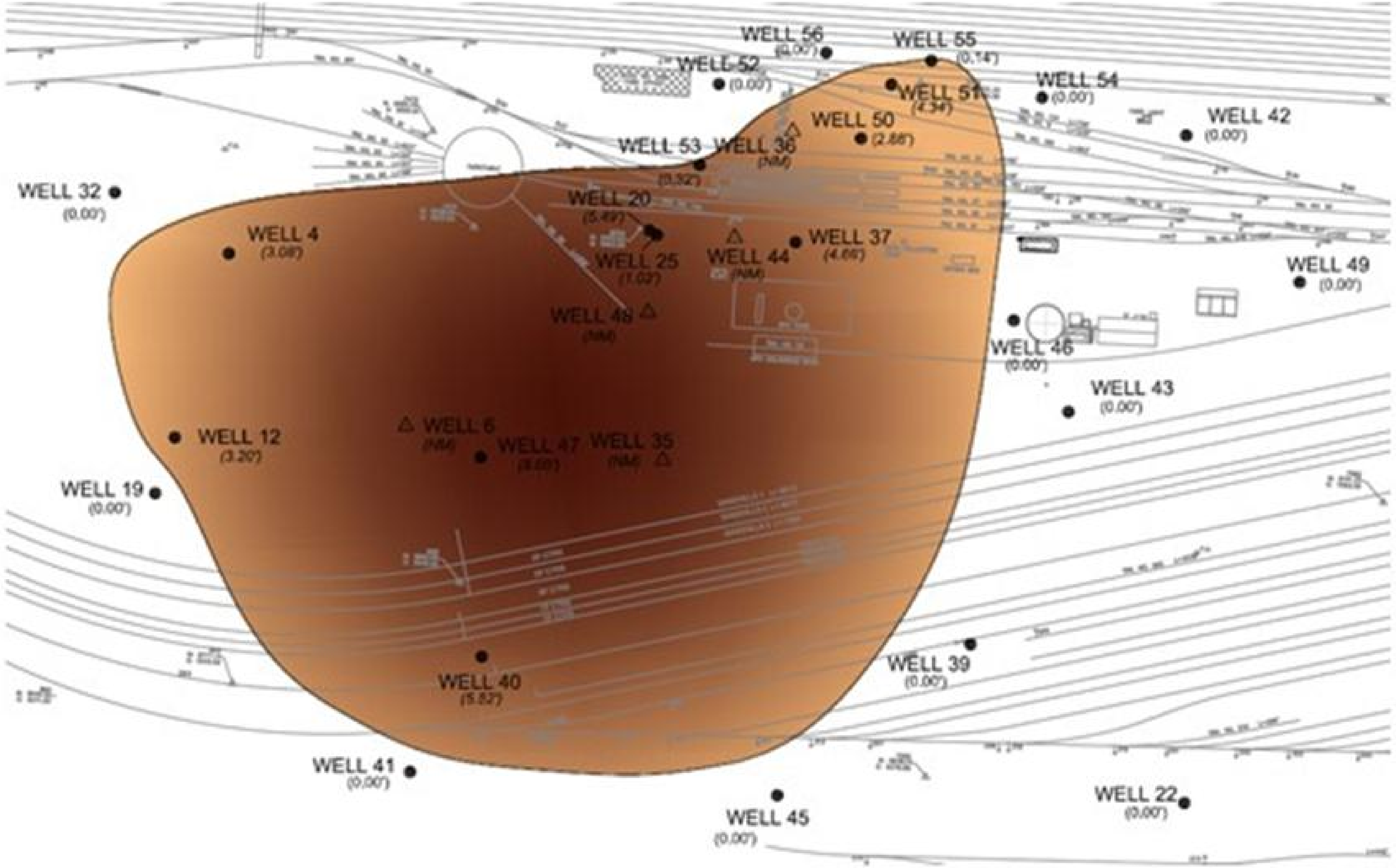
Return on Investigation

Site stuck in LNAPL recovery moving to NFA

LNAPL Recovery

Smart characterization

LNAPL Recovery



Return on Investigation

Validated high cost of LNAPL recovery from deep wells

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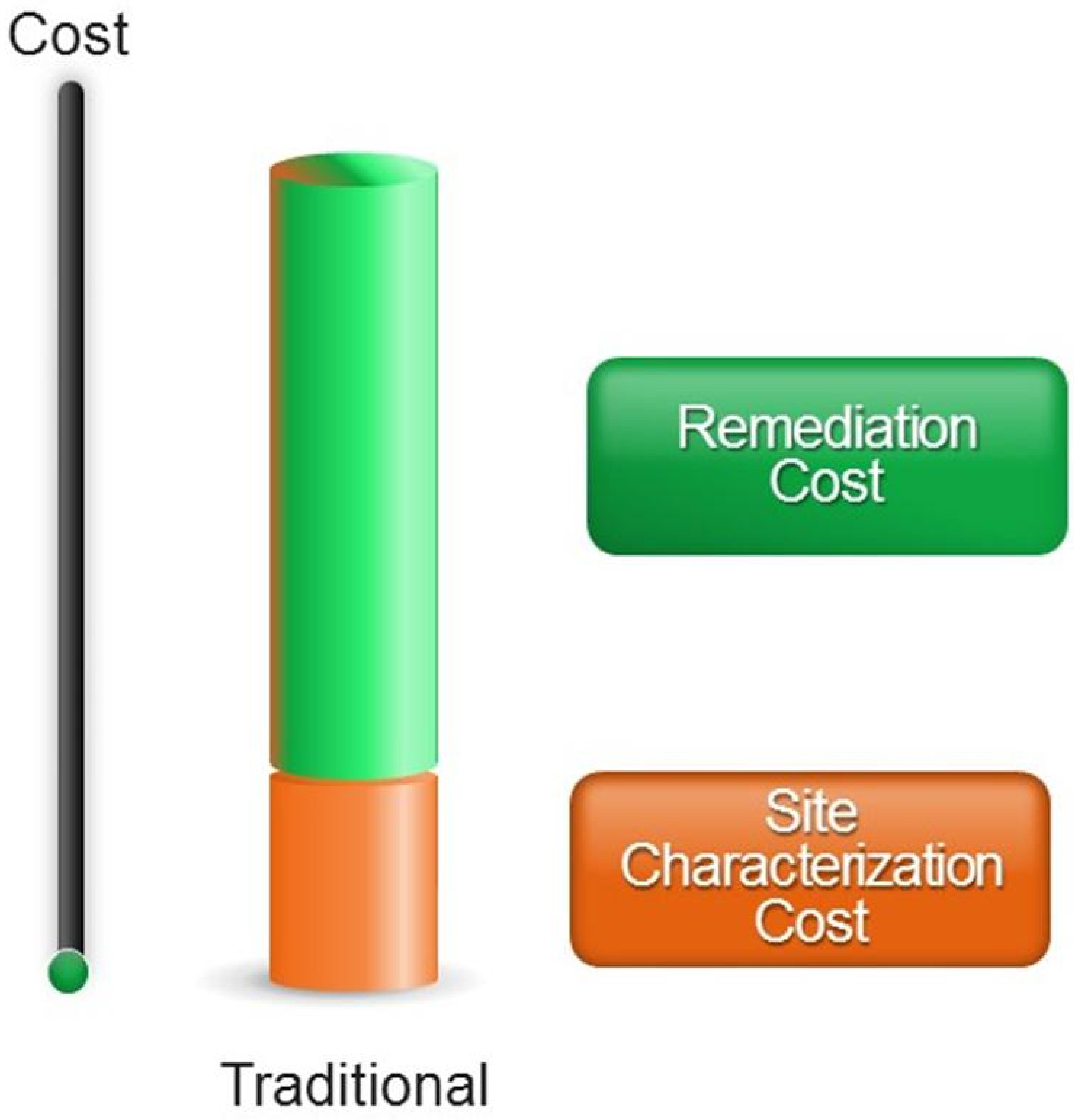


Cost

Remediation Cost

Site Characterization Cost

Traditional

What we were seeing

What we were seeing

Characterization	Remedies
Monitoring wells	Pump & treat
	Excavation

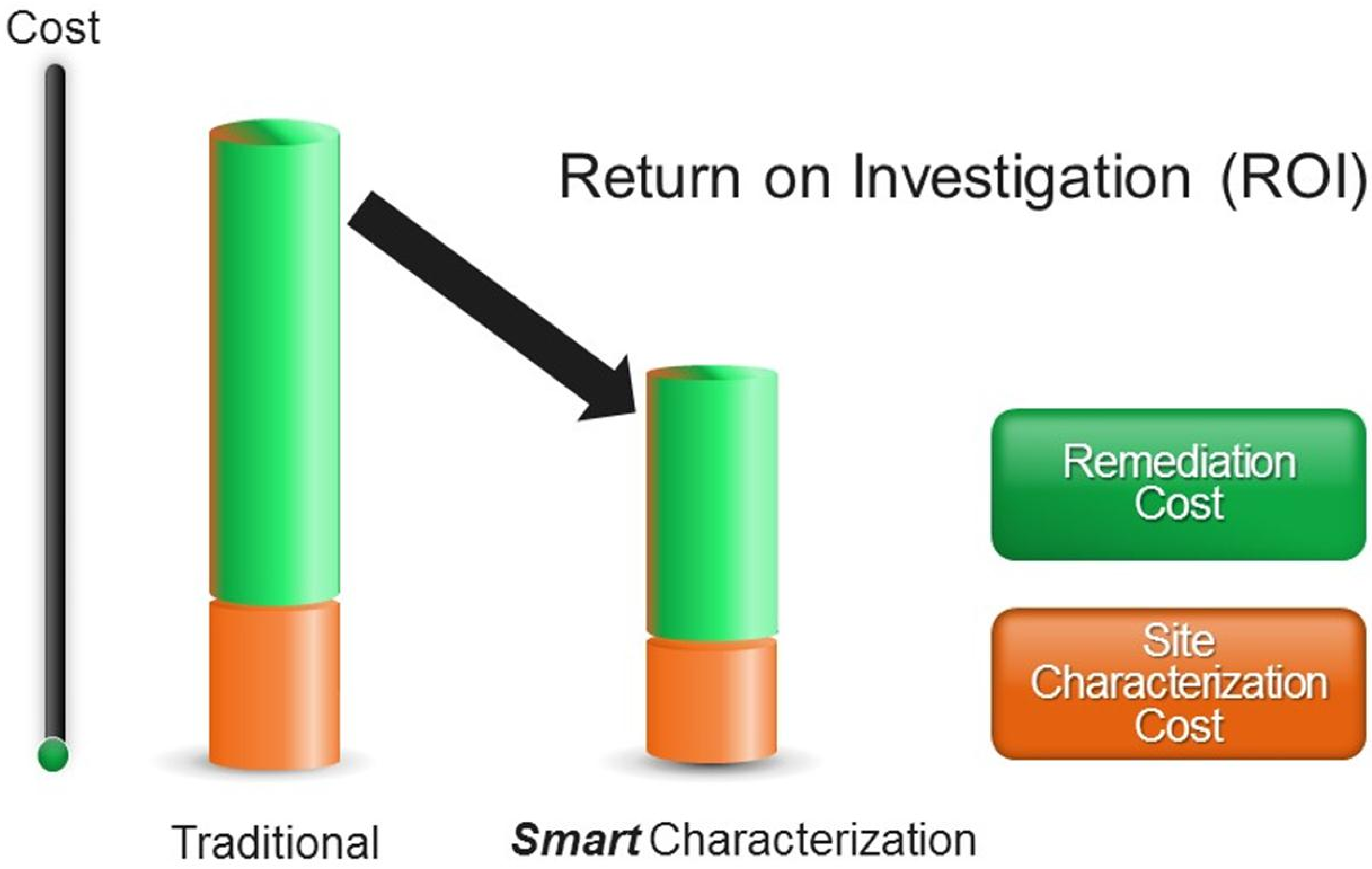
What we were seeing

High-Resolution Characterization	Remedies
• Permeability injection profiling • LIF • Vertical aquifer profiling	• ISCO • ERD • DGR

ISCO: In-situ chemical oxidation
ERD: Enhanced reductive dechlorination
DGR: Dynamic groundwater recirculation

What is actually there

Return on Investigation (ROI)



Why to *not* use wells for characterization

Characterization ≠ Monitoring

Precision vs. Accuracy

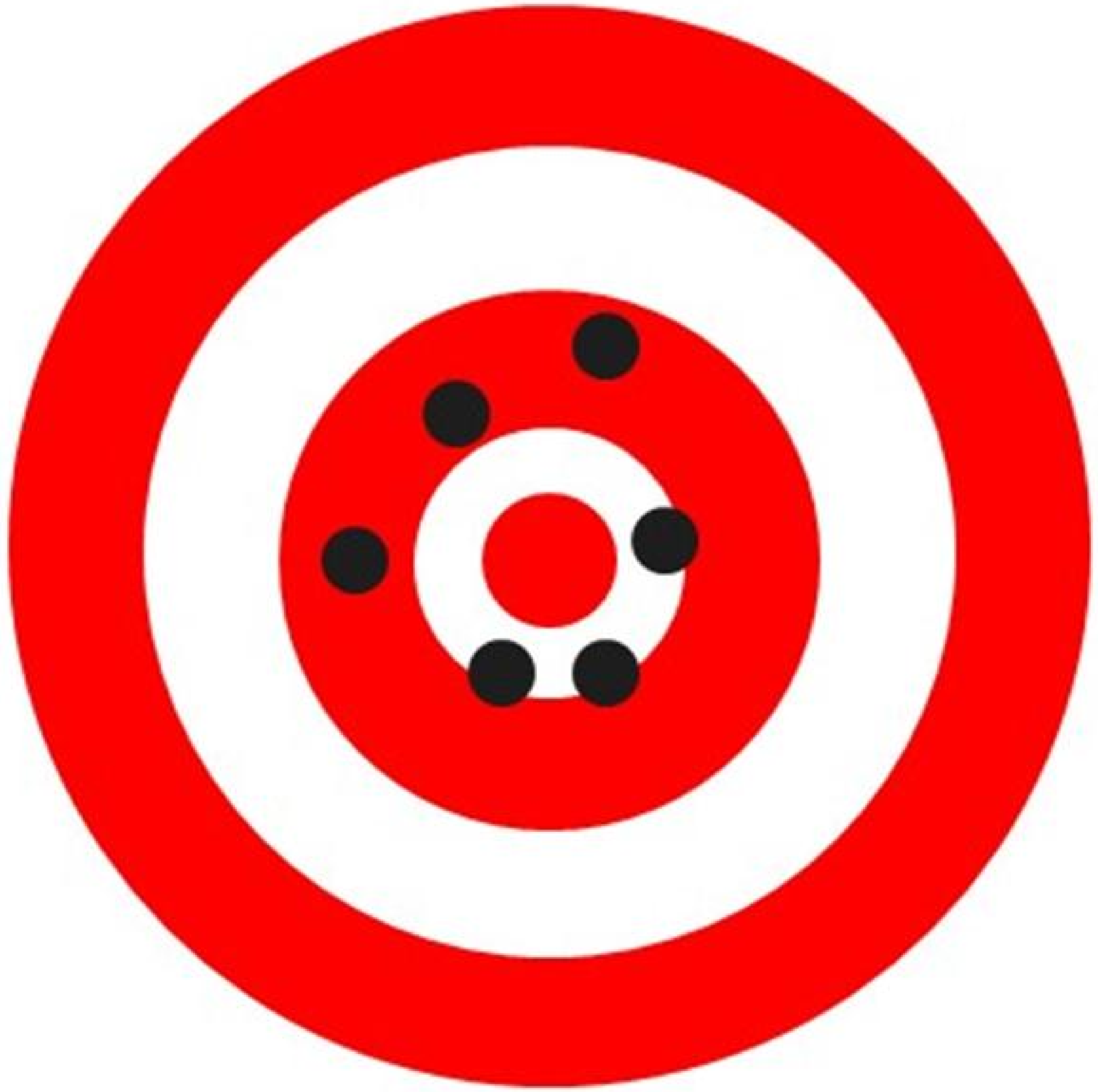
Precision: Is it repeatable?

Accuracy: Is it correct?

High precision
Low accuracy

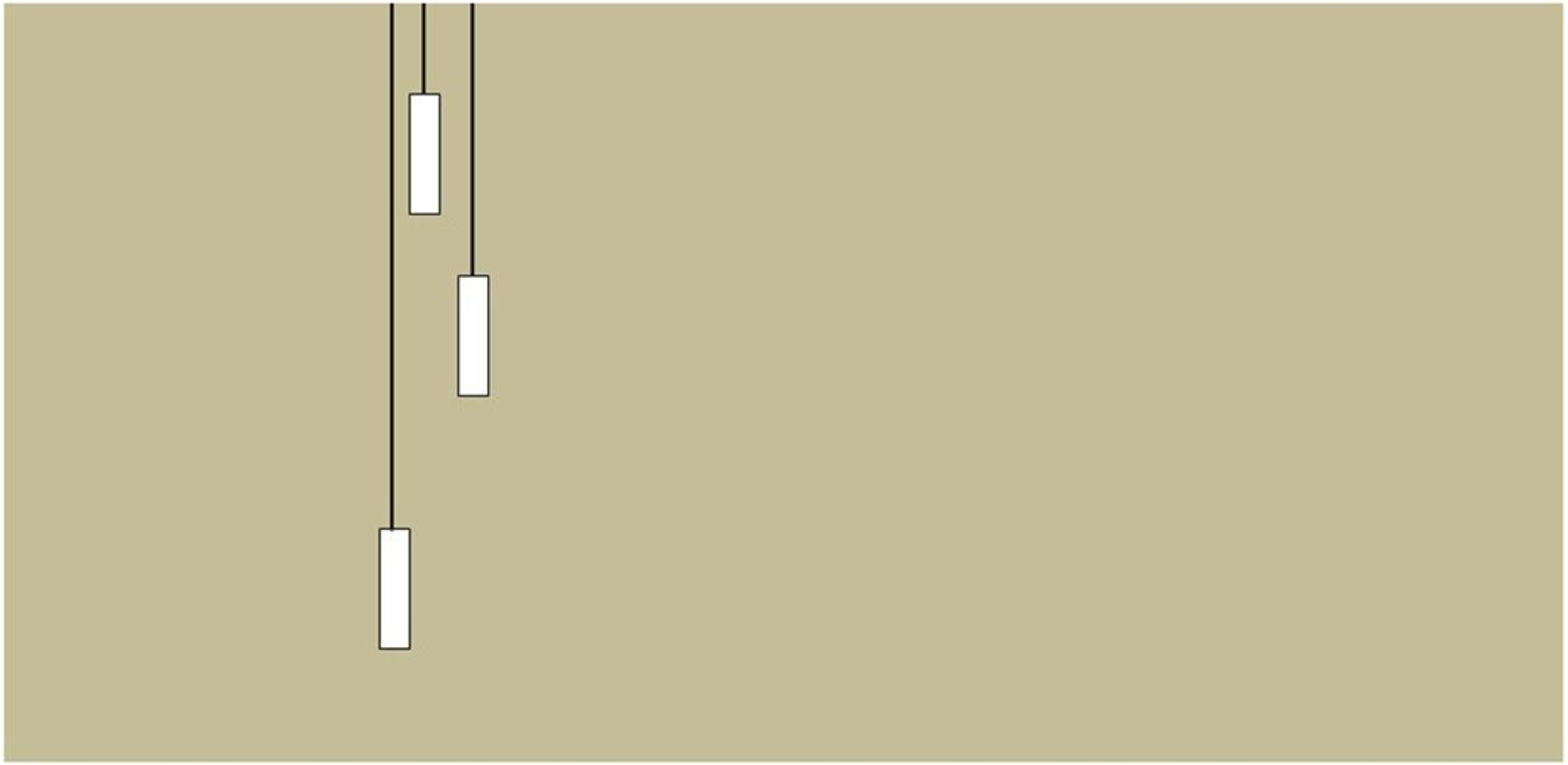
Monitoring wells

Low precision
High accuracy

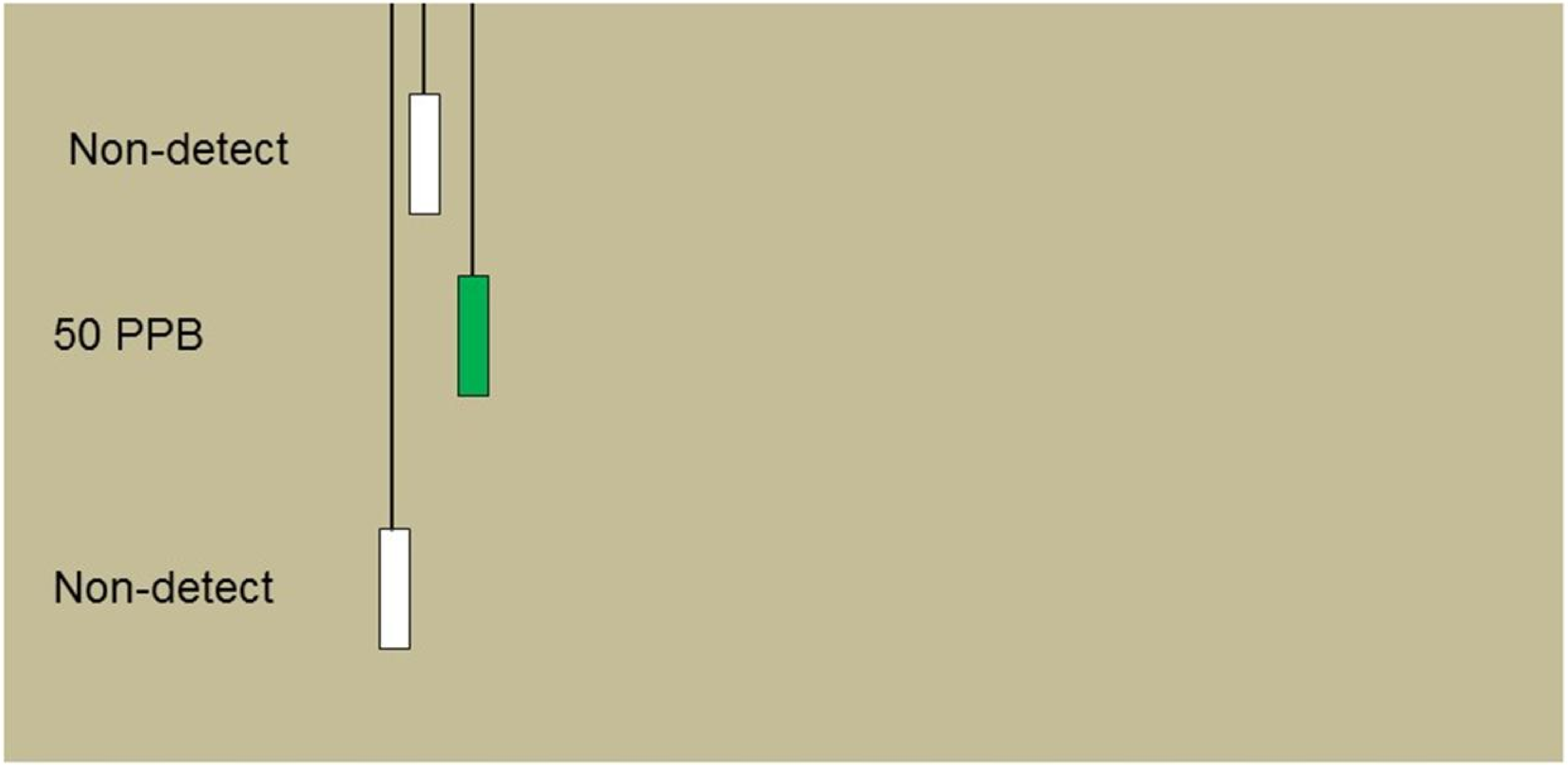


Smart Characterization

Monitoring well nest



Monitoring well nest

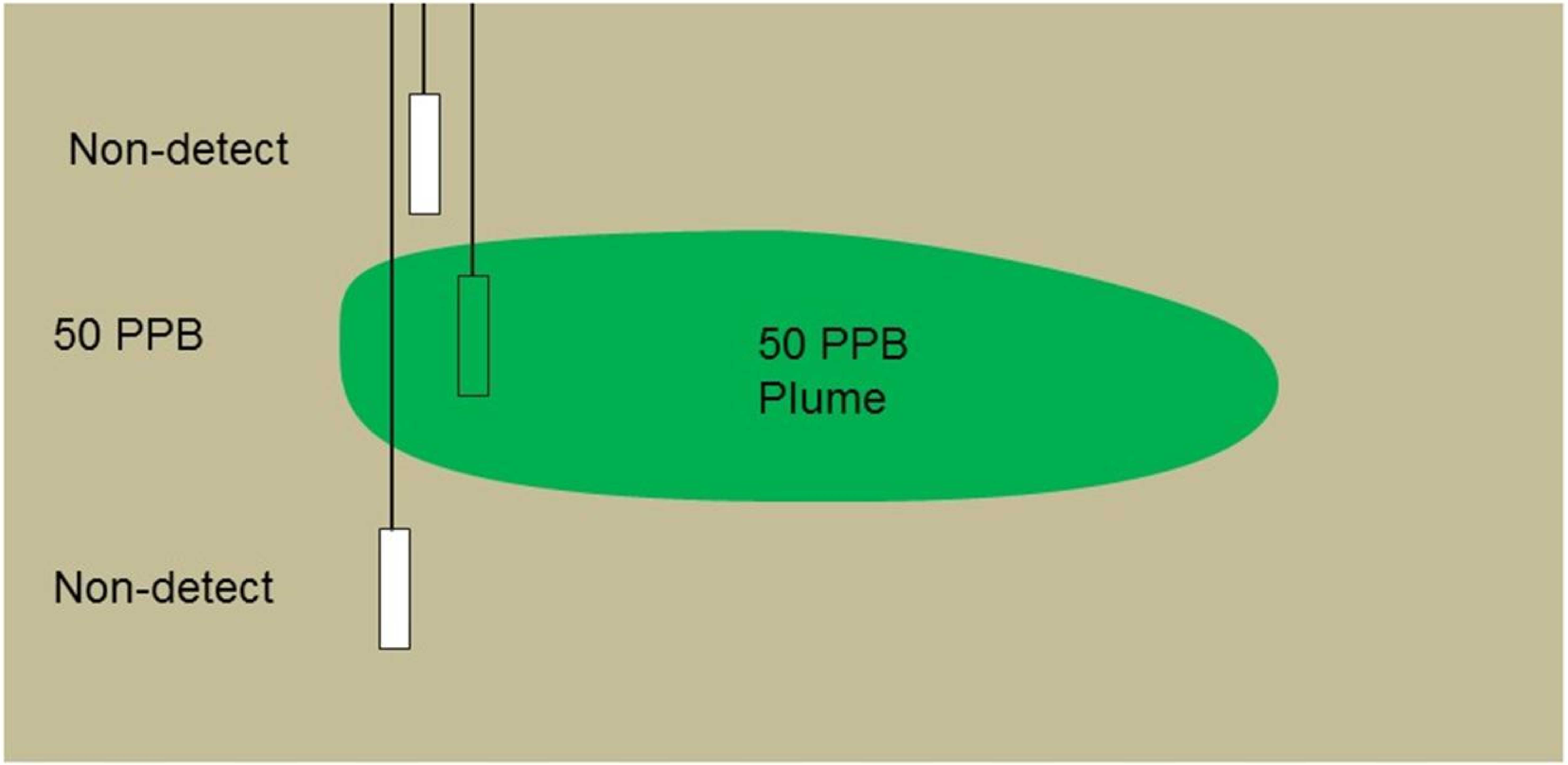


Non-detect

50 PPB

Non-detect

Monitoring well nest



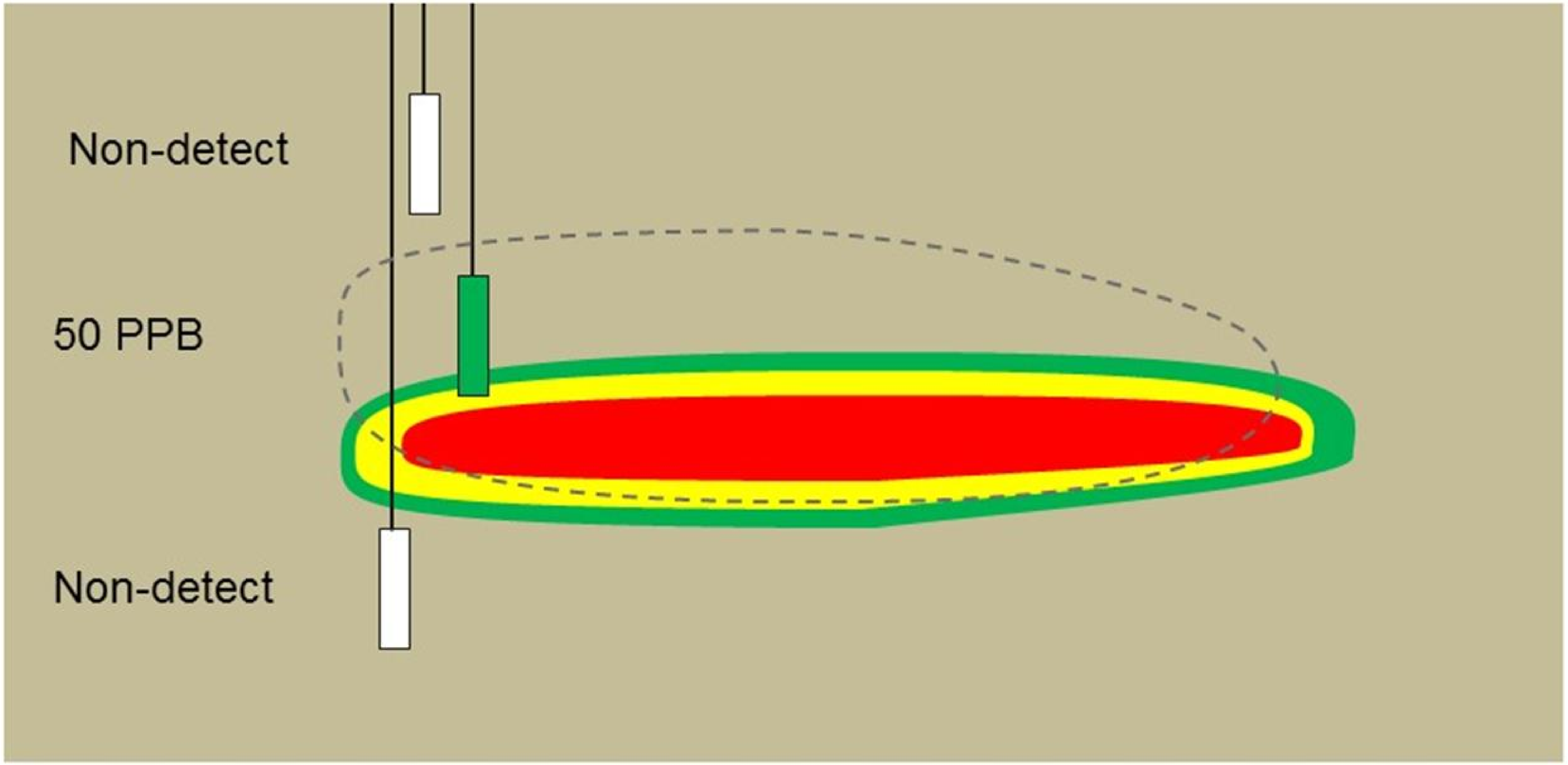
Non-detect

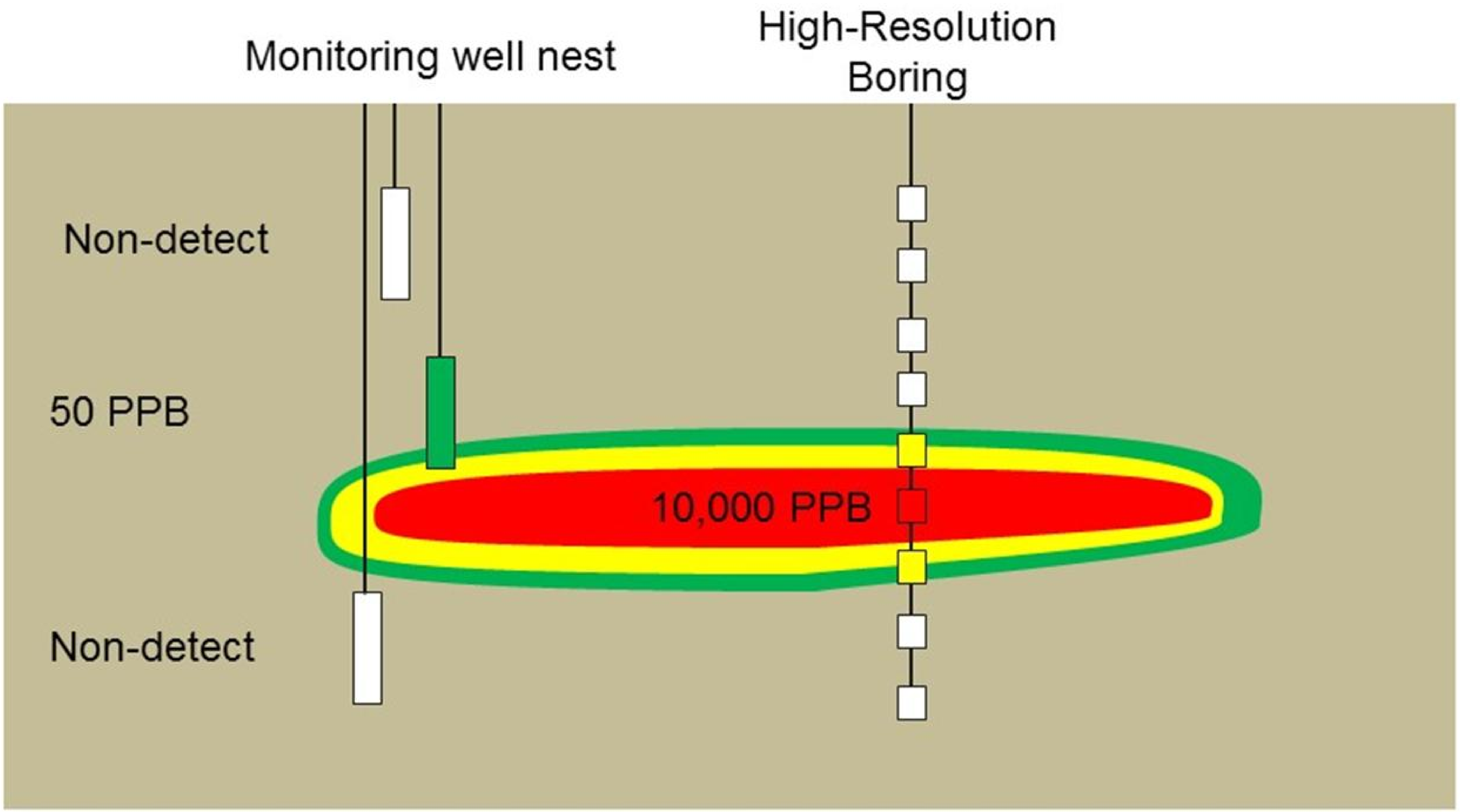
50 PPB

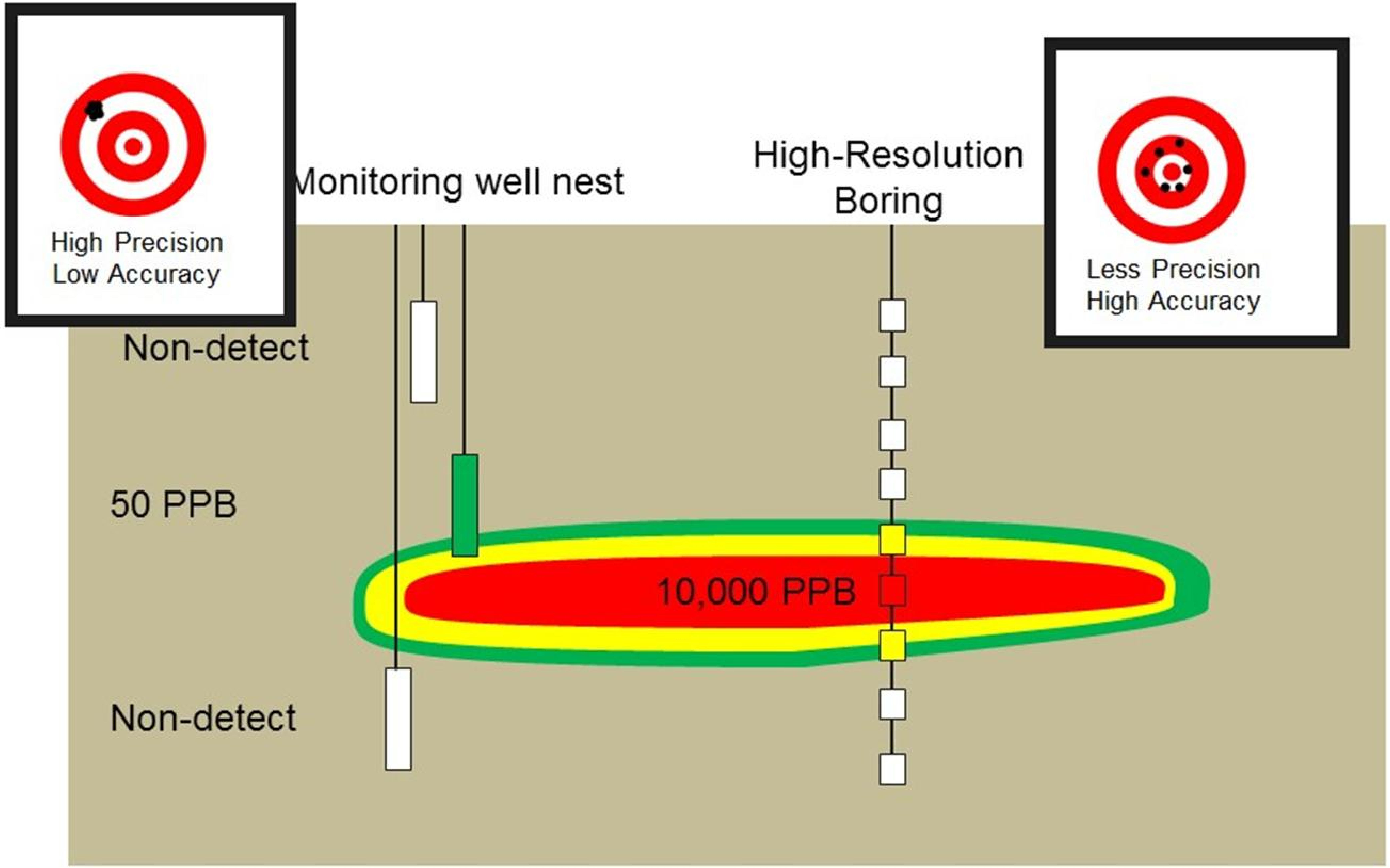
50 PPB
Plume

Non-detect

Monitoring well nest




Monitoring well nest
High-Resolution Boring
Non-detect
50 PPB
10,000 PPB
Non-detect



High Precision
Low Accuracy

Monitoring well nest

High-Resolution
Boring

Less Precision
High Accuracy

Non-detect

50 PPB

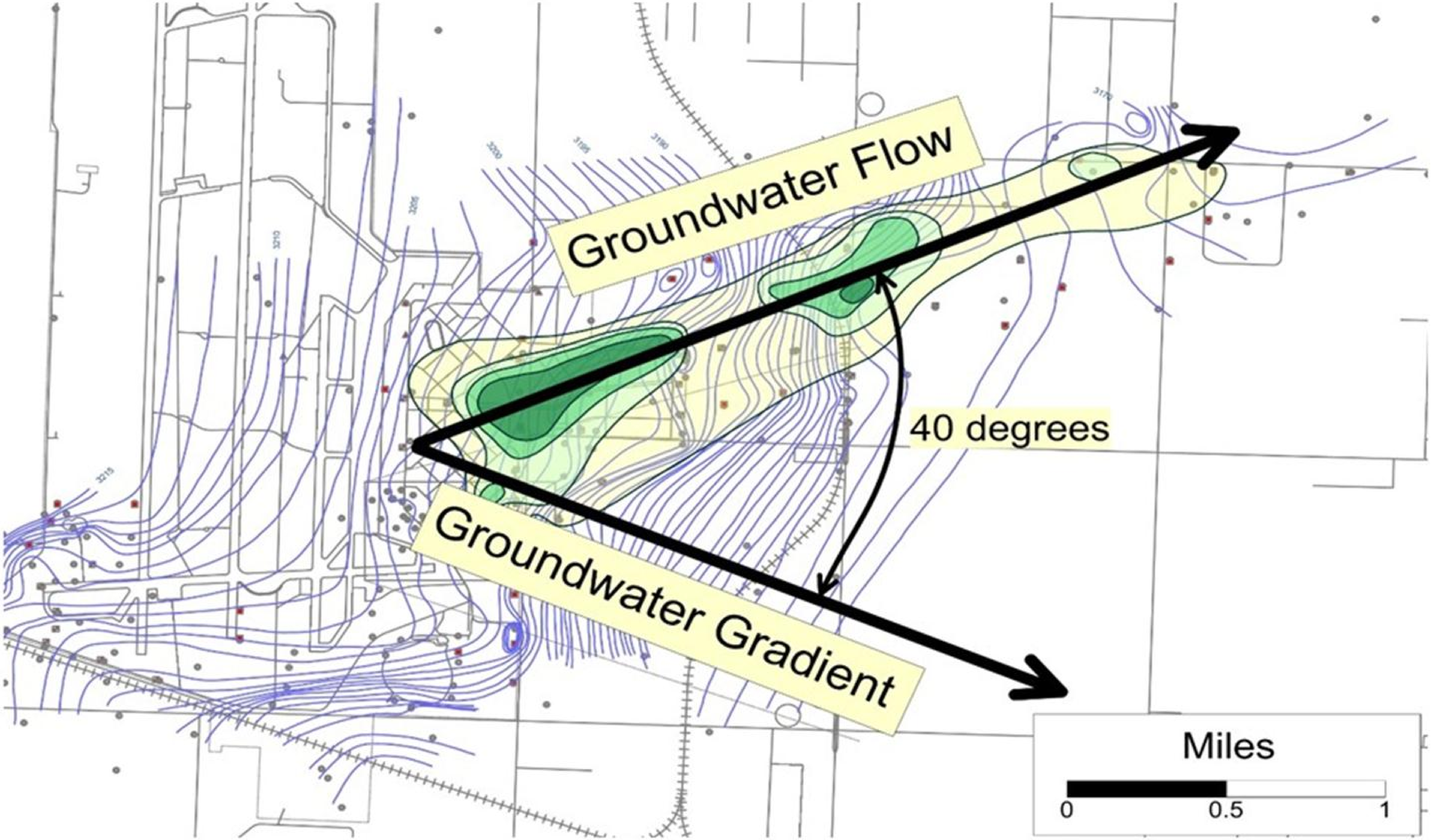
10,000 PPB

Non-detect

Hydraulic Gradient

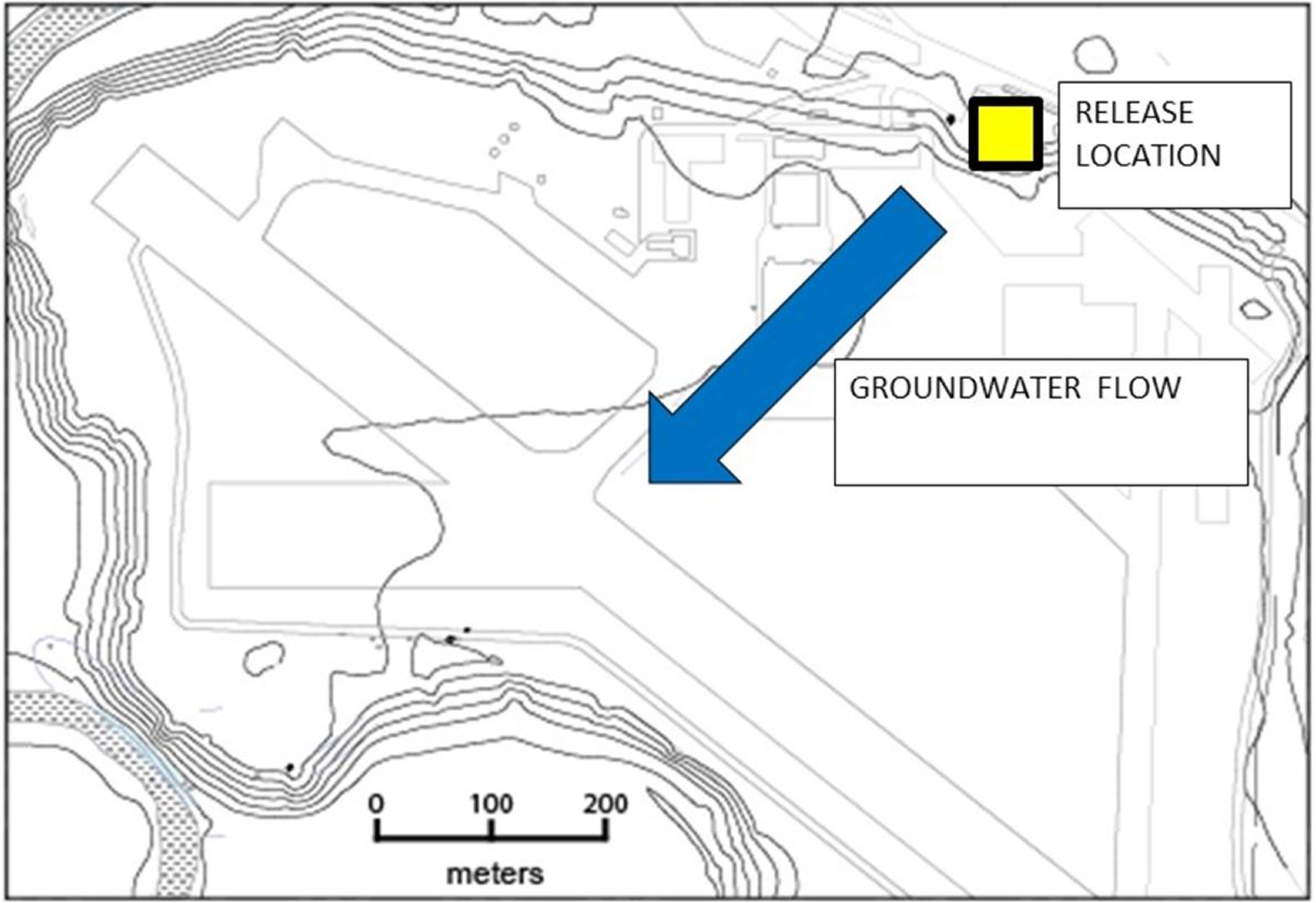
PERMEABILITY x GRADIENT

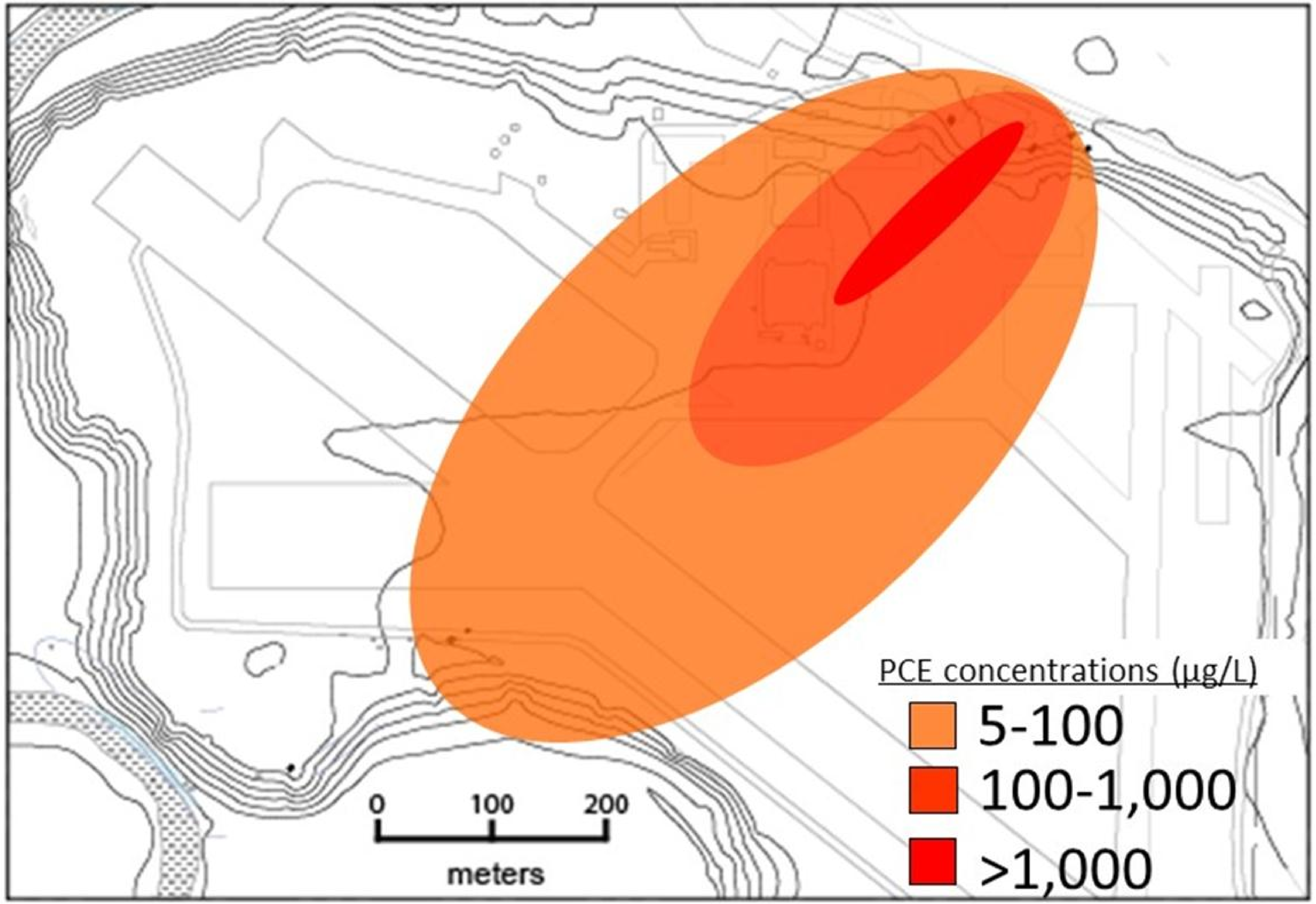
PERMEABILITY x GRADIENT

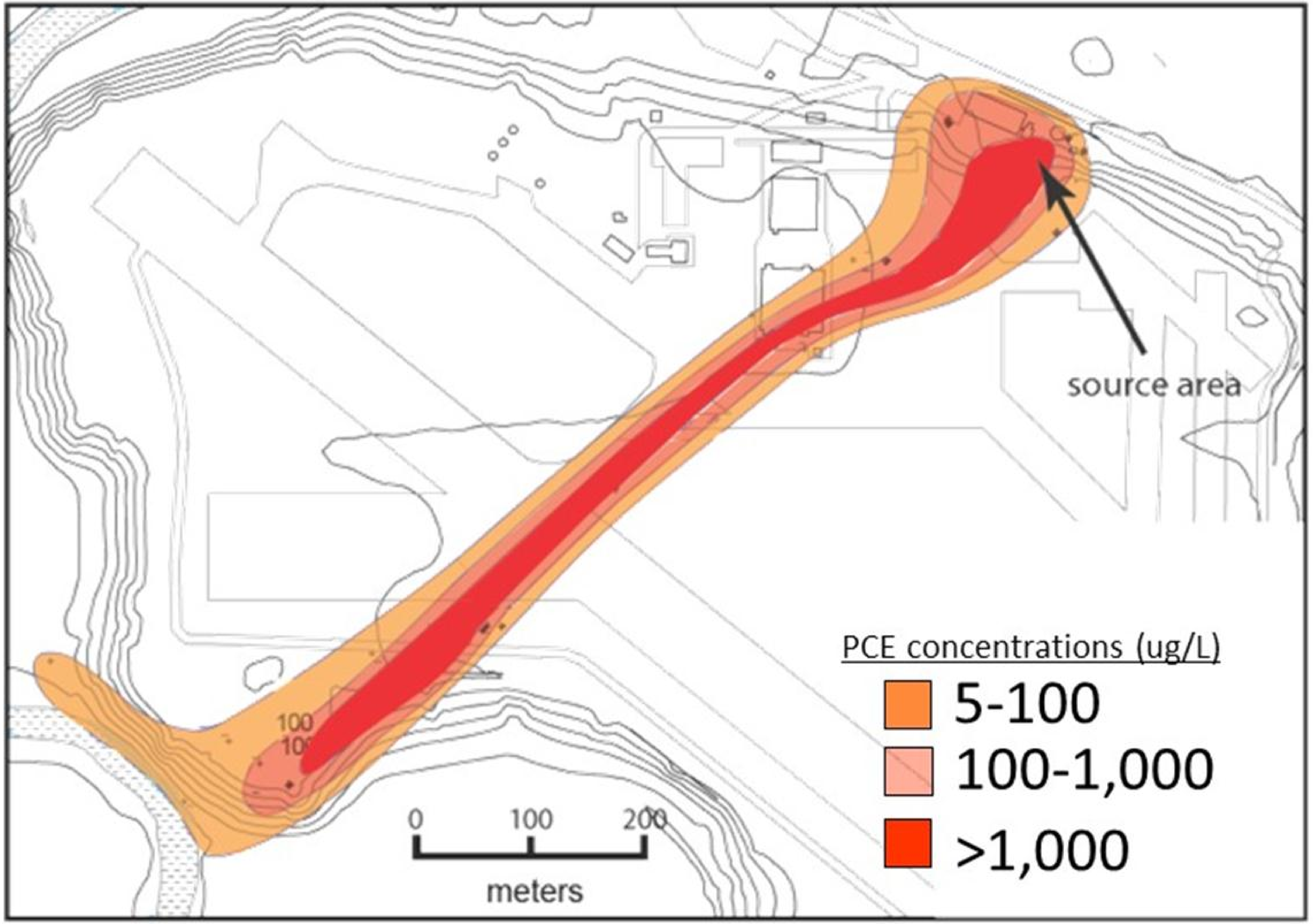

Groundwater Flow
40 degrees
Groundwater Gradient
Miles
0
0.5
1

Wells give a false sense of security:

Dispersion

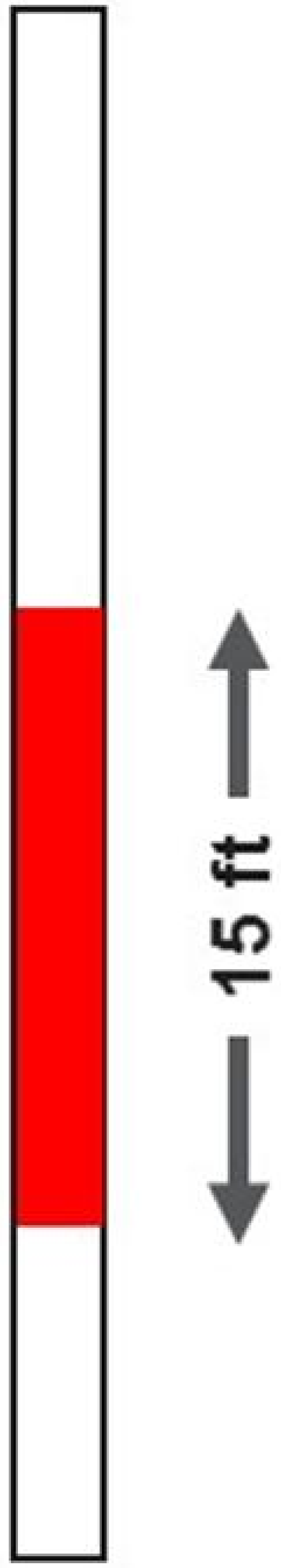

RELEASE LOCATION
GROUNDWATER FLOW
0
100
200
meters


PCE concentrations (µg/L)
🟧 5-100
🟥 100-1,000
🟥 >1,000
0
100
200
meters

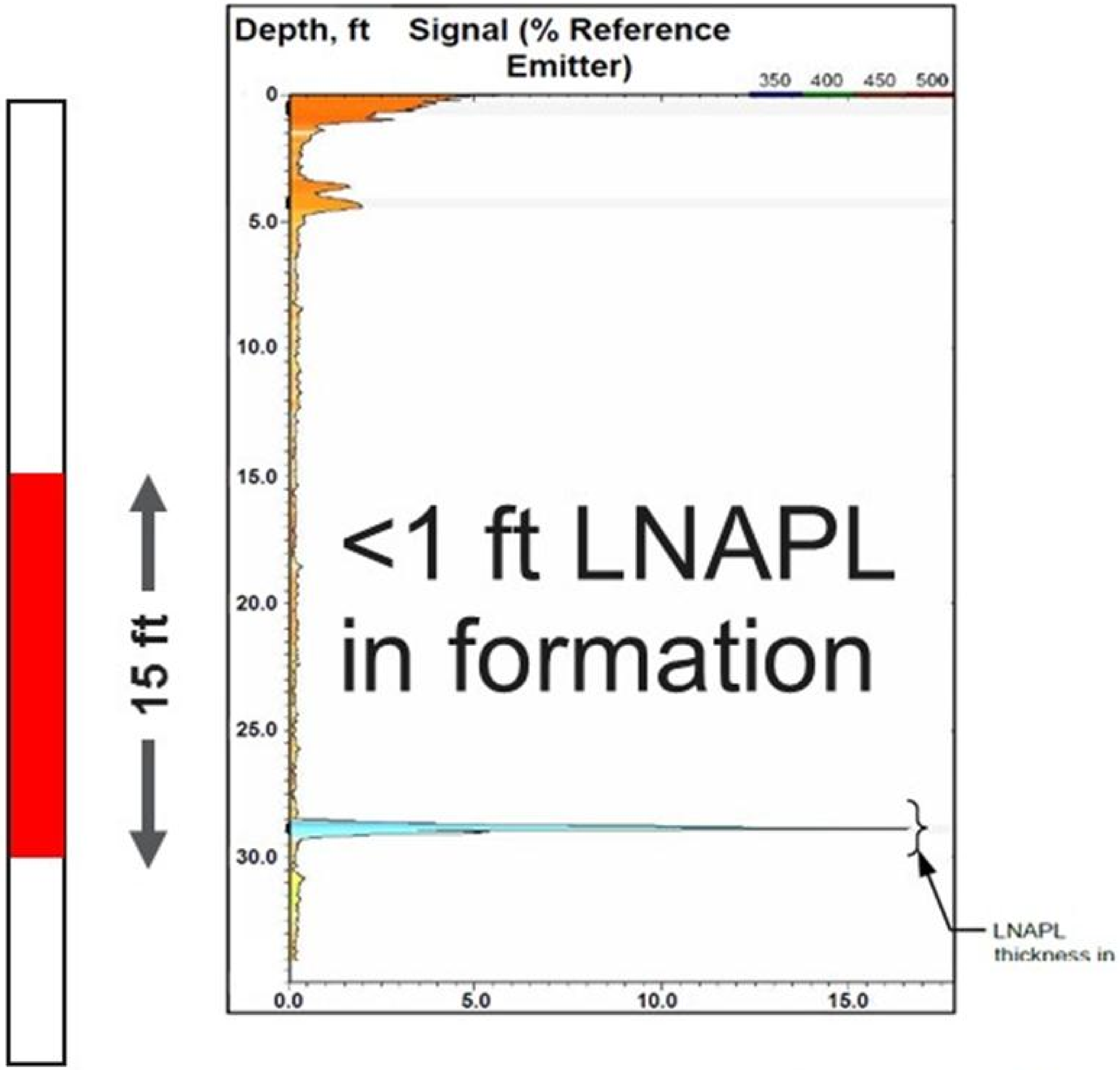

source area
PCE concentrations (ug/L)
5-100
100-1,000
>1,000
100
10
0
100
200
meters

Wells are bad at mapping NAPL

Does 15 ft of LNAPL in a well mean lots of LNAPL in soil?

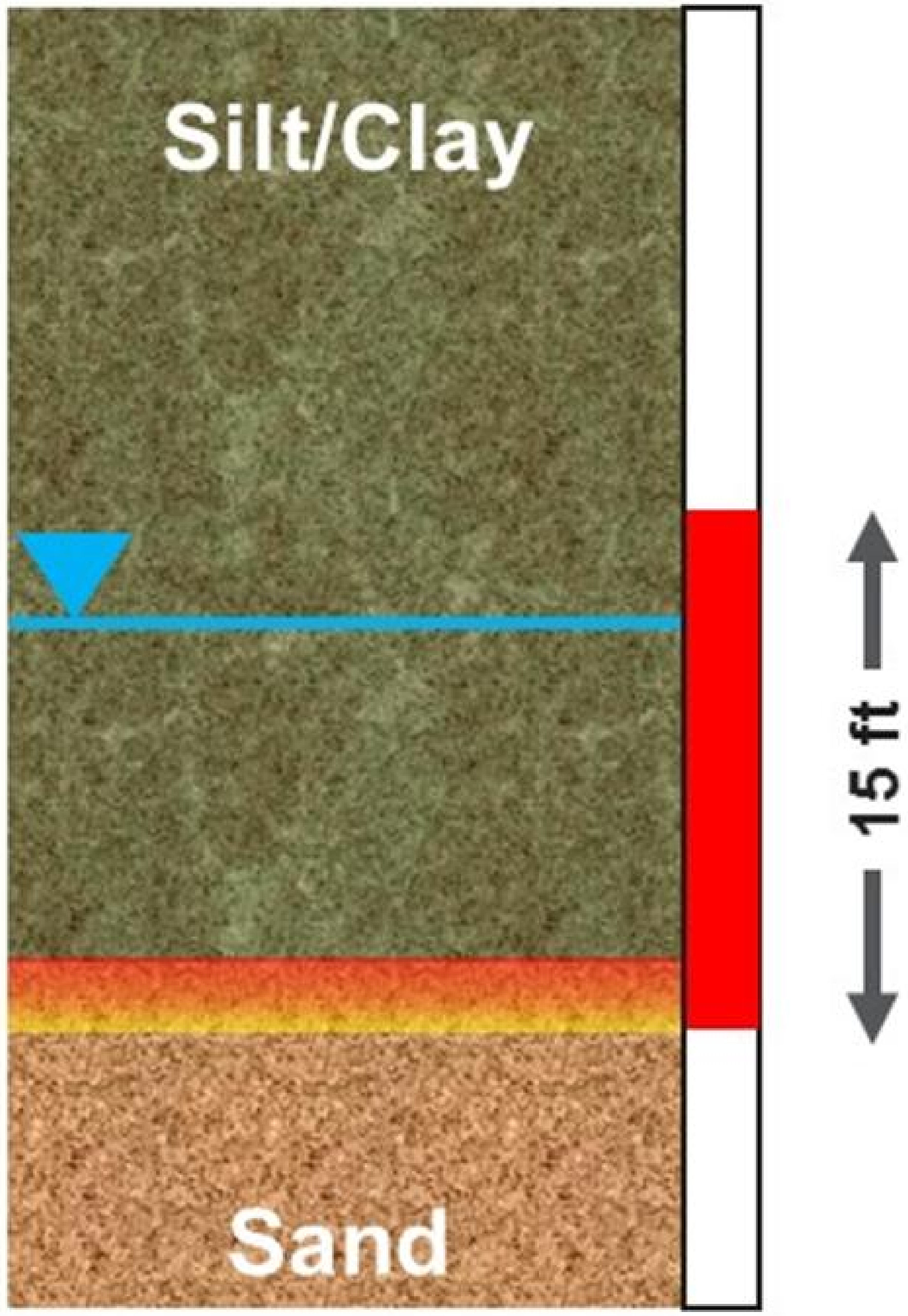


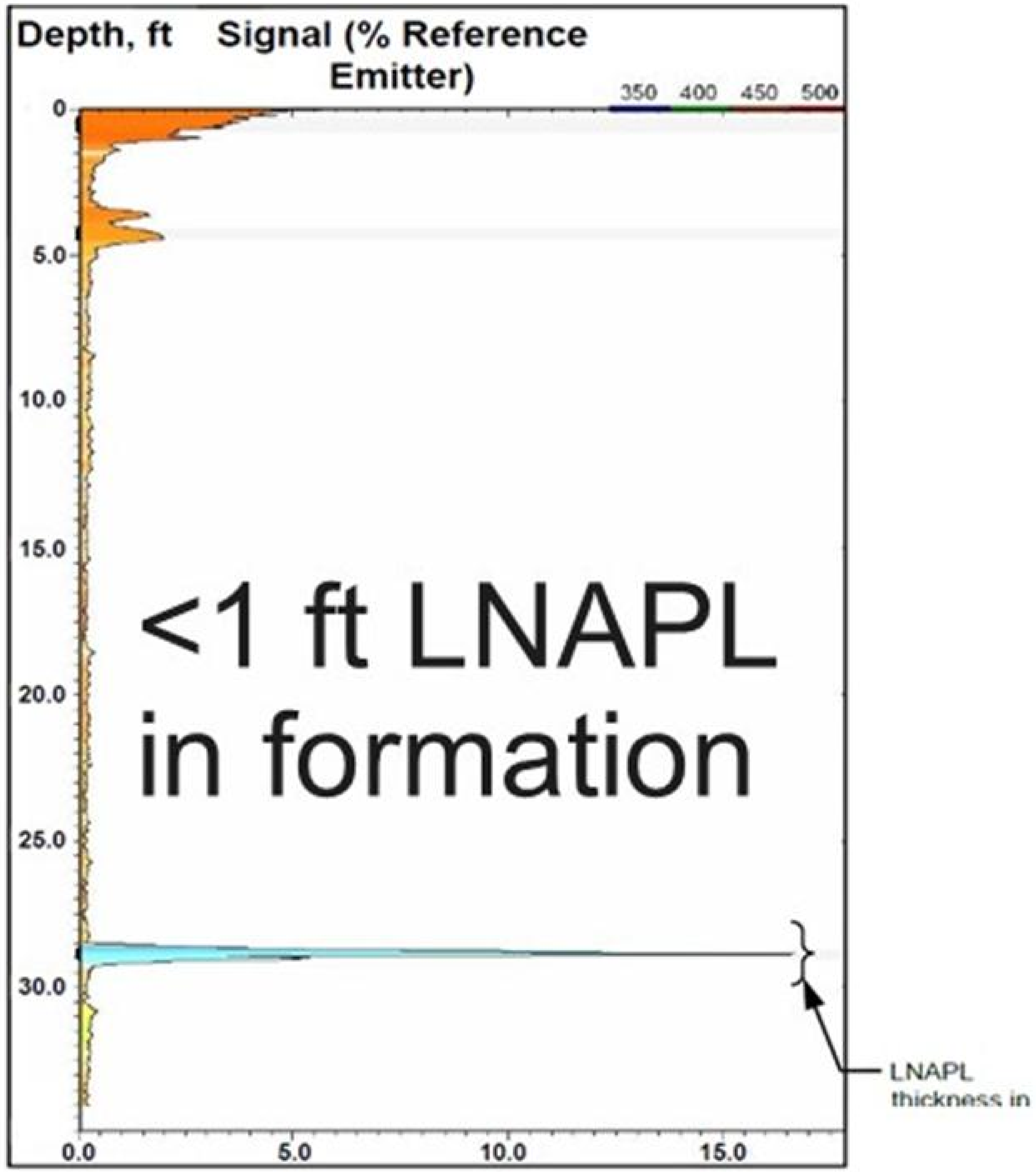
Does 15 ft of LNAPL in a well mean lots of LNAPL in soil?



<1 ft LNAPL in formation

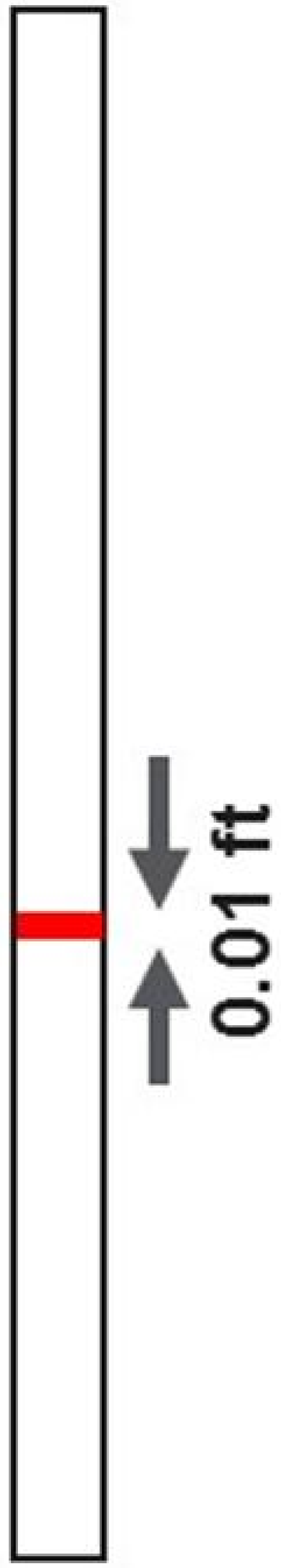
Does 15 ft of LNAPL in a well mean lots of LNAPL in soil?



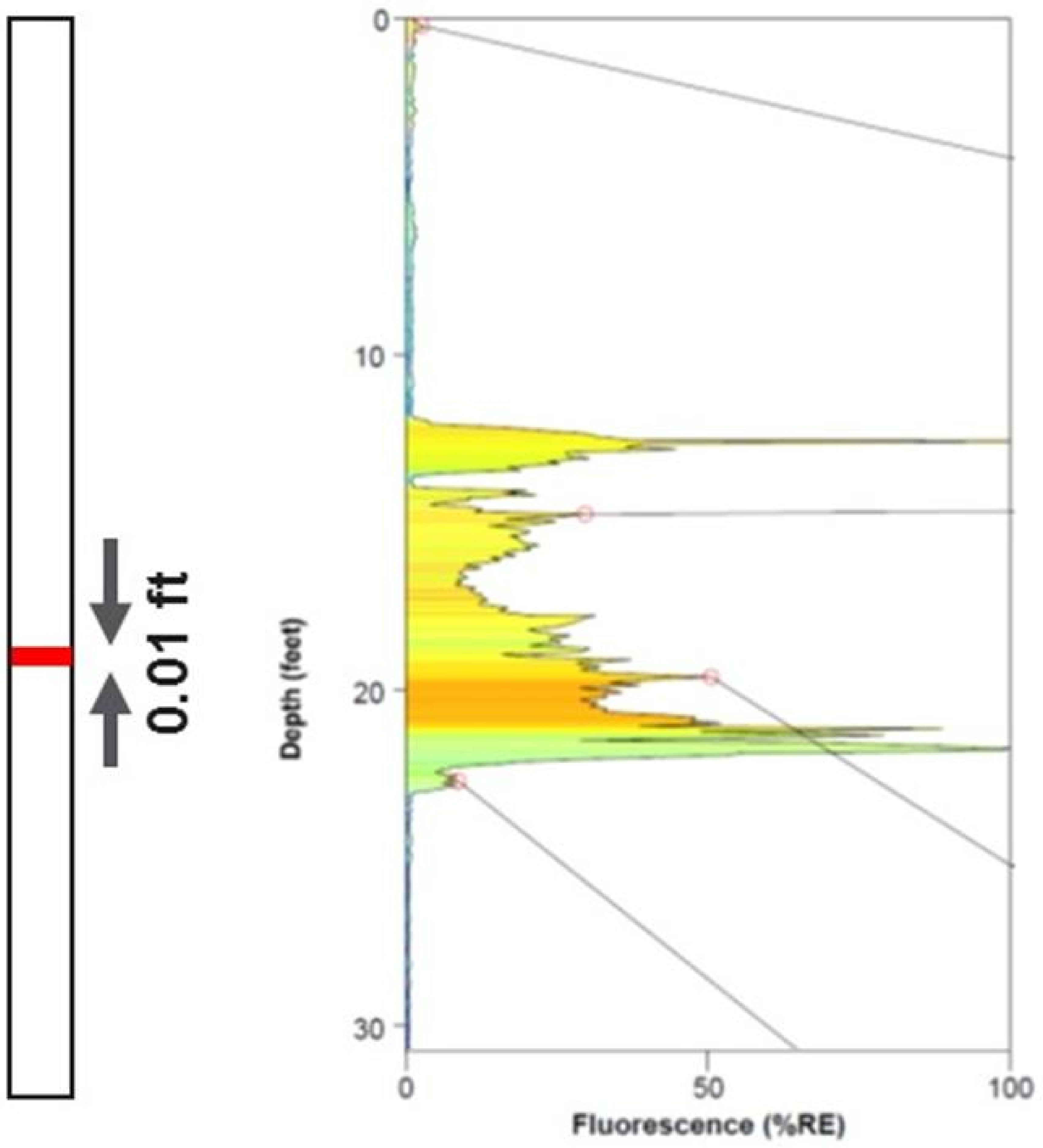


<1 ft LNAPL in formation

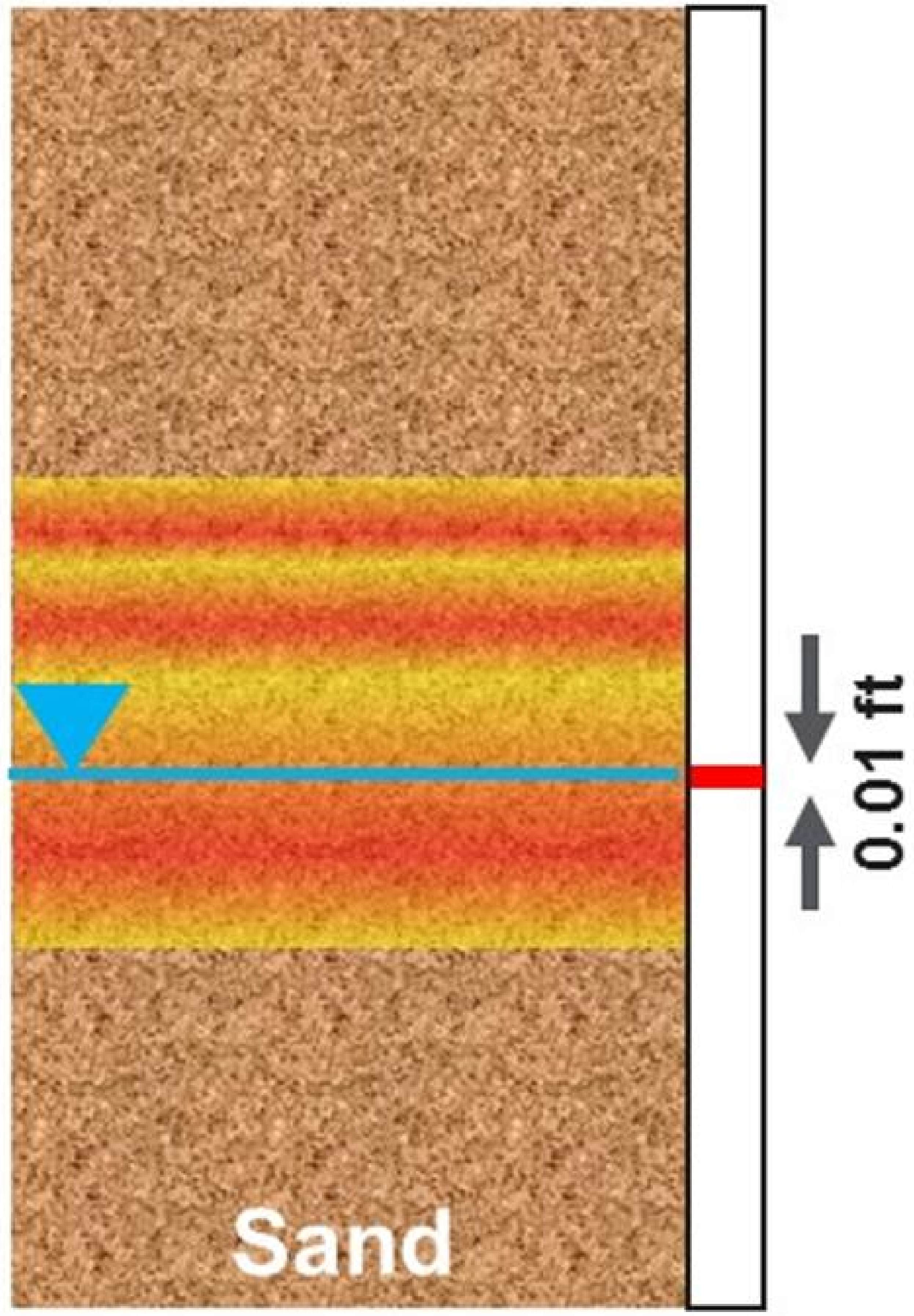
Does 0.01 ft of LNAPL in a well mean little LNAPL in soil?

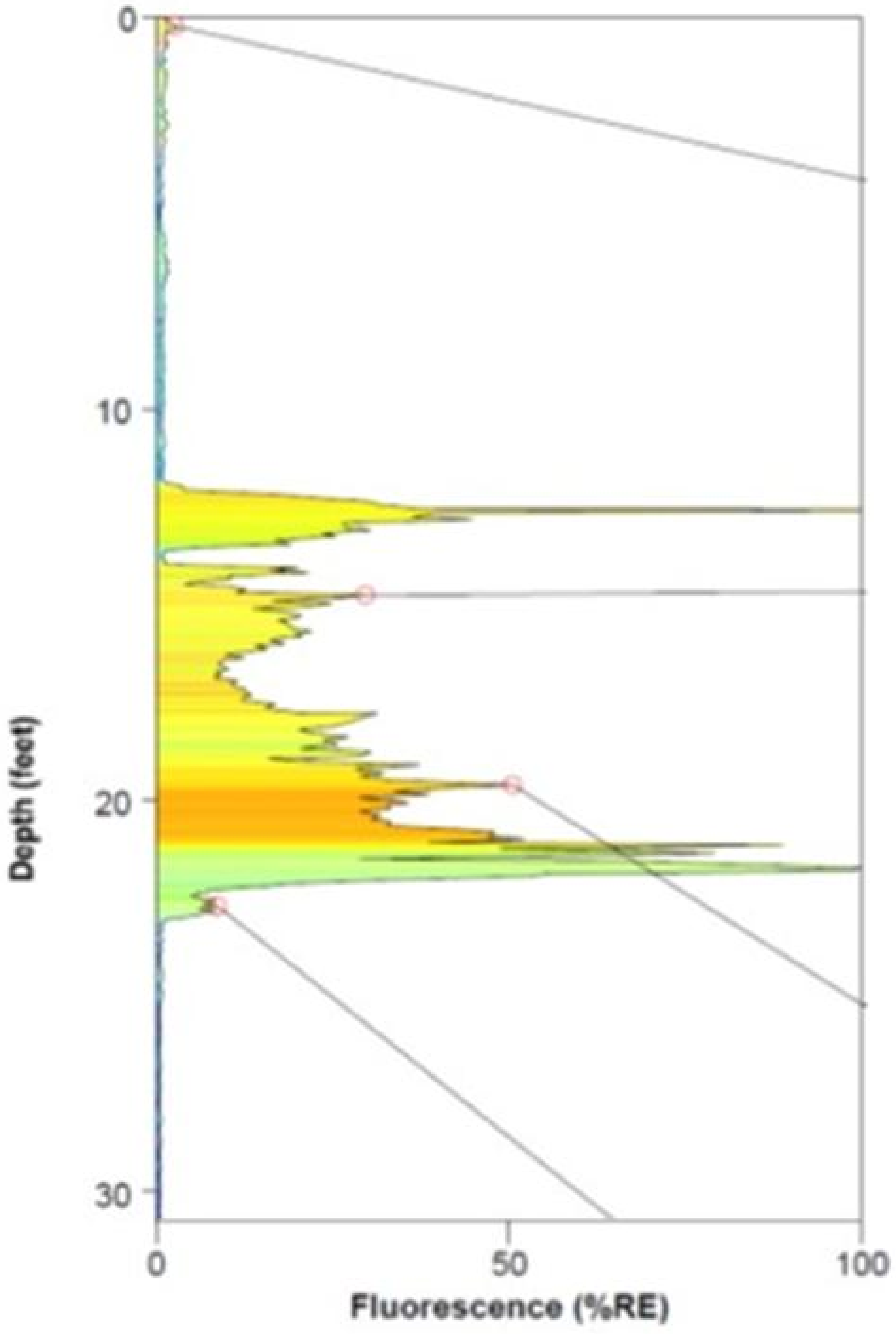


Does 0.01 ft of LNAPL in a well mean little LNAPL in soil?



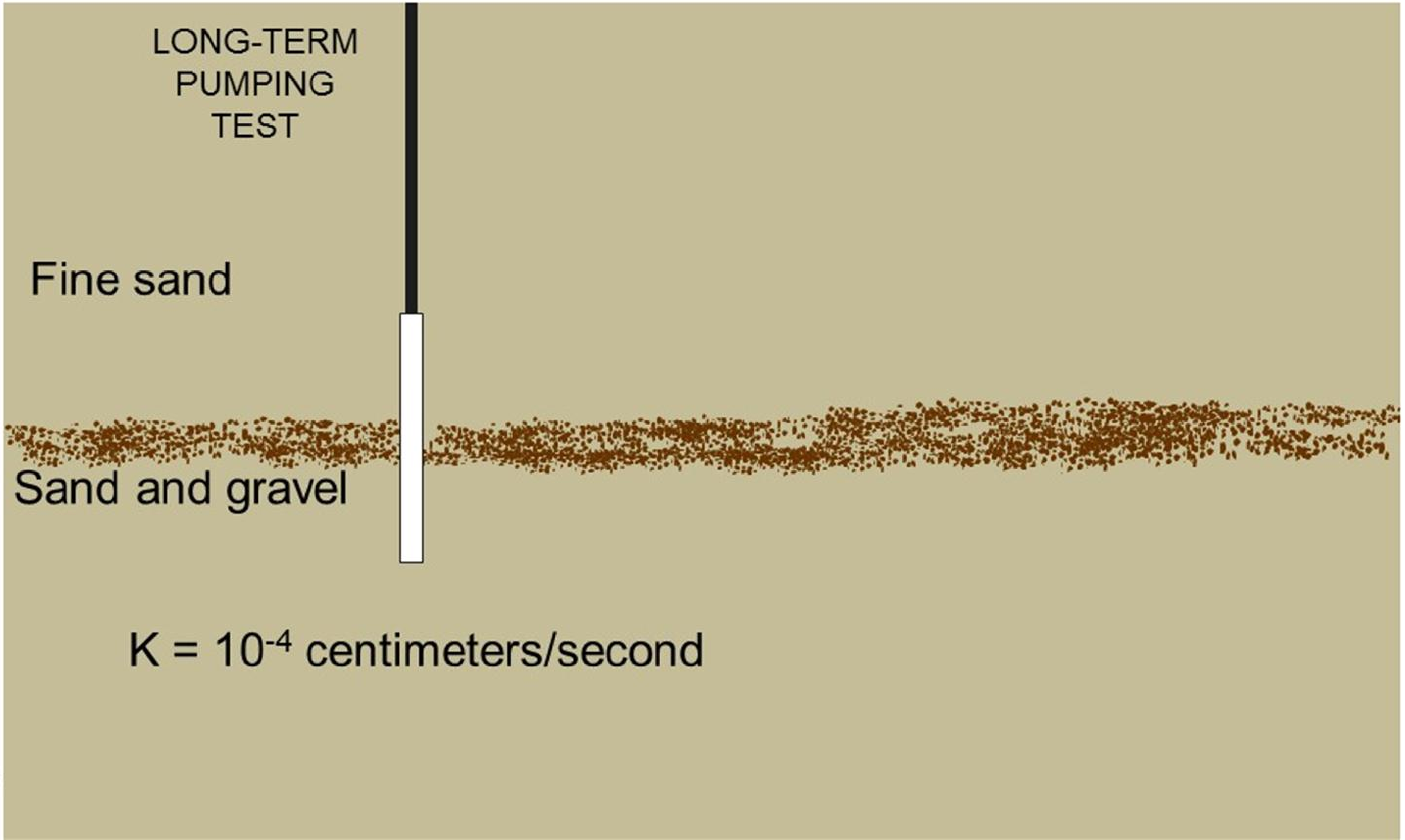
Does 0.01 ft of LNAPL in a well mean little LNAPL in soil?



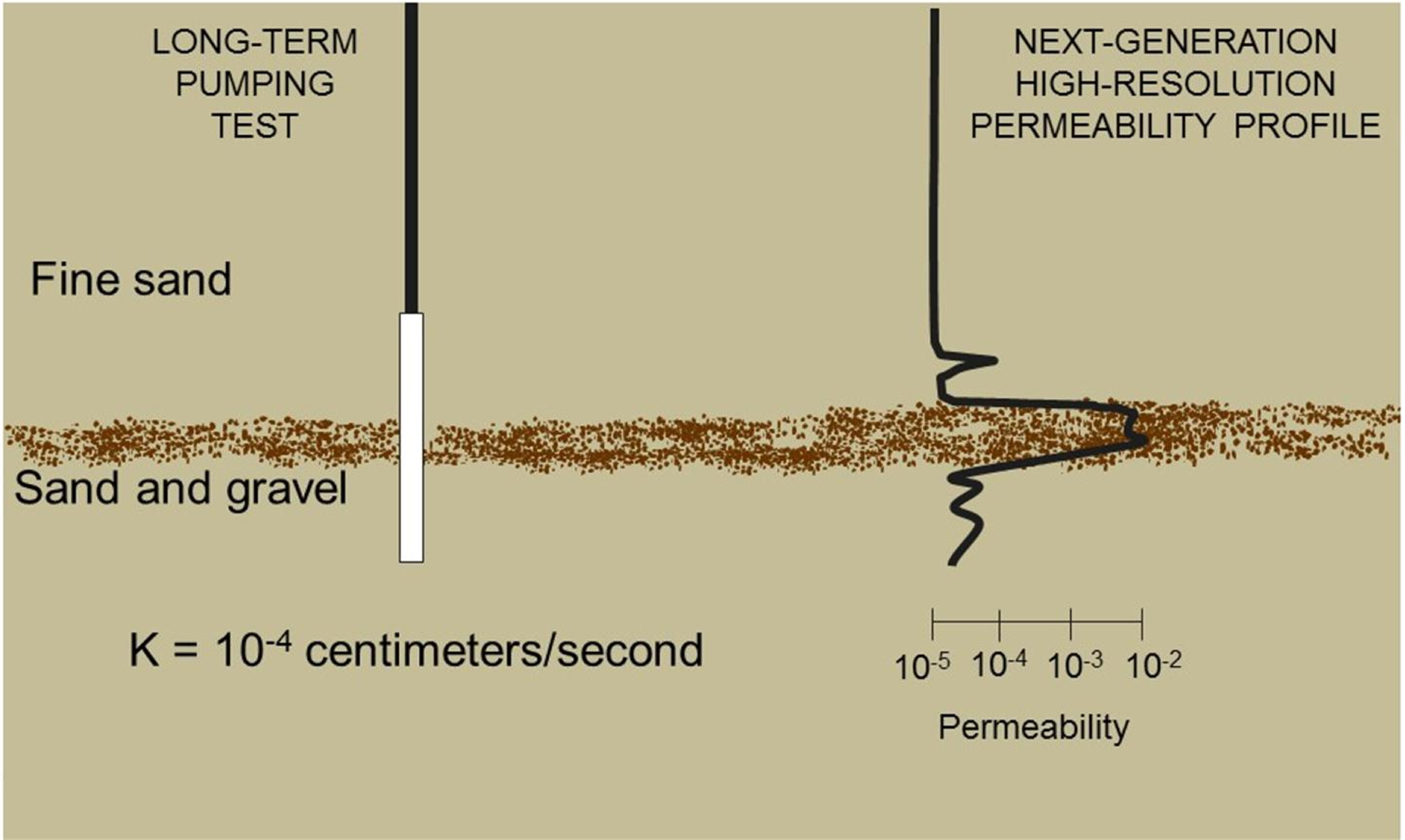


Residual LNAPL does not drain into a well

Wells provide average permeability



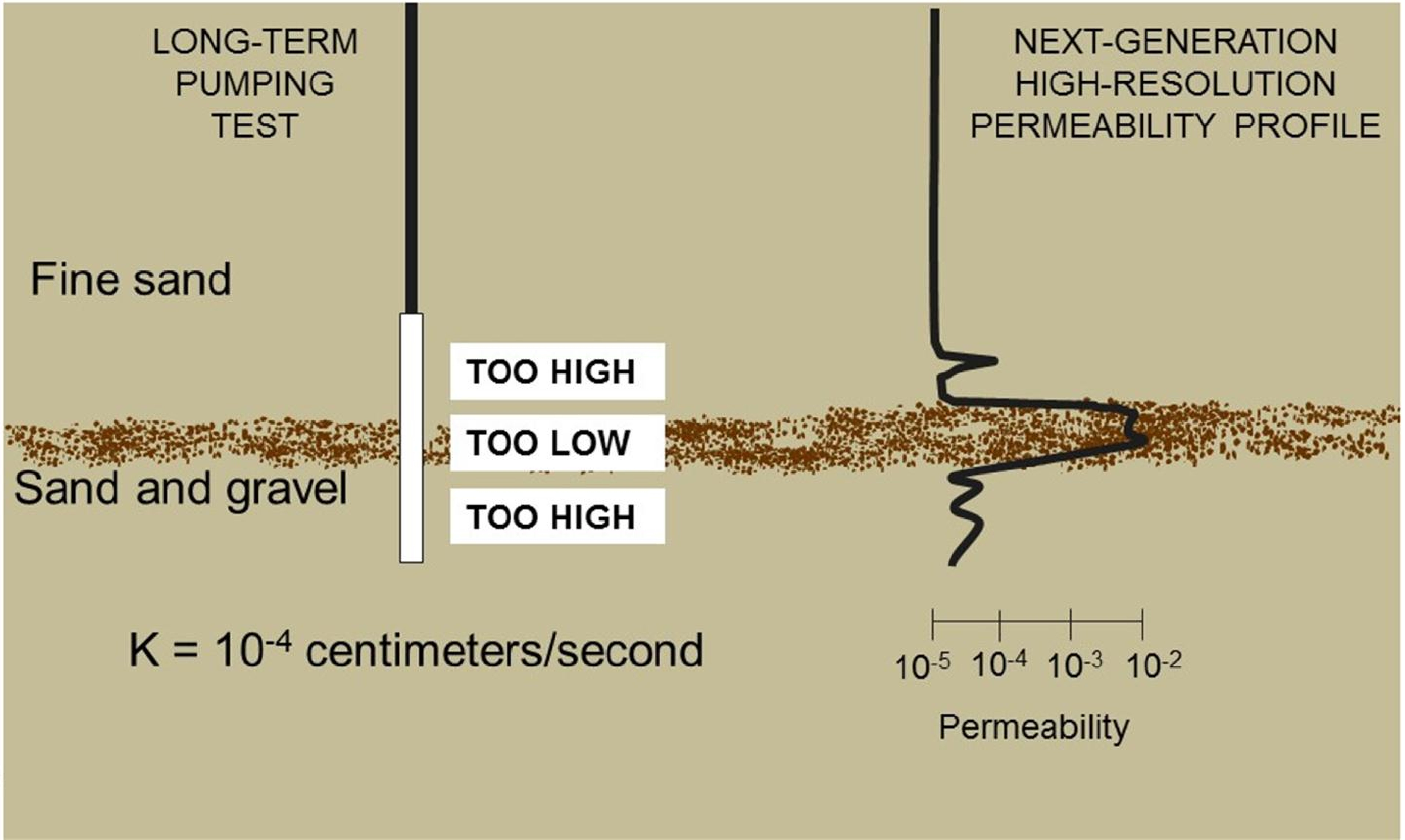
K = 10^{-4} centimeters/second



LONG-TERM PUMPING TEST

NEXT-GENERATION HIGH-RESOLUTION PERMEABILITY PROFILE

K = 10^{-4} centimeters/second



LONG-TERM PUMPING TEST

NEXT-GENERATION HIGH-RESOLUTION PERMEABILITY PROFILE

Fine sand

Sand and gravel

TOO HIGH

TOO LOW

TOO HIGH

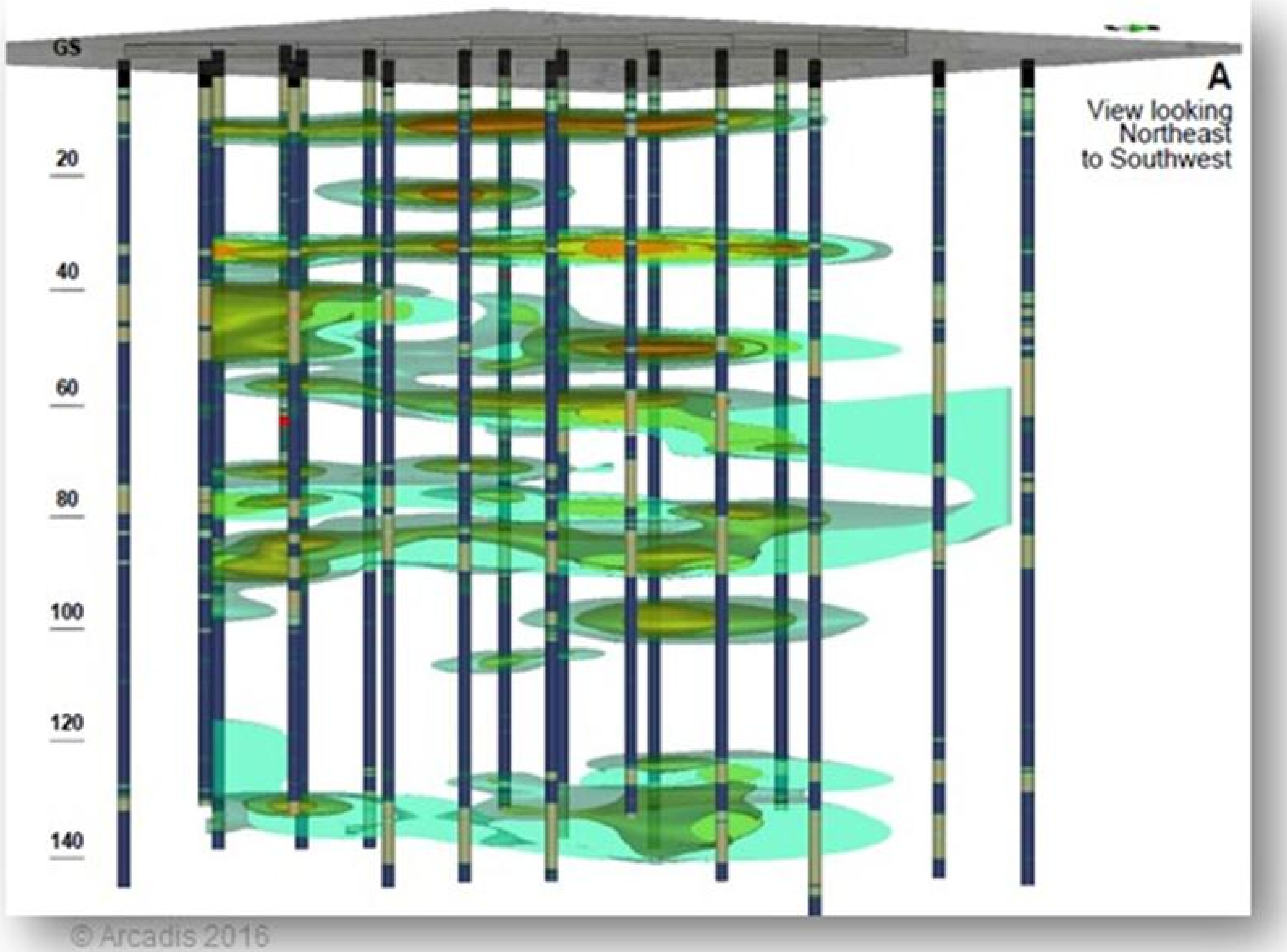
K = 10^{-4} centimeters/second

Questions?

Smart Characterization & mass flux

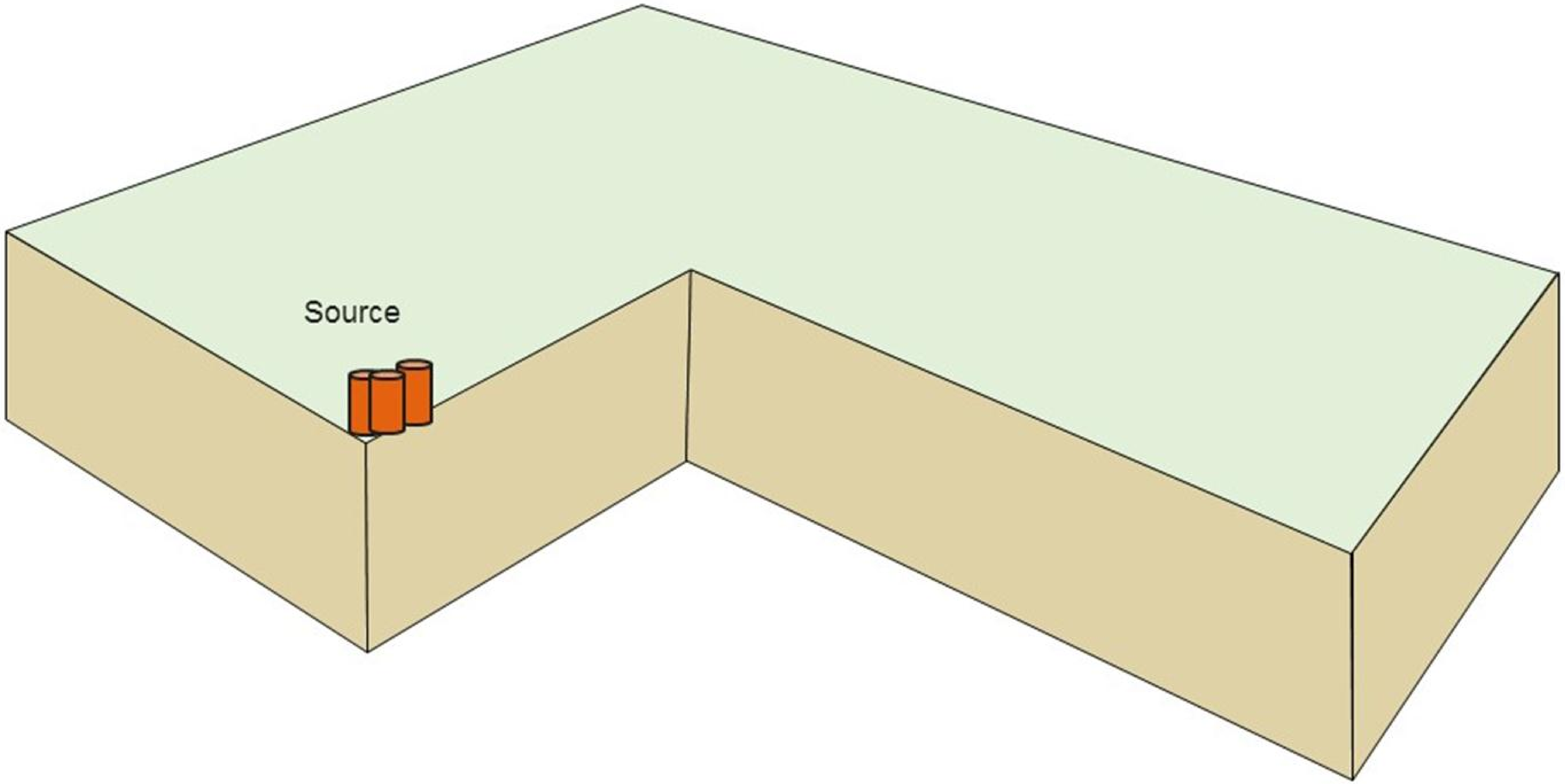
Smart Characterization

Dynamic, flux-focused approach defines the relevant mass…
mass that moves leads to risk and liability

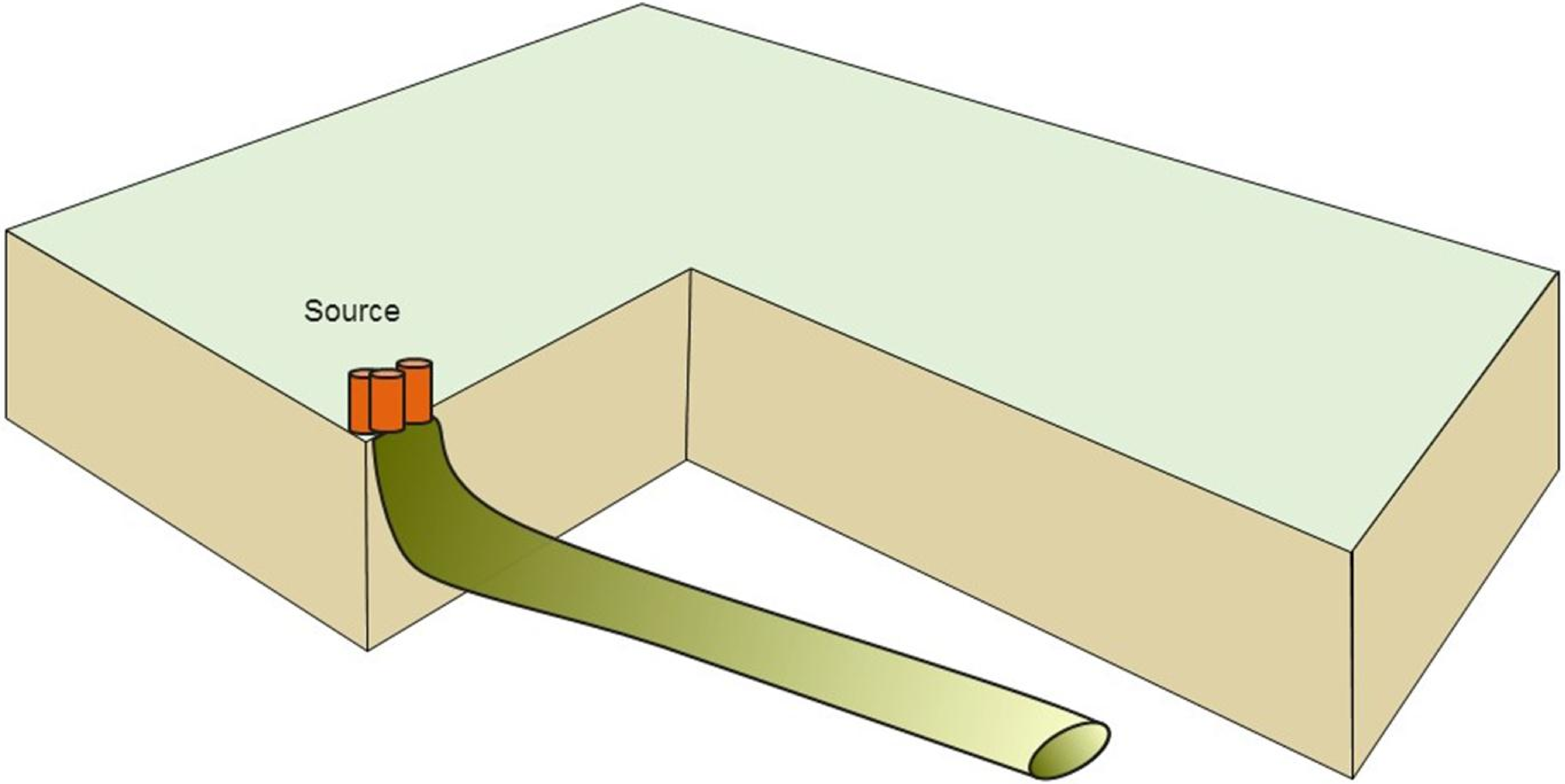


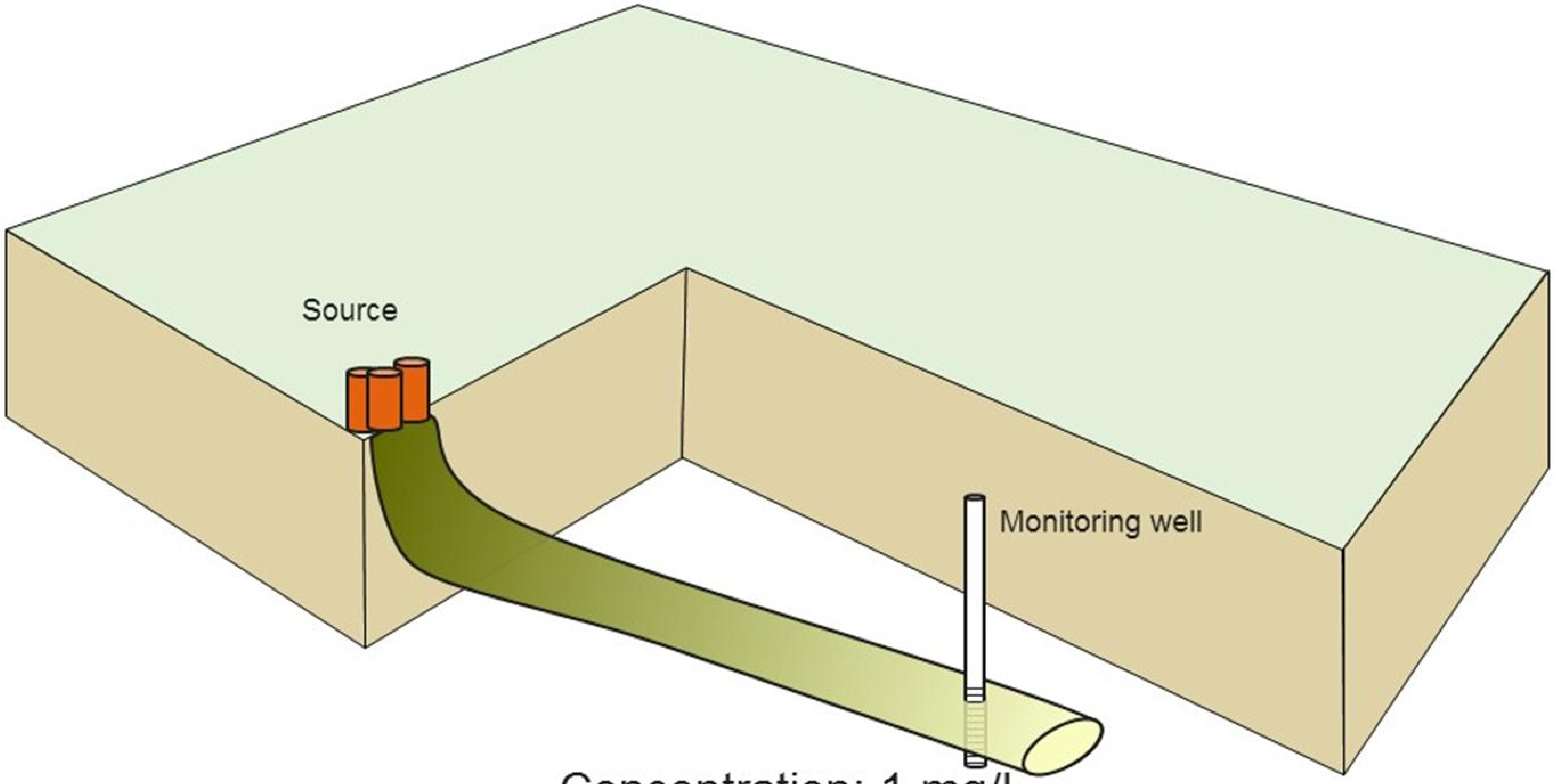
Components

- Classical geologic interpretation
- The right tool for the job to map flux
- Real-time, quantitative data
- 3D analysis
- Adaptive investigation strategy
- Dynamic conceptual site models



Source

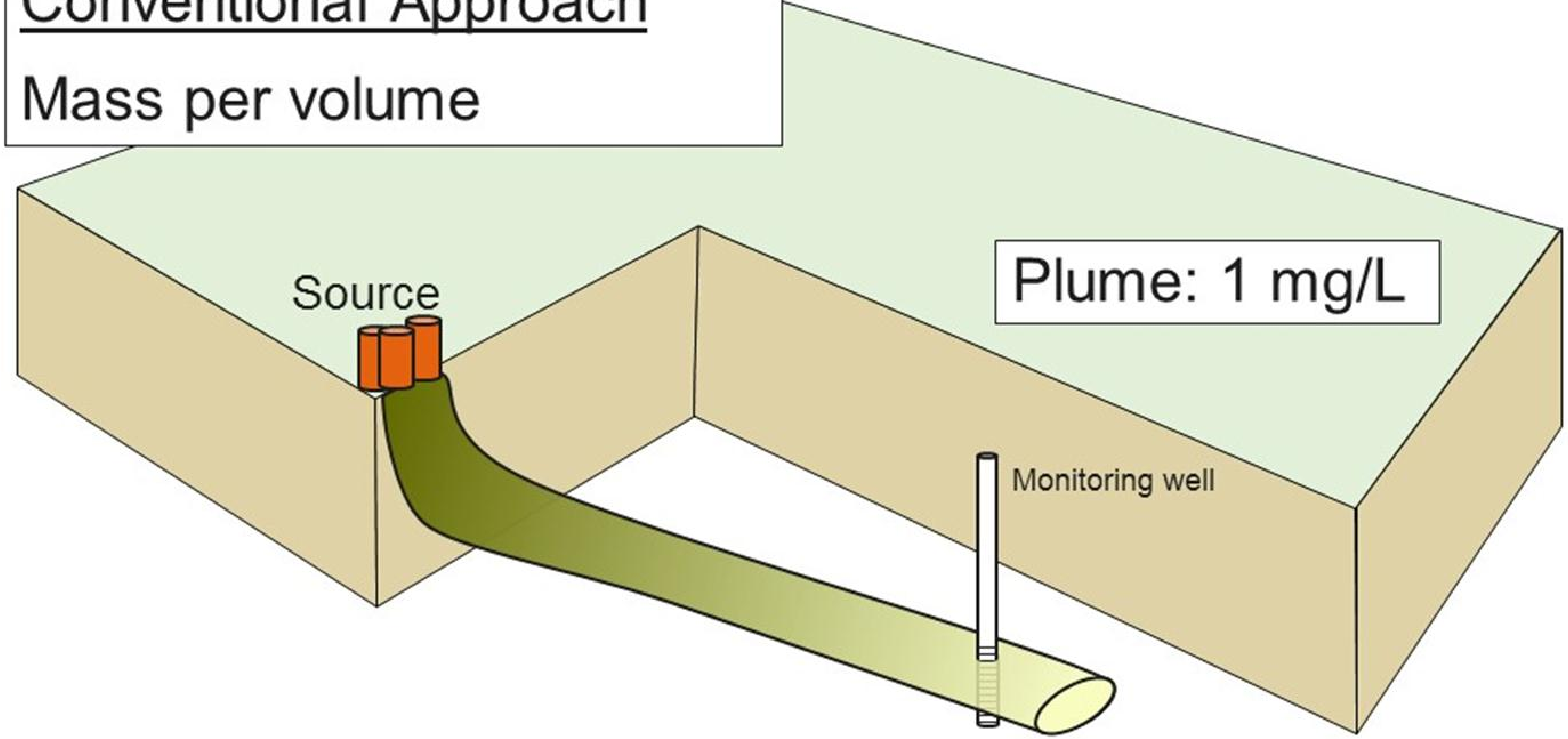

Source



Concentration: 1 mg/L

Conventional Approach

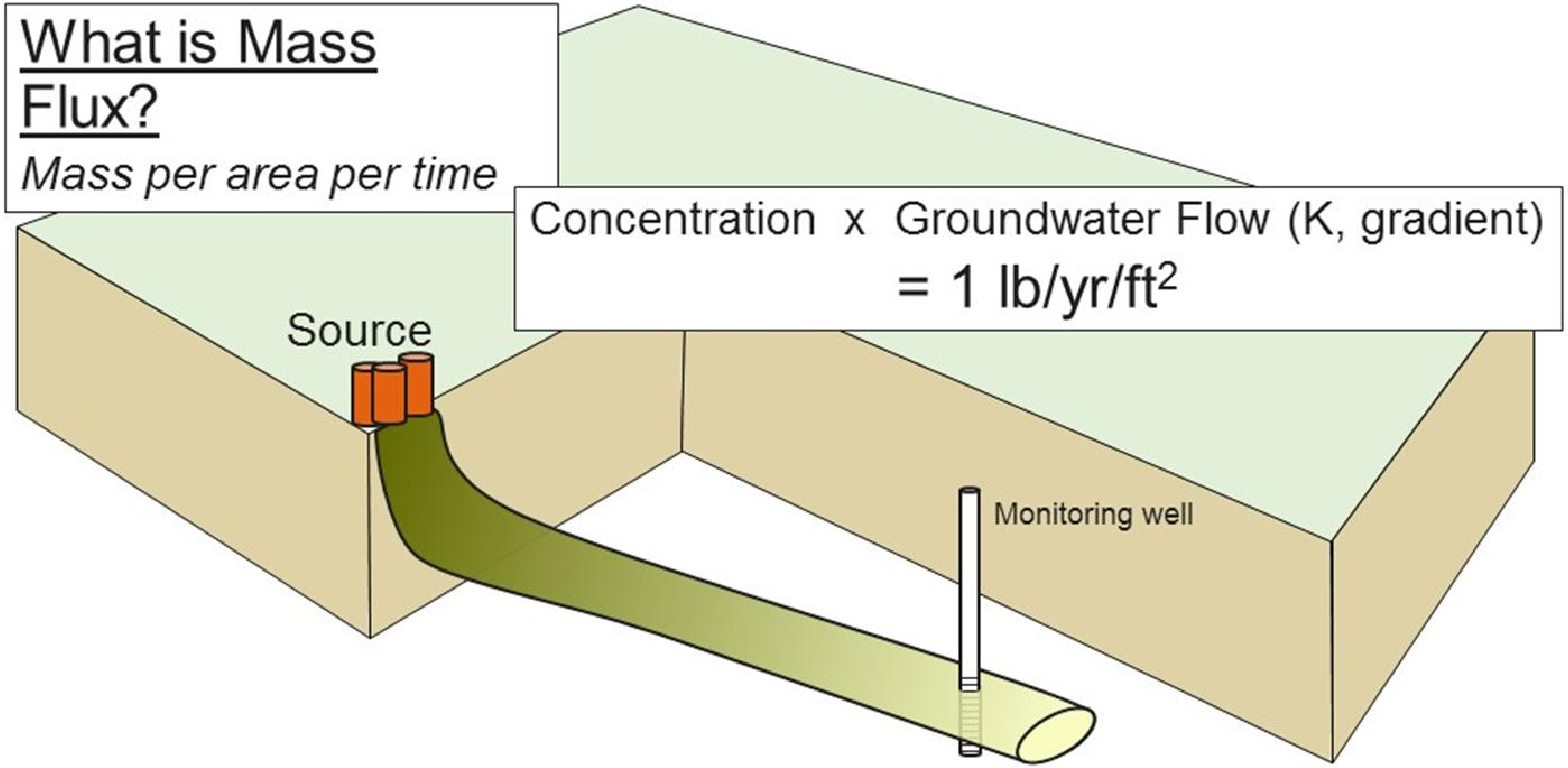
Mass per volume



Plume: 1 mg/L

What is Mass Flux?

Mass per area per time

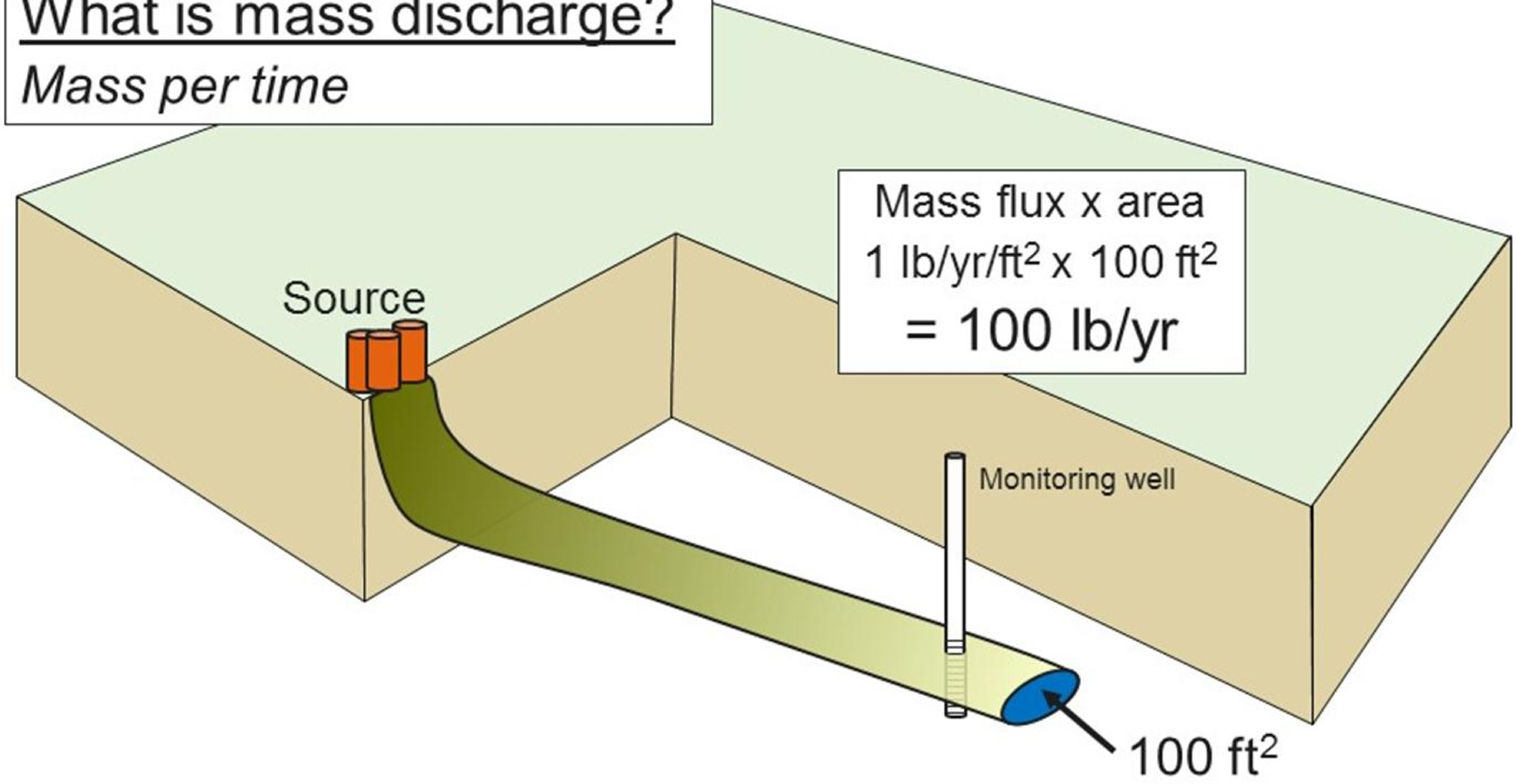


Concentration x Groundwater Flow (K, gradient)

$= 1$ lb/yr/ft^2

What is mass discharge?

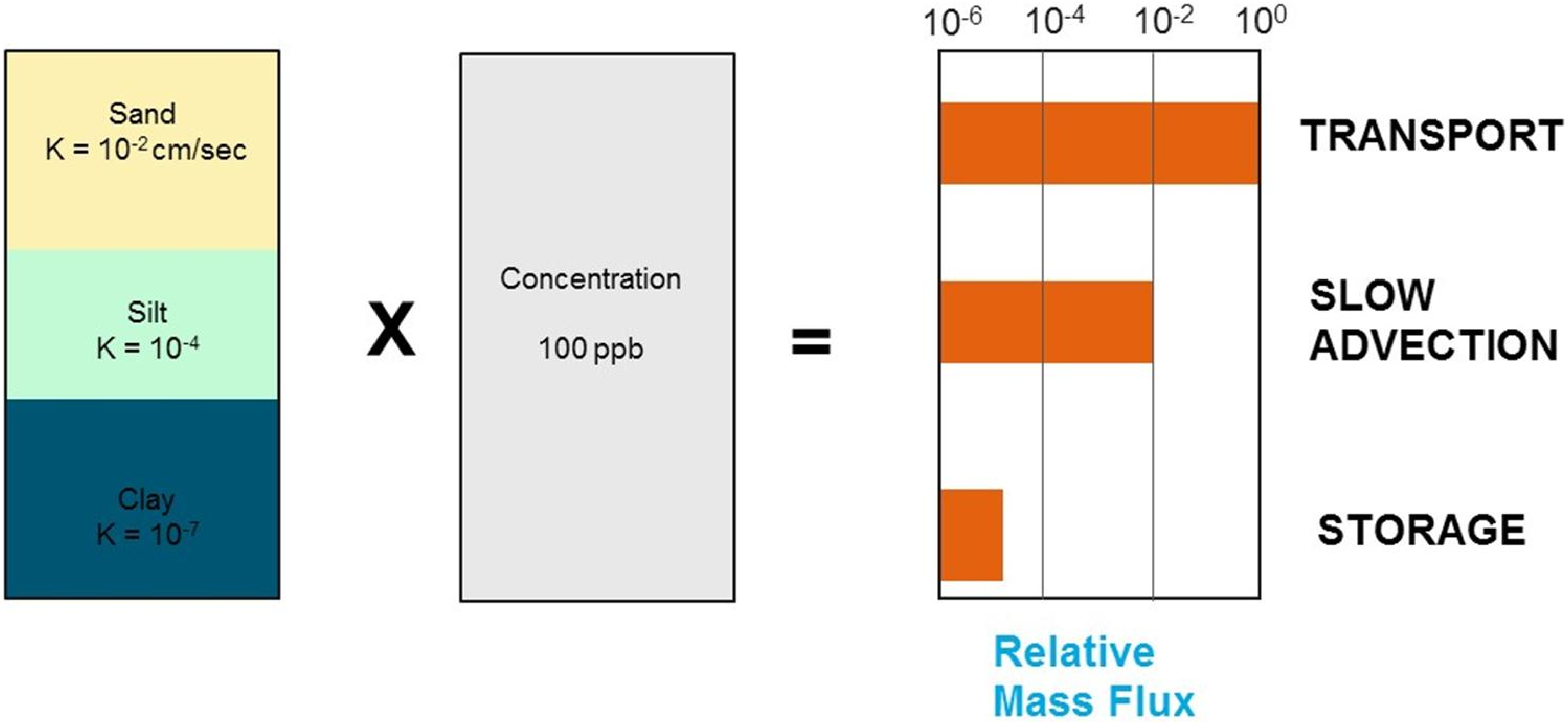
Mass per time



Mass flux x area

$1 \text{ lb/yr/ft}^2 \times 100 \text{ ft}^2$

$= 100 \text{ lb/yr}$



Sand
K = 10^{-2} cm/sec

Silt
K = 10^{-4}

Clay
K = 10^{-7}

X

Concentration

100 ppb

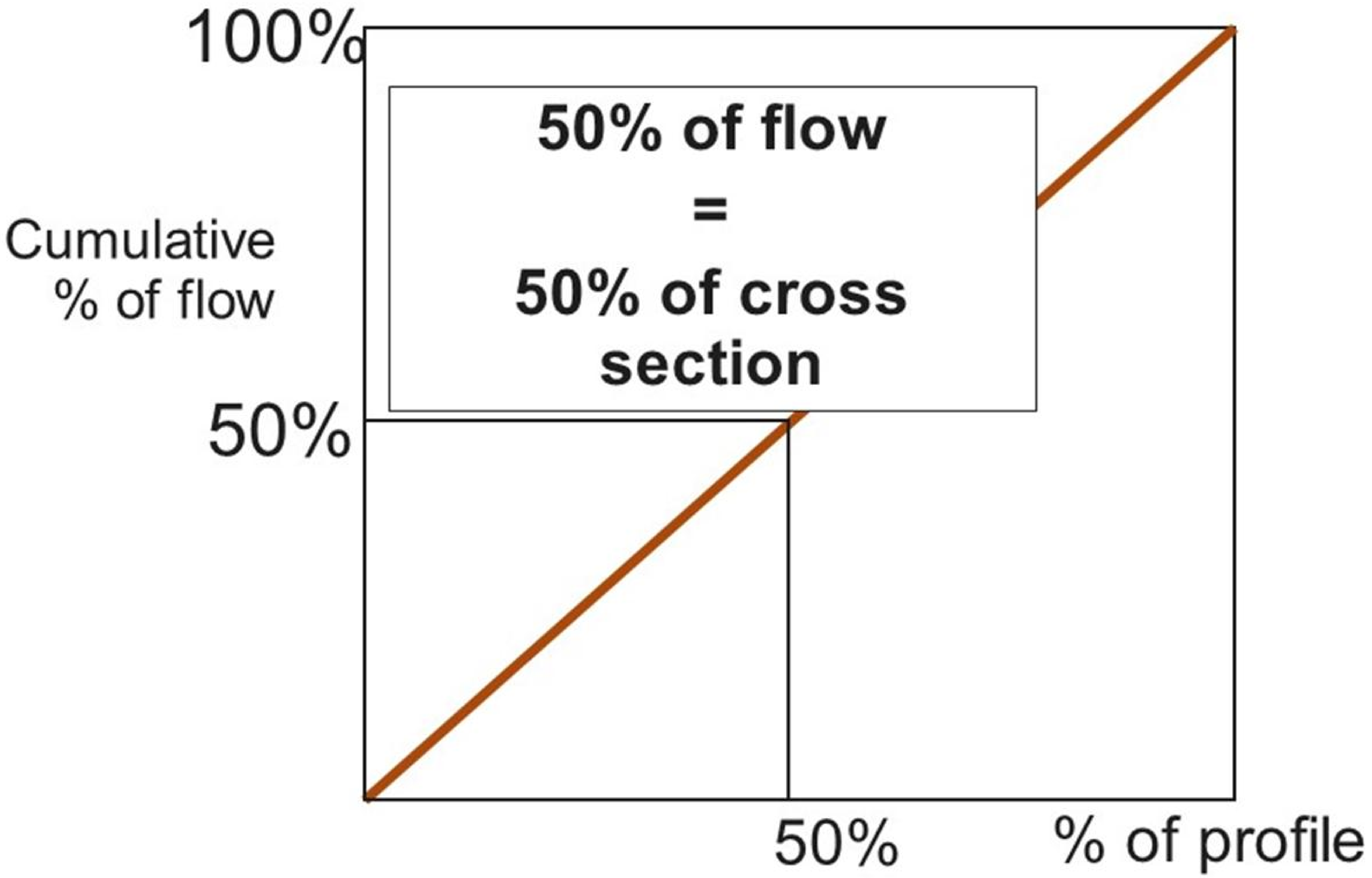
=

TRANSPORT

SLOW ADVECTION

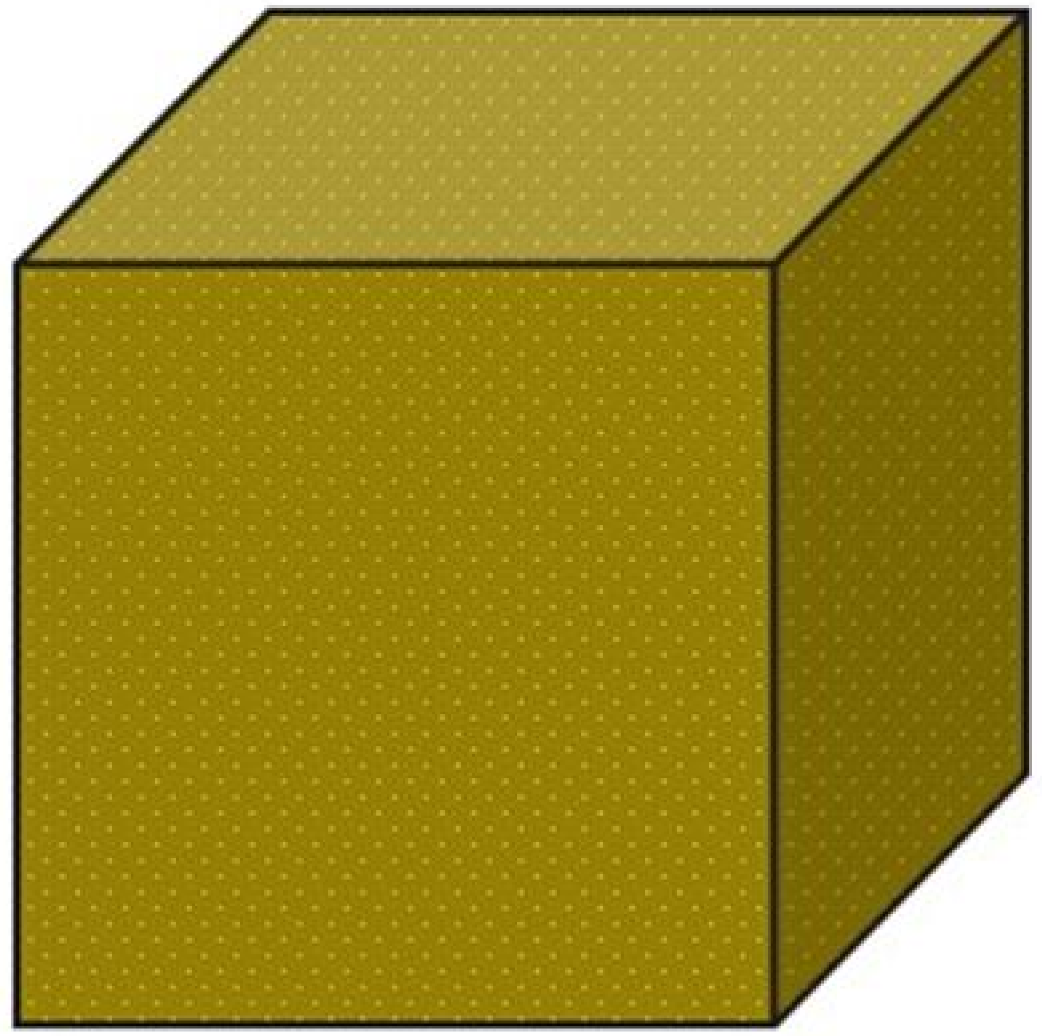
STORAGE

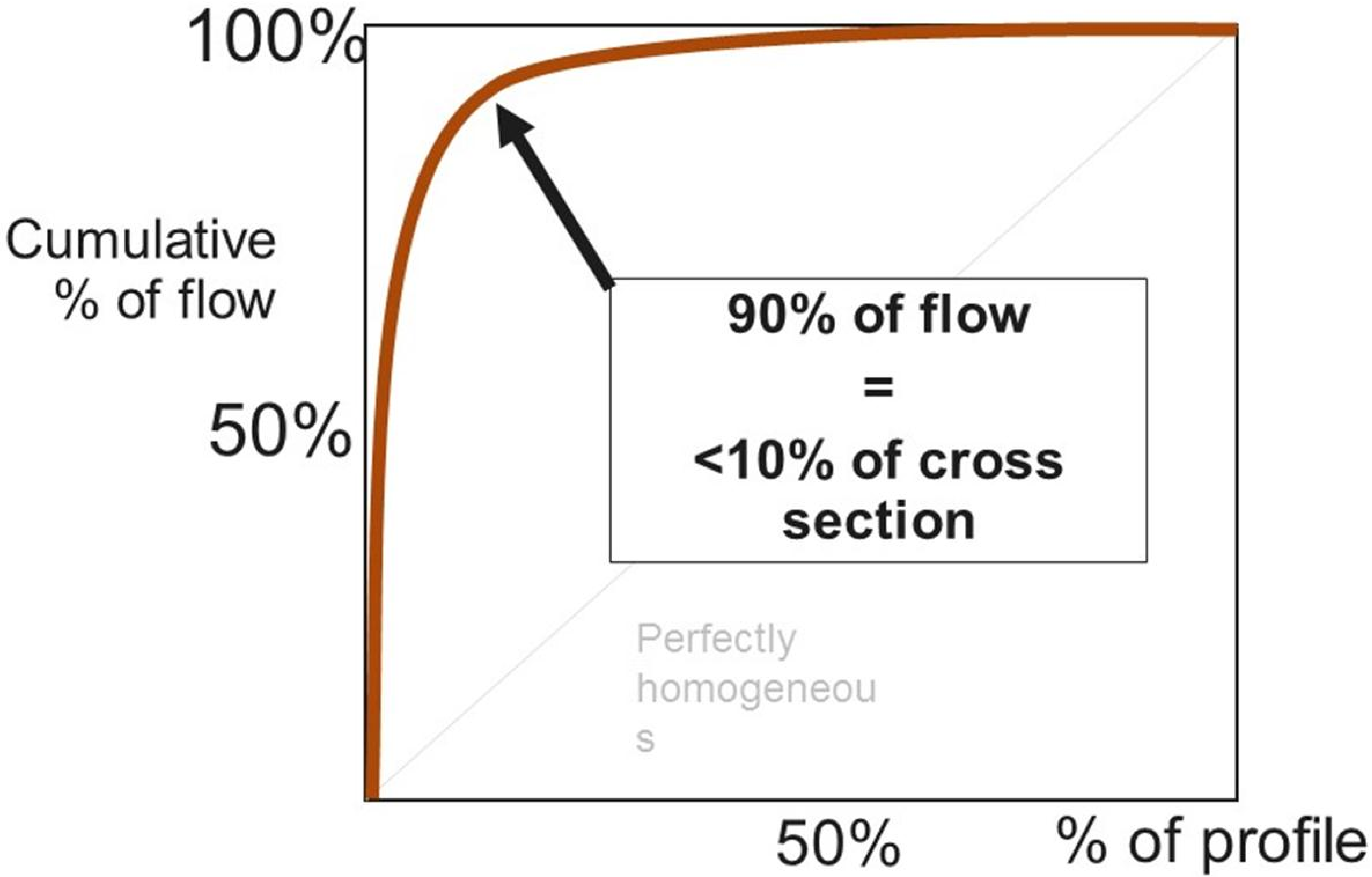
Relative Mass Flux



50% of flow
=
50% of cross section

Perfectly homogeneous system

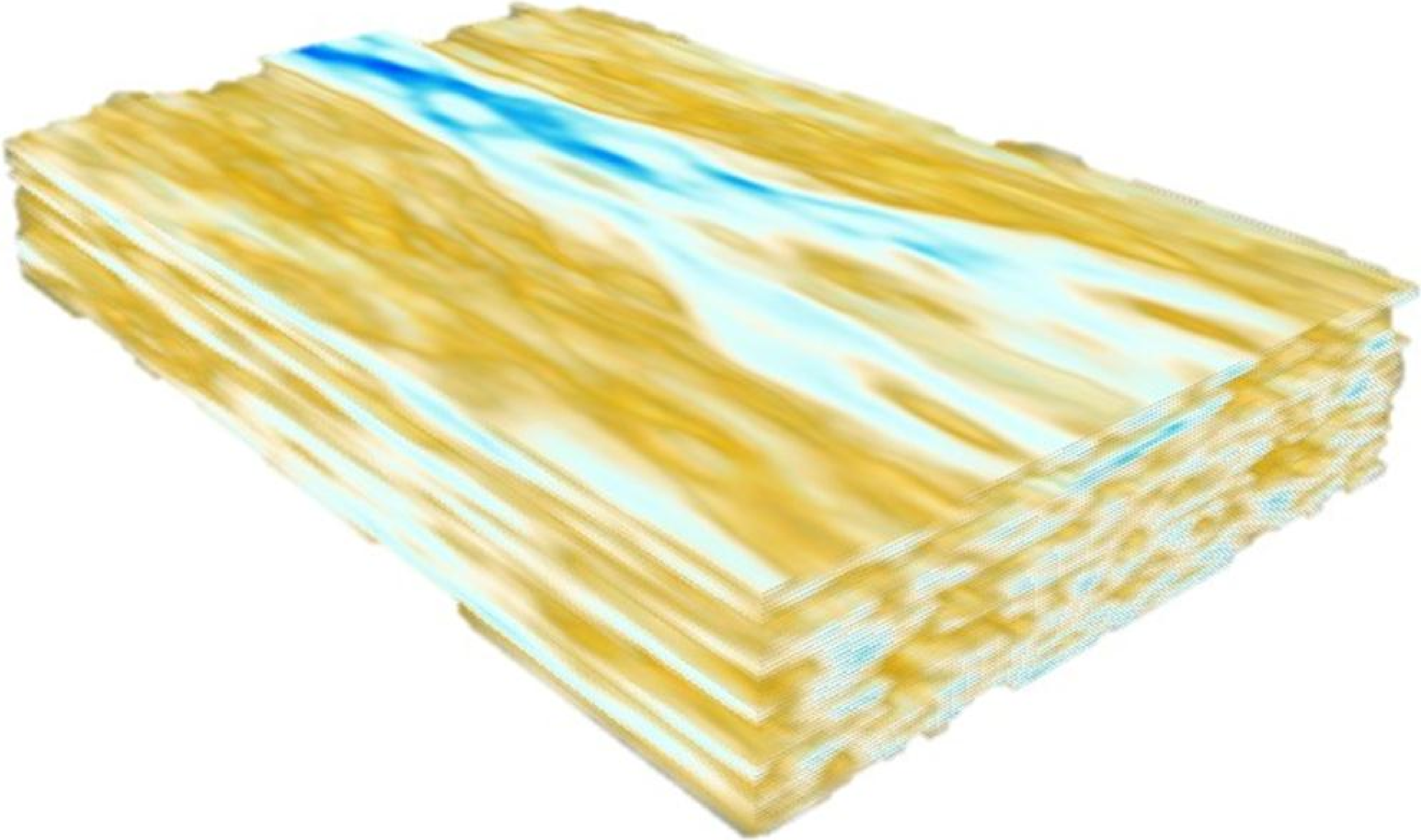




90% of flow = <10% of cross section

Real world

Aquifer deposition creates complex permeability networks, and zones of higher and lower mass flux



Flux-mapping tools

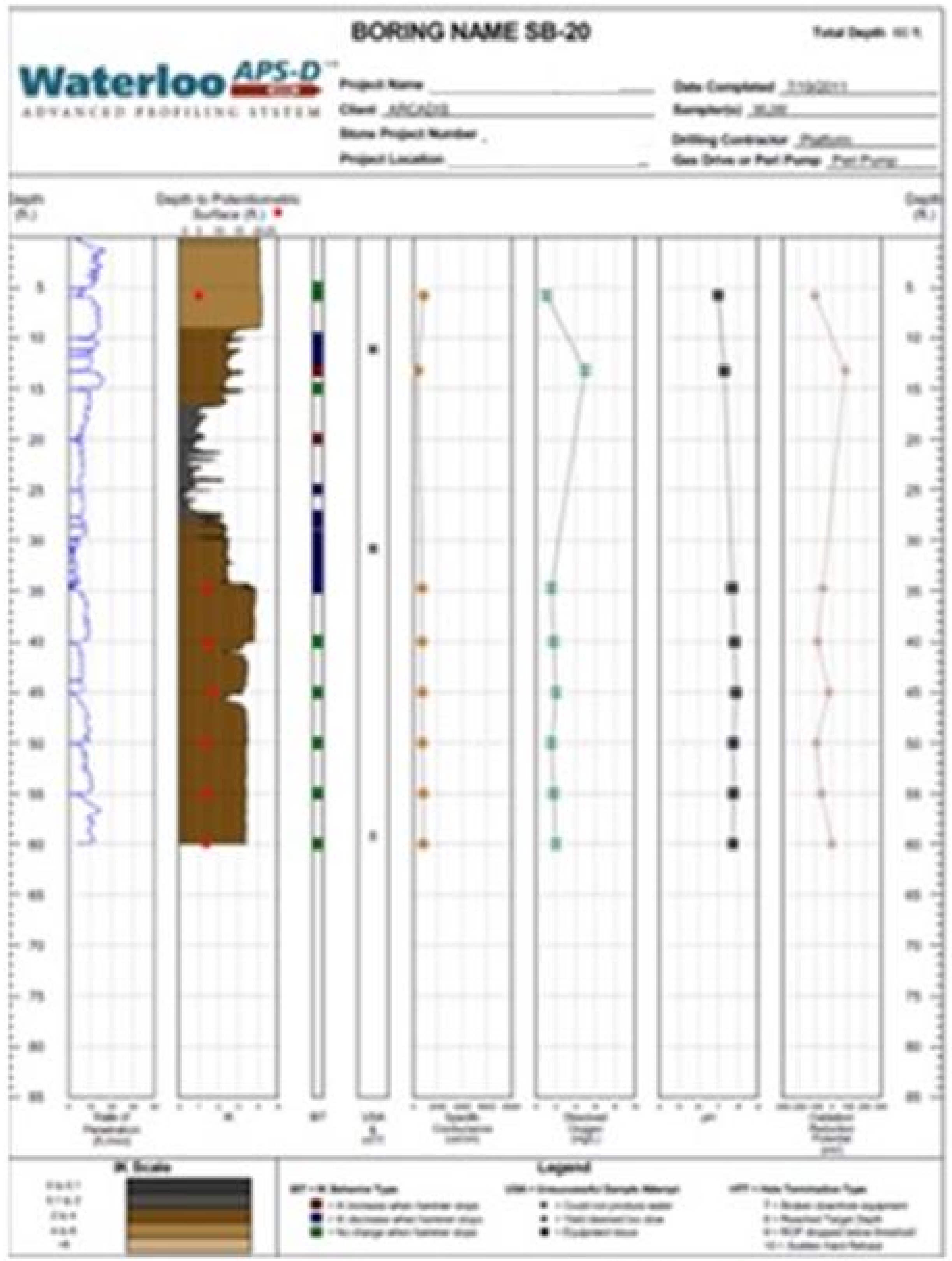
Smart Characterization Methods

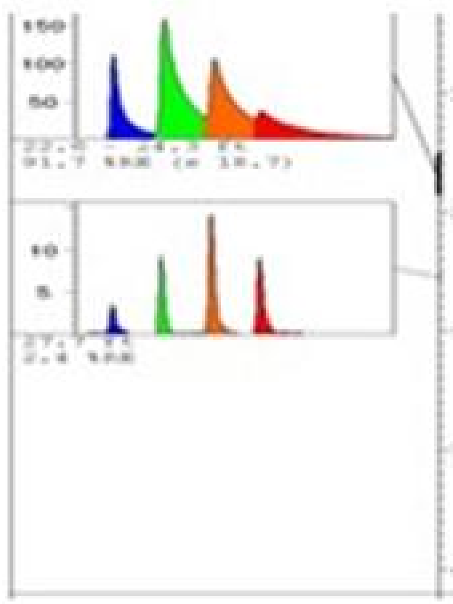
Permeability mapping

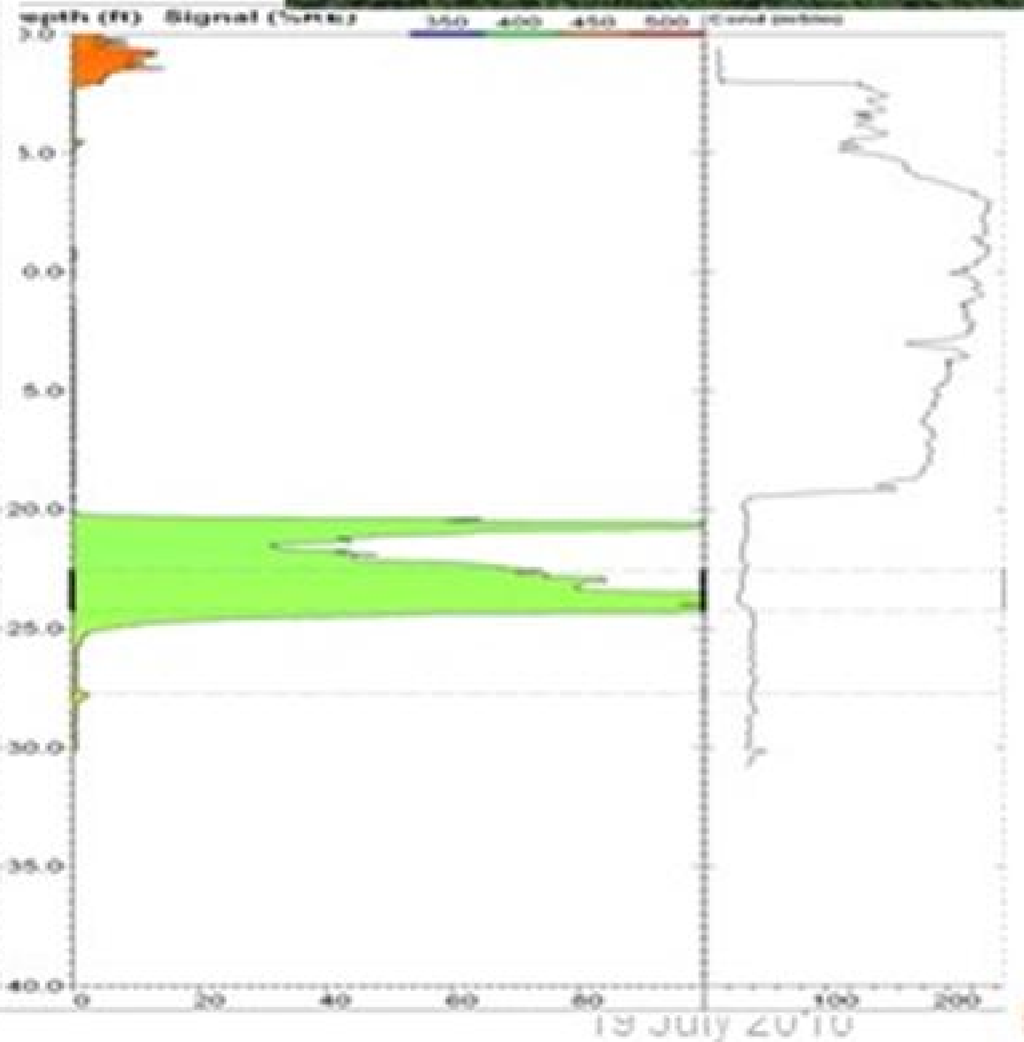
- Cone penetrometer testing (CPT)
- Hydraulic profiling tool (HPT)
- Waterloo profiler
- Sieve data

Plume mapping

- Vertical aquifer profile GW sampling
- Screening tools (like MIP)
- Whole-core saturated soil
- Optical screening (LIF)
- DyeLIF chlorinated solvent DNAPL mapping
- UVOST-HP/TarGOST-HP for relative NAPL mobility
- Passive flux meters







Permeability Profiling Tools

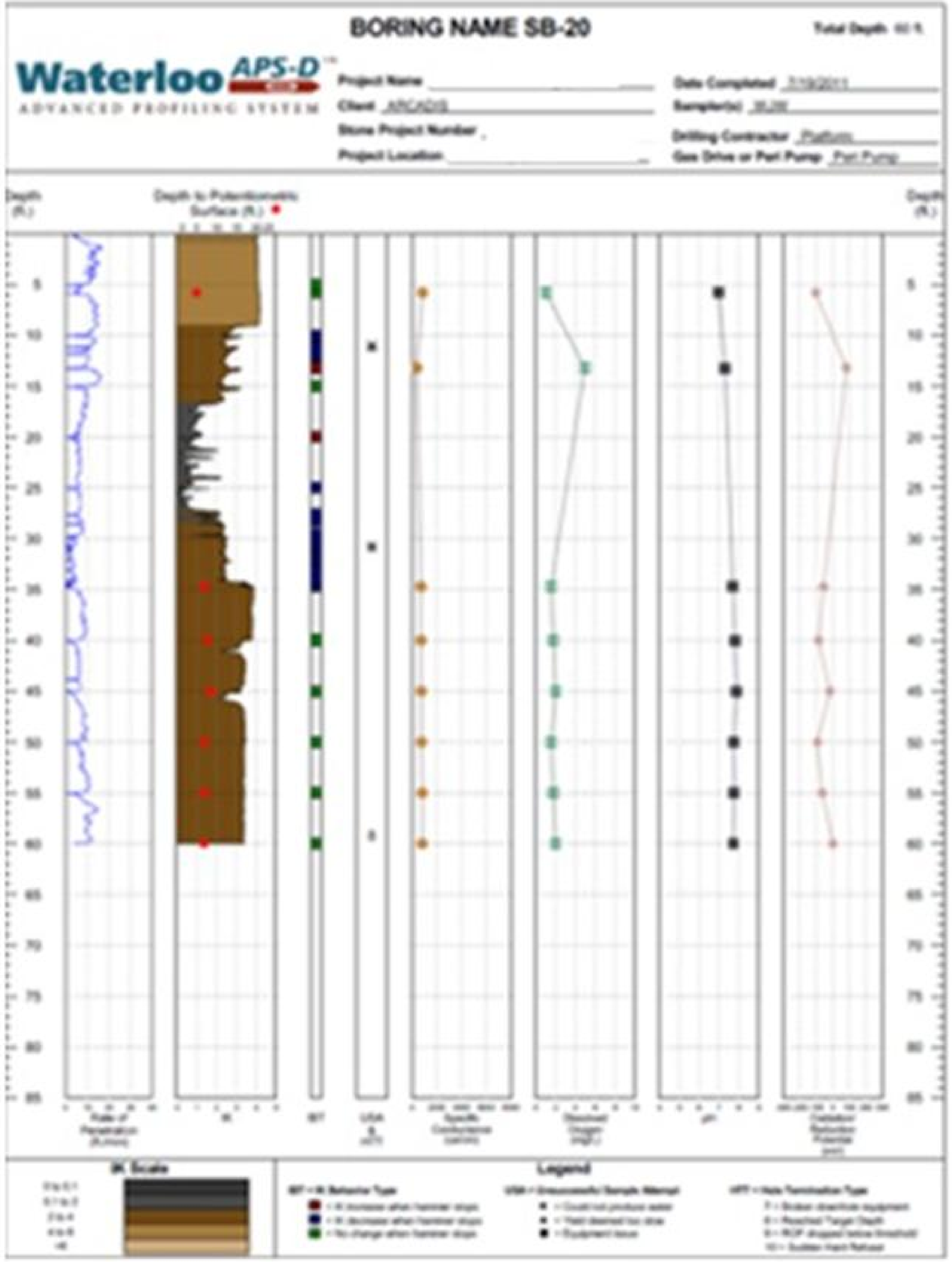
Design & Consultancy for natural and built assets

Geoprobe HPT, Waterloo APS:

- Inject 200-300 ml/min of water
- Record aquifer response
- Collect GW samples

CPT:

- Ambient pressure response to cone advancement



BORING NAME SB-20

Total Depth 60 ft.

Waterloo APS-D

ADVANCED PROFILING SYSTEM

Project Name

Client ARCADIS

Stone Project Number

Project Location

Date Completed 7/19/2011

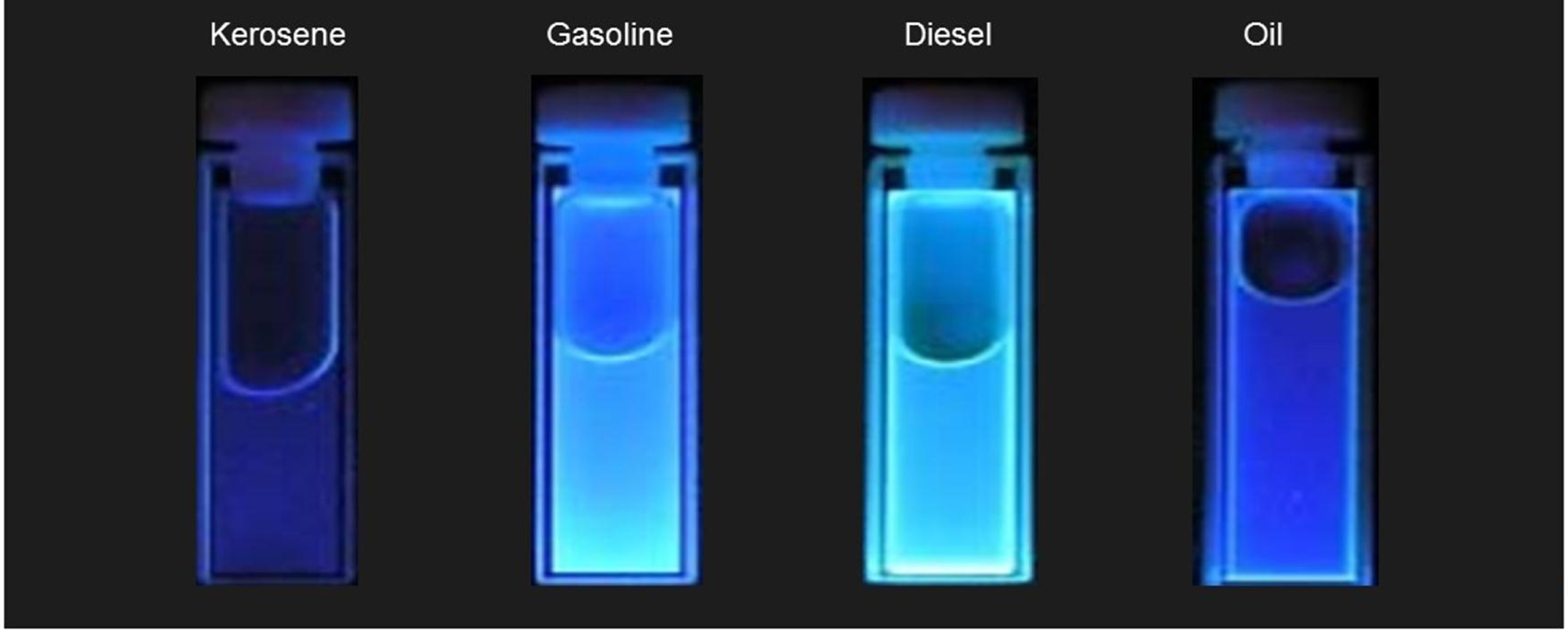
Sampler(s)

Drilling Contractor

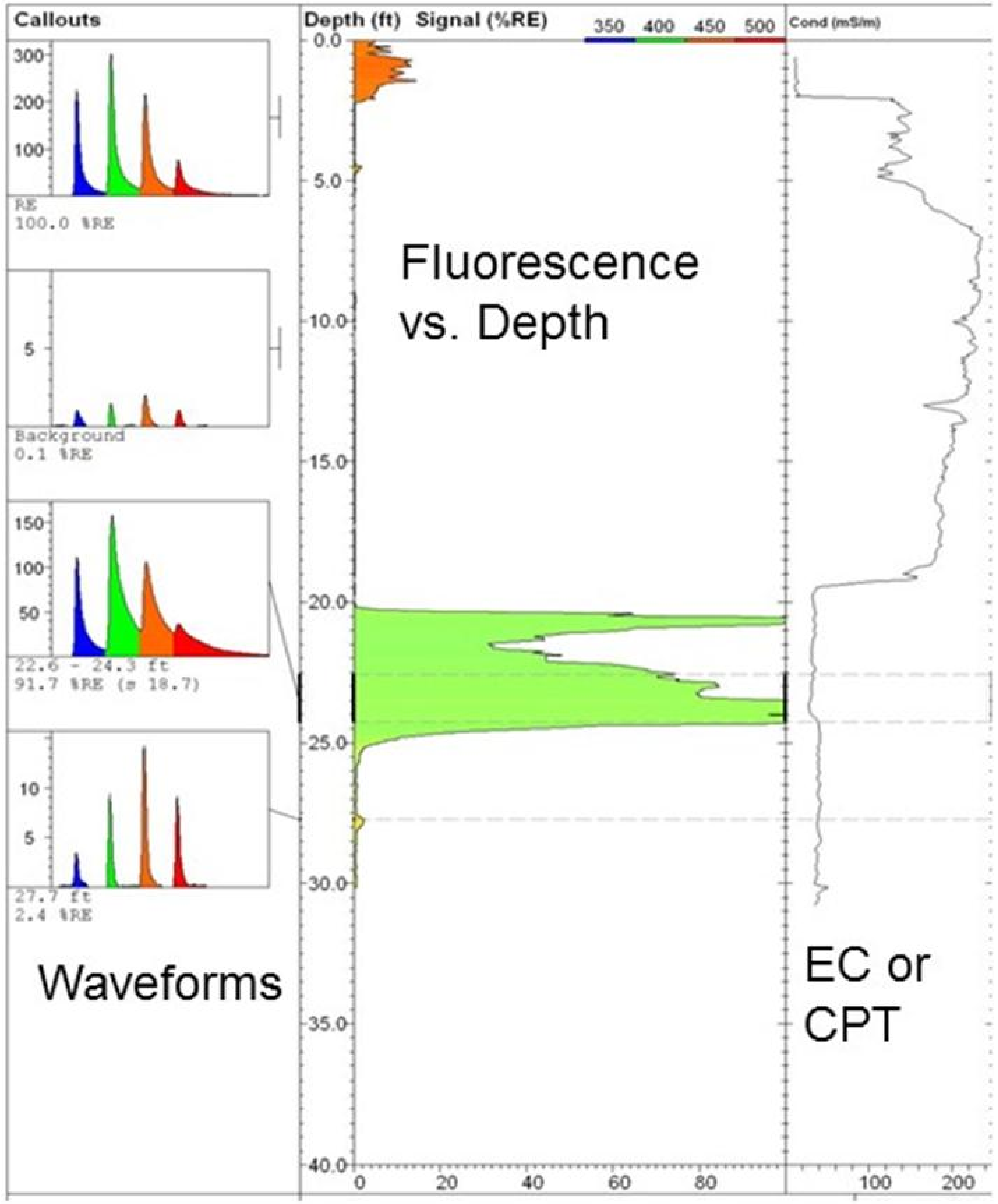
Gas Drive or Peri Pump Peri Pump

Optical Screening Tools

Polycyclic aromatic hydrocarbons (PAHs) fluoresce in response to excitation by specific wave-lengths of light



Real Time Data Acquisition

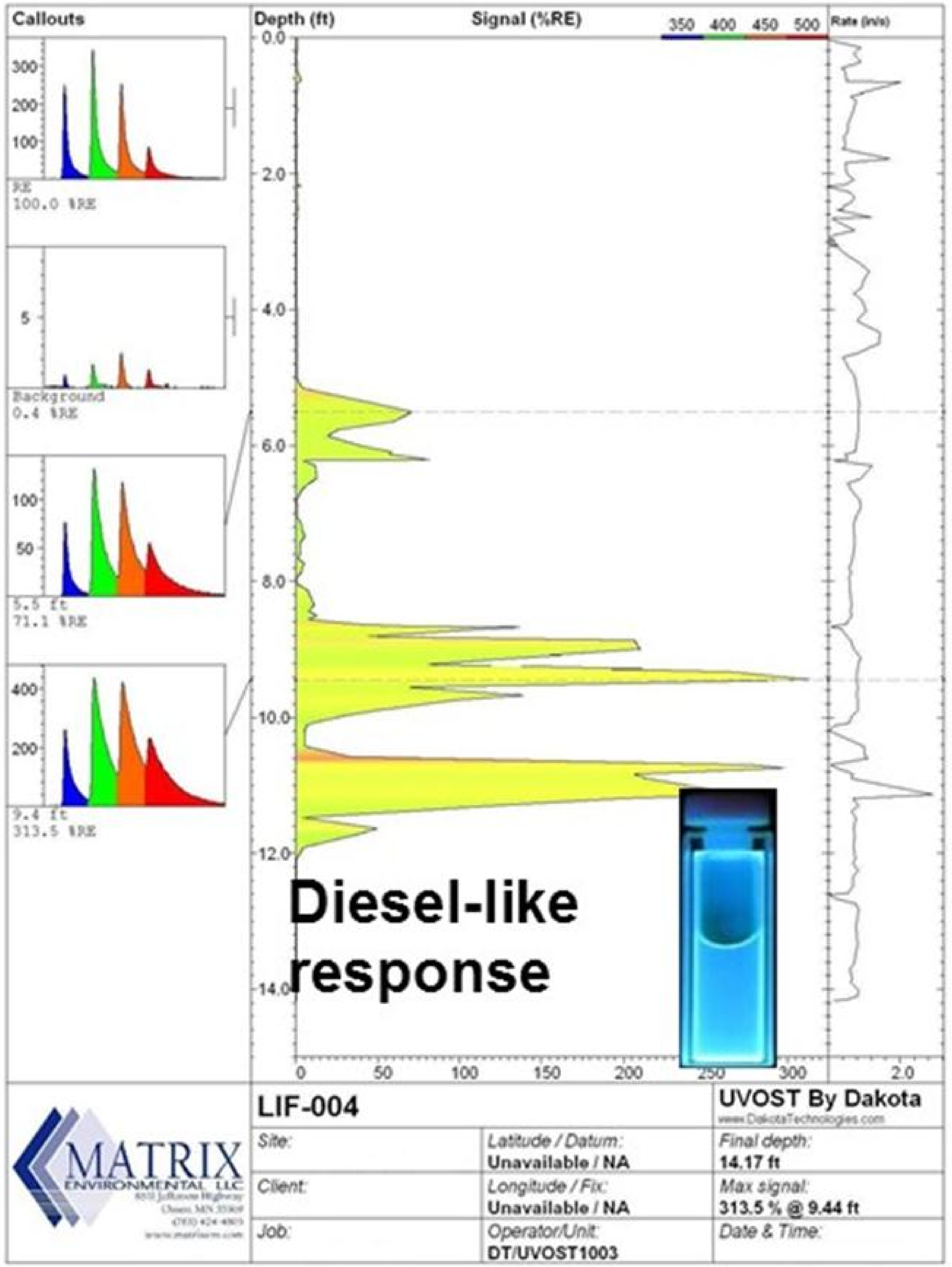


Fluorescence vs. Depth

Waveforms

EC or CPT

Fingerprinting



Diesel-like response

LIF-004

UVOST By Dakota
www.DakotaTechnologies.com

Site:

Latitude / Datum: Unavailable / NA

Final depth: 14.17 ft

Client:

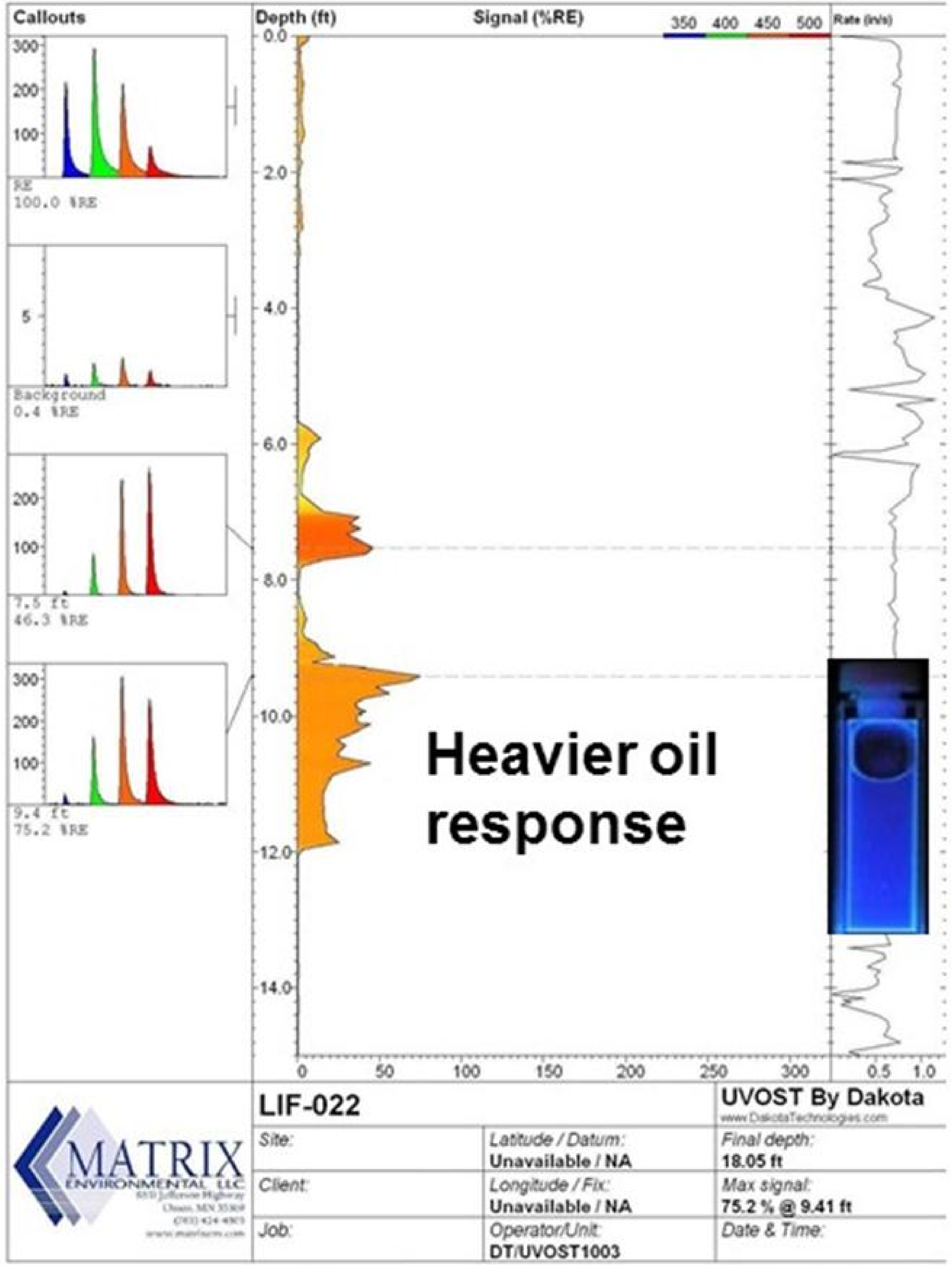
Longitude / Fix: Unavailable / NA

Max signal: 313.5 % @ 9.44 ft

Job:

Operator/Unit: DT/UVOST1003

Date & Time:



Heavier oil response

LIF-022

UVOST By Dakota
www.DakotaTechnologies.com

Site:

Latitude / Datum: Unavailable / NA

Final depth: 18.05 ft

Client:

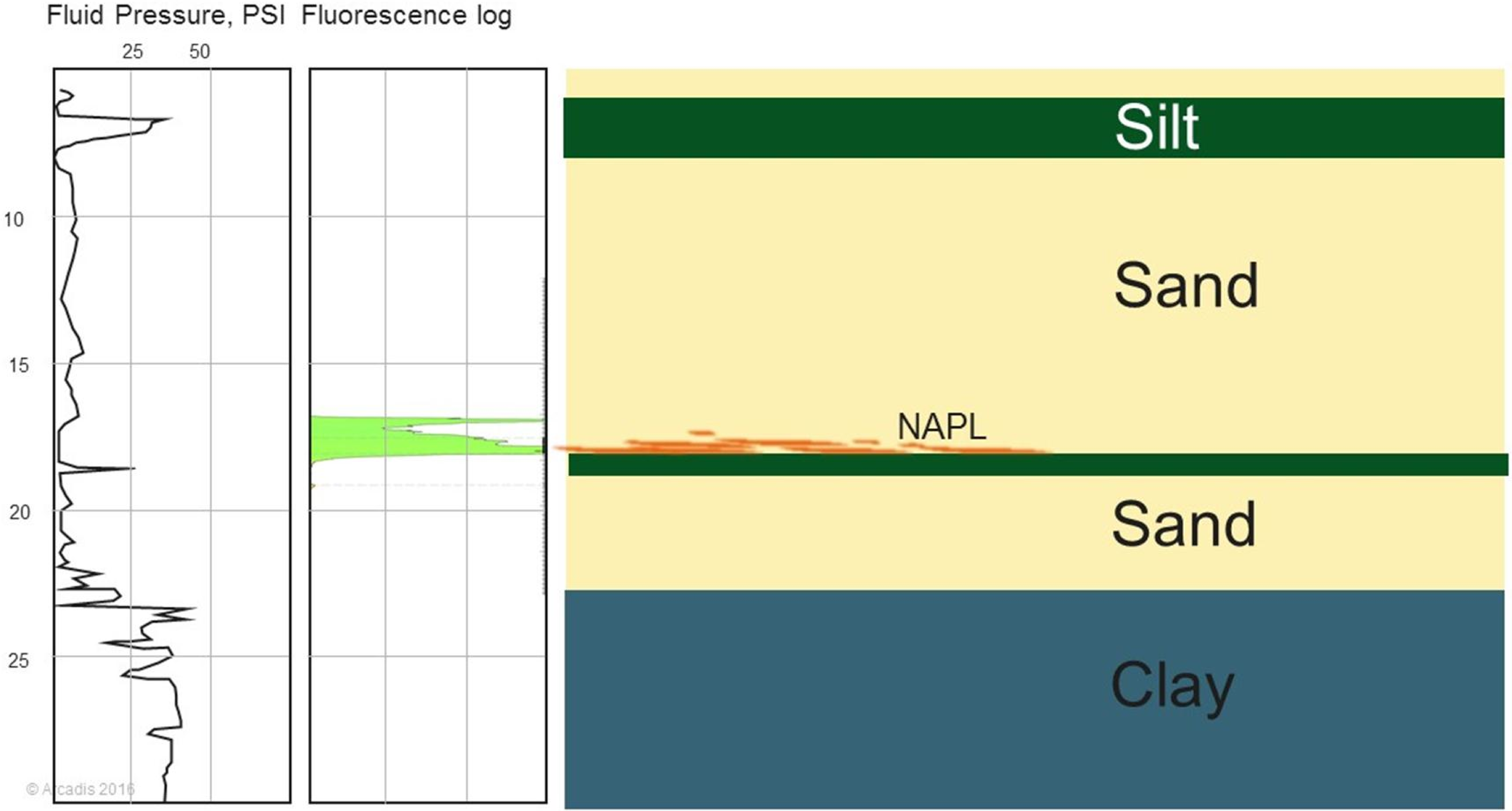
Longitude / Fix: Unavailable / NA

Max signal: 75.2 % @ 9.41 ft

Job:

Operator/Unit: DT/UVOST1003

Date & Time:


Fluid Pressure, PSI
Fluorescence log
25
50
10
15
20
25
Silt
Sand
NAPL
Sand
Clay

Vertical Aquifer Profiling (VAP)

What is it?

Dissolved phase groundwater sampling

What does it provide?

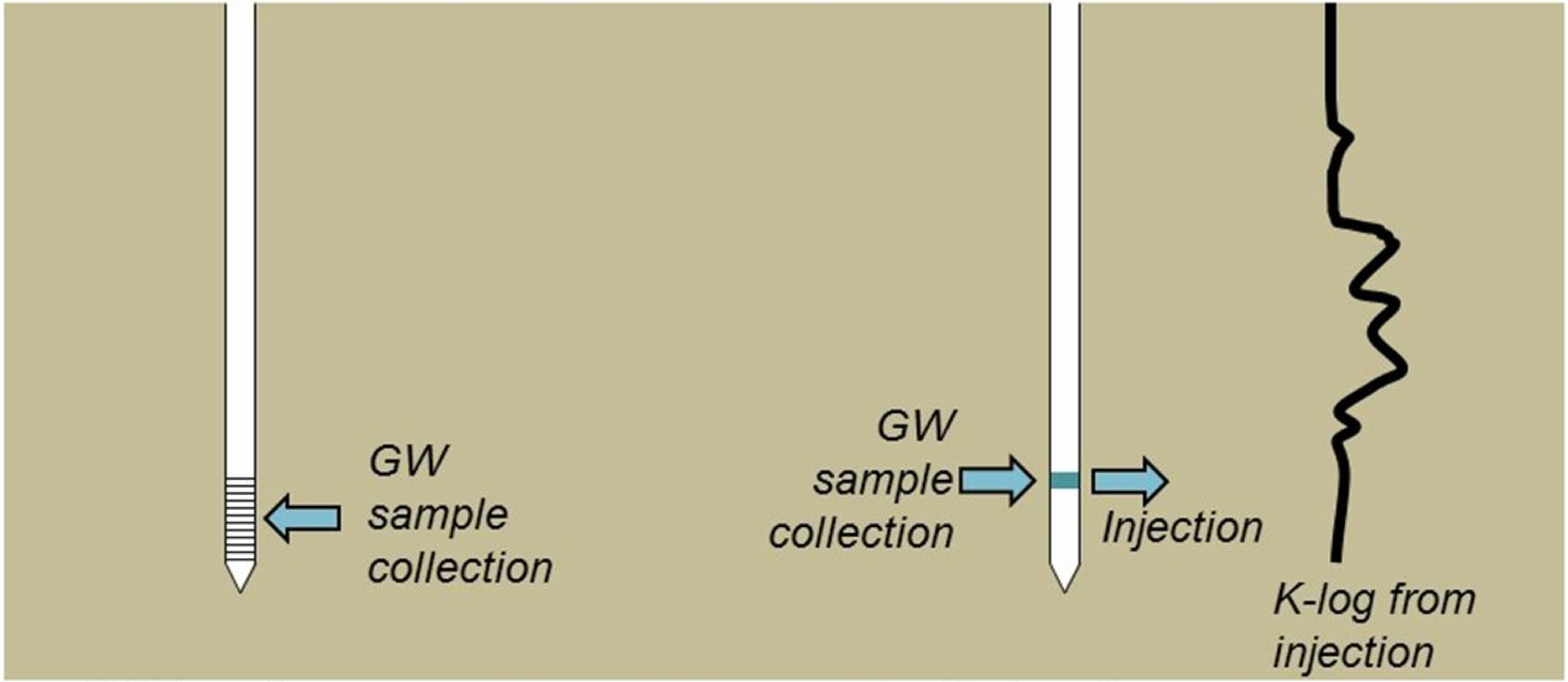
Concentration profile across depth of aquifer

Methods:

- Screen-based
- Combo w/ permeability-profiling tools

Screen-Based

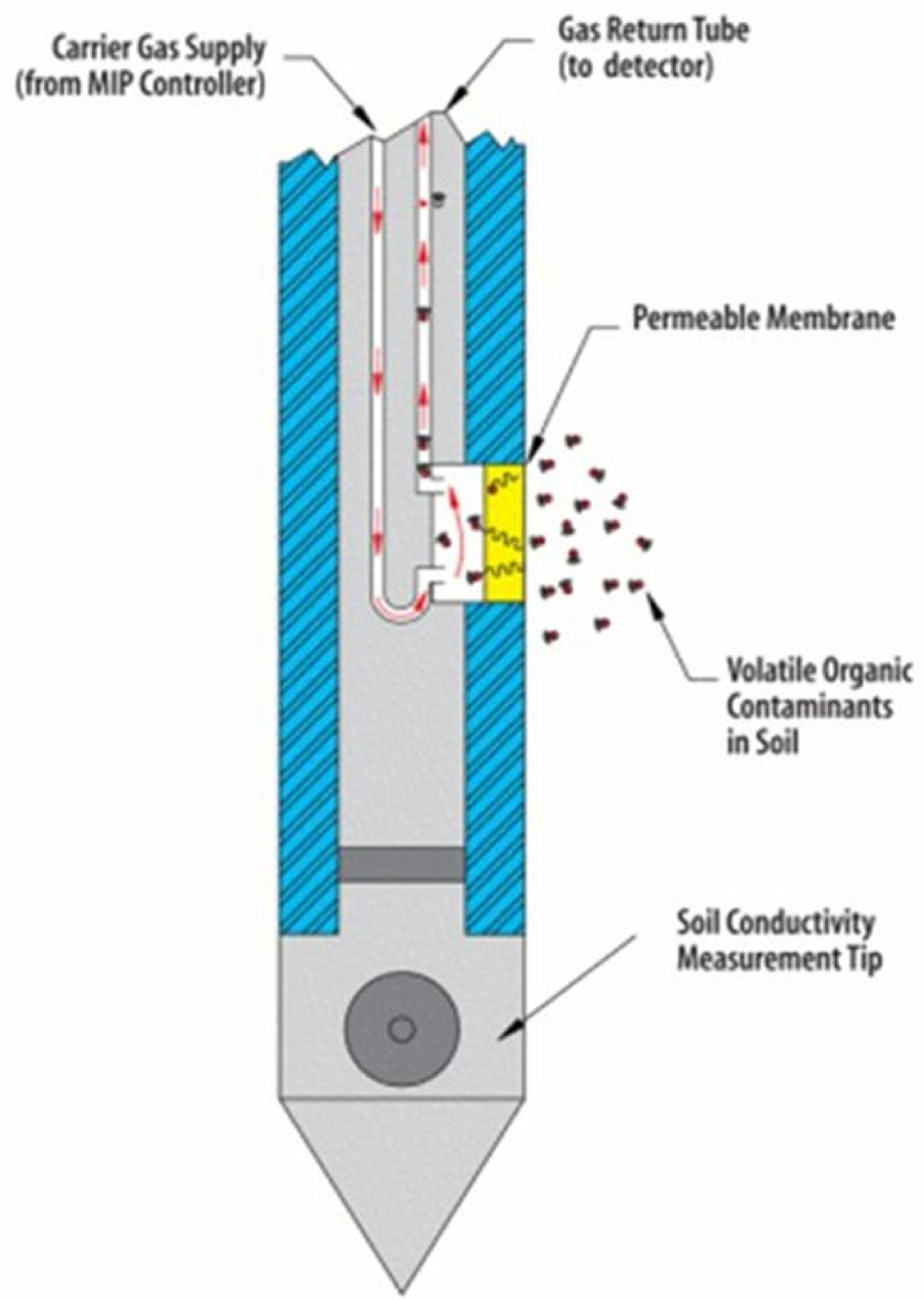
Waterloo/HPT-GW



Multiple-push	Single-push
Able to sample moderate-lower K	Slow/no sampling in moderate-lower K zones
Cost-effective for lower #s of samples	Cost-effective for higher #s of samples
No K-data integrated	K-data integrated
Slug-testing possible	No slug testing

Depths: 100+ ft reachable with direct-push 8040 rigs

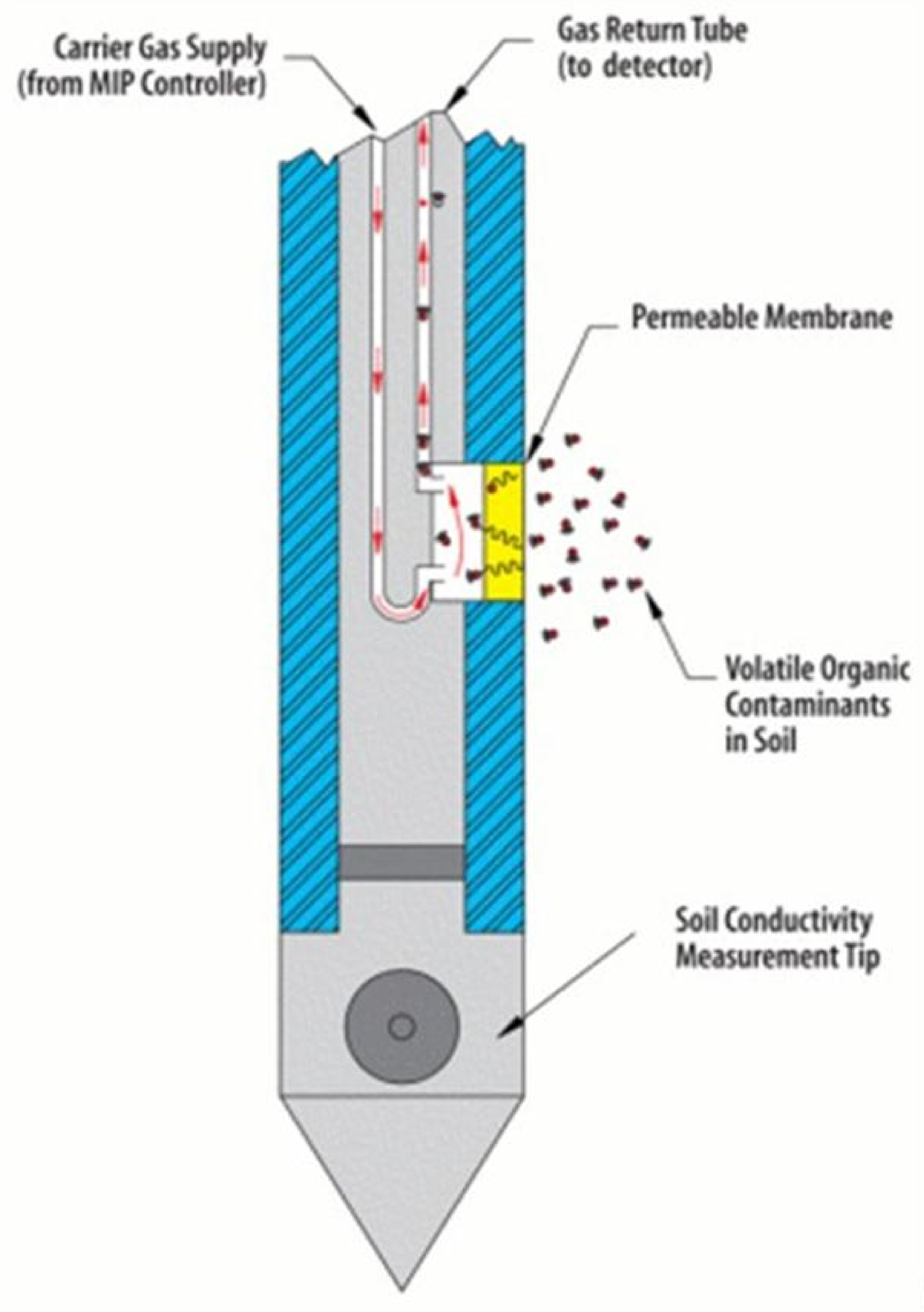
Membrane Interface Probe (MIP)



MIP changed the rules…

Prior to MIP, conventional wisdom was **NOT** to sample soil below water table

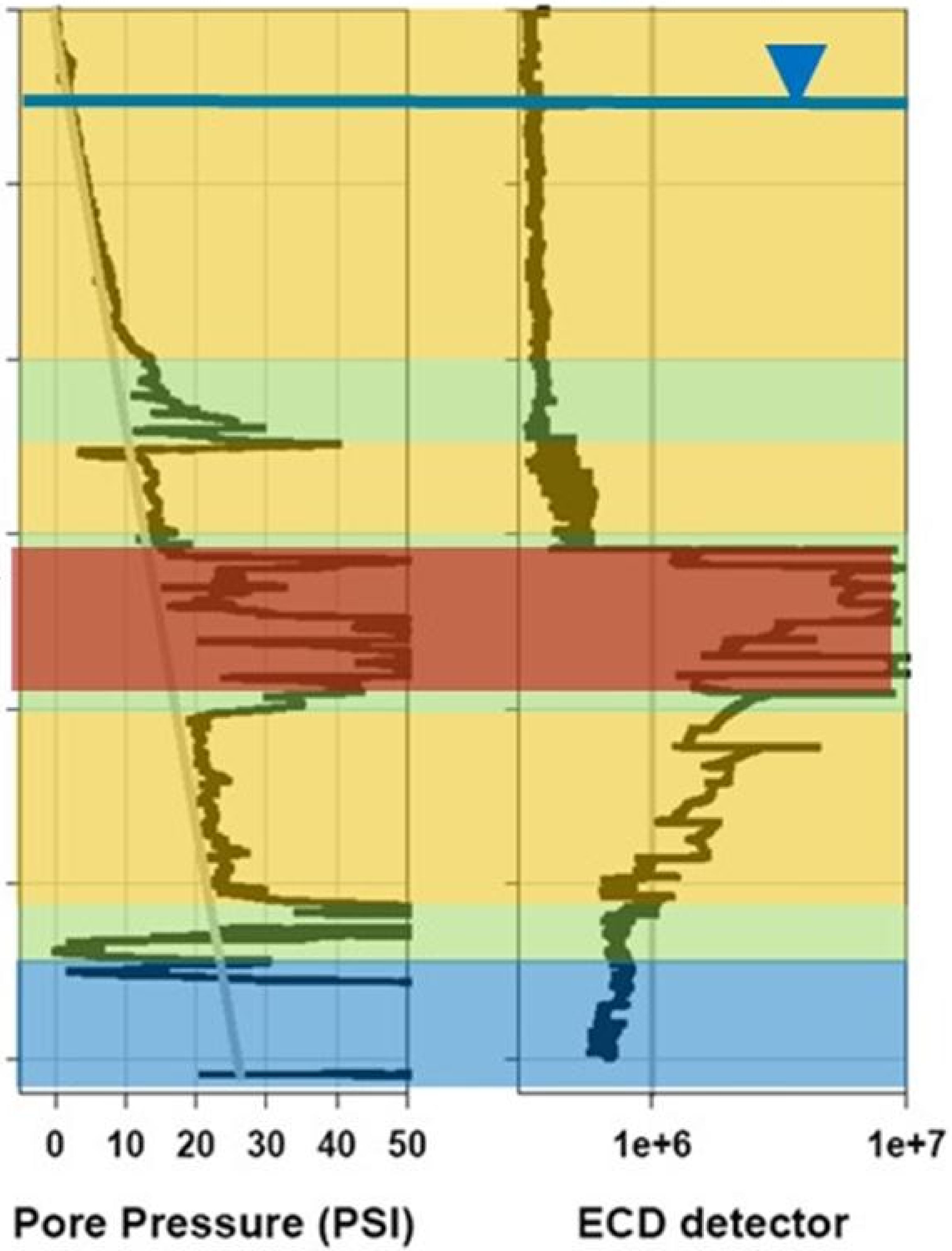
…and we couldn't sample groundwater in low-K formations



We never knew what we were missing…

- Provided insights about mass distribution in low-K storage zones
- Changed our CSM to re-evaluate importance of diffusion in our transport framework

Low-K zone with more than 90 % of mass and less than 1% of flow



Design & Consultancy for natural and built assets

MIP is a great screening tool, but…

MIP is more than just concentration:

Concentration

+ Composition

+ Aquifer permeability and geology

+ Membrane variability

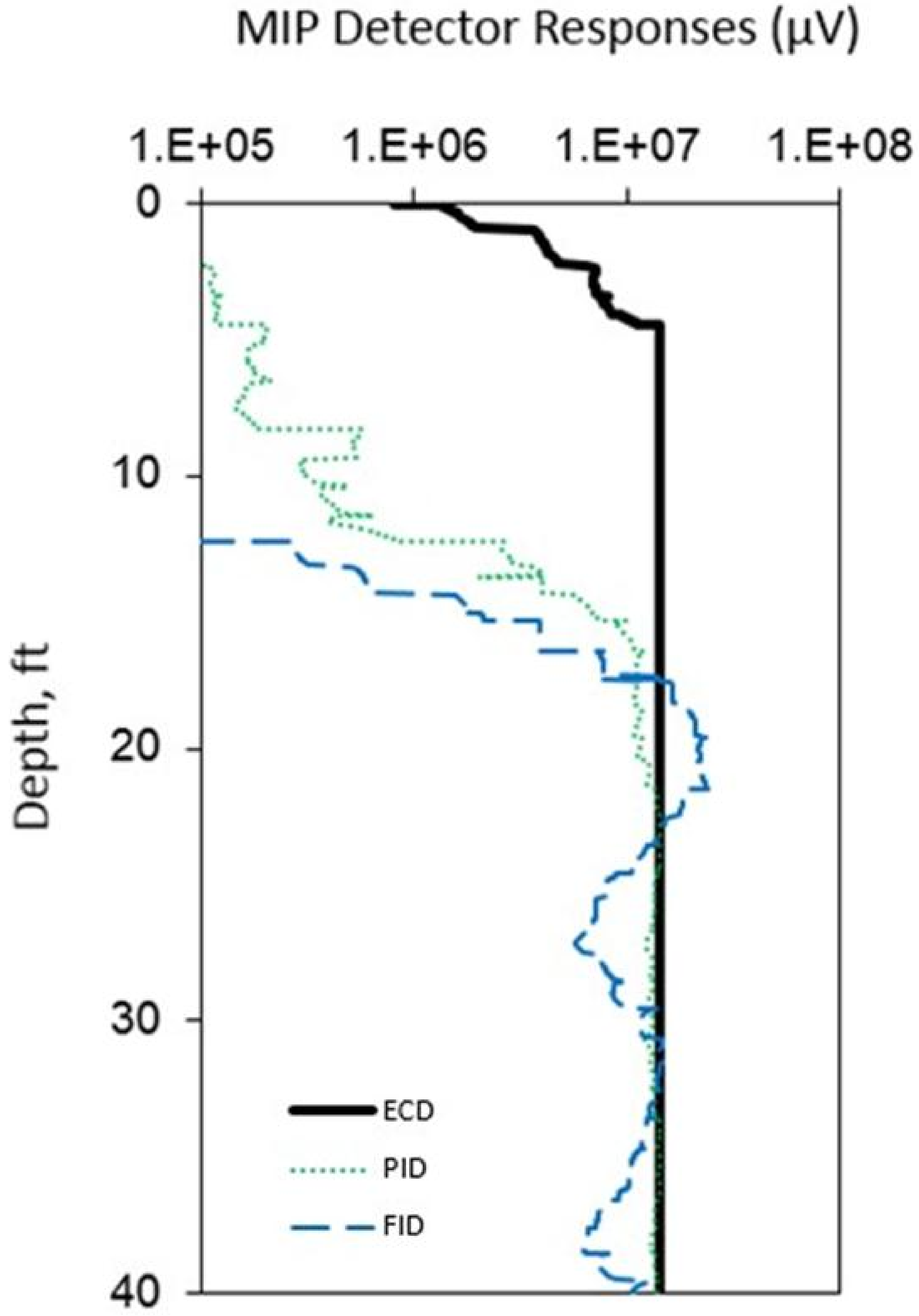
+ NAPL presence/absence

MIP RESPONSE

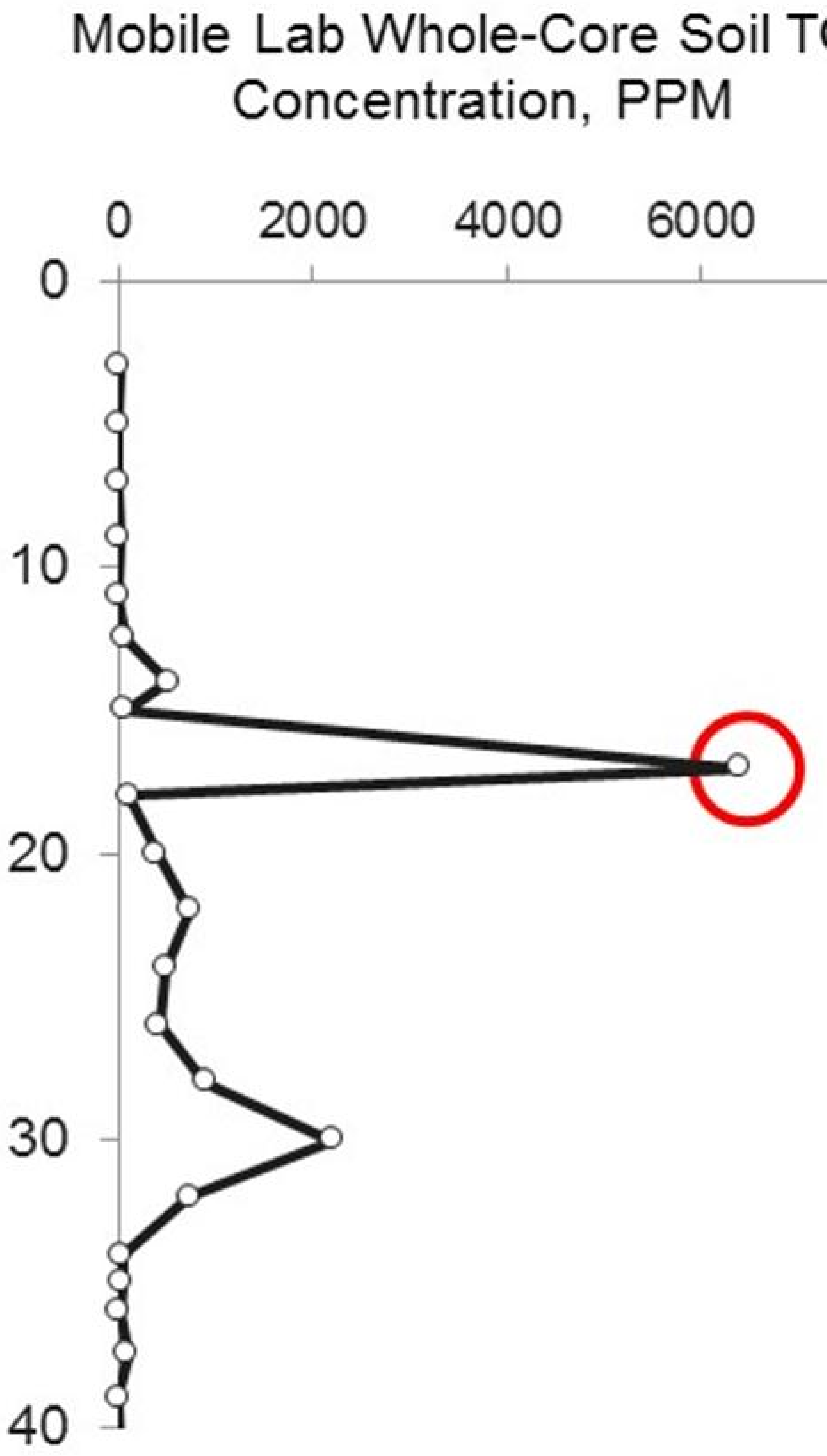
MIP is not quantitative

- Cannot use output to design remedy or delineate plume/NAPL

Data from a DNAPL Source Zone



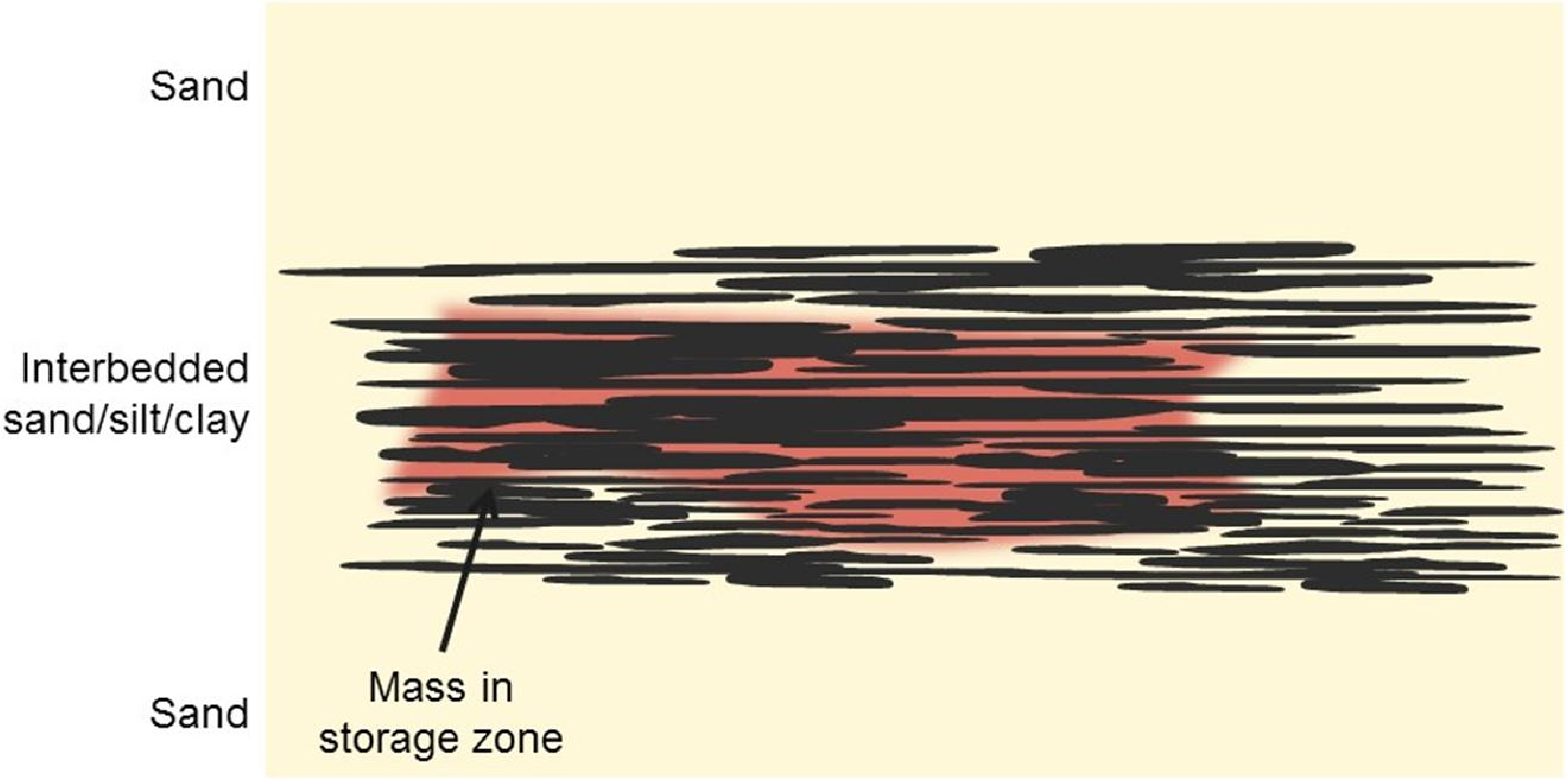
MIP Detector Responses (µV)

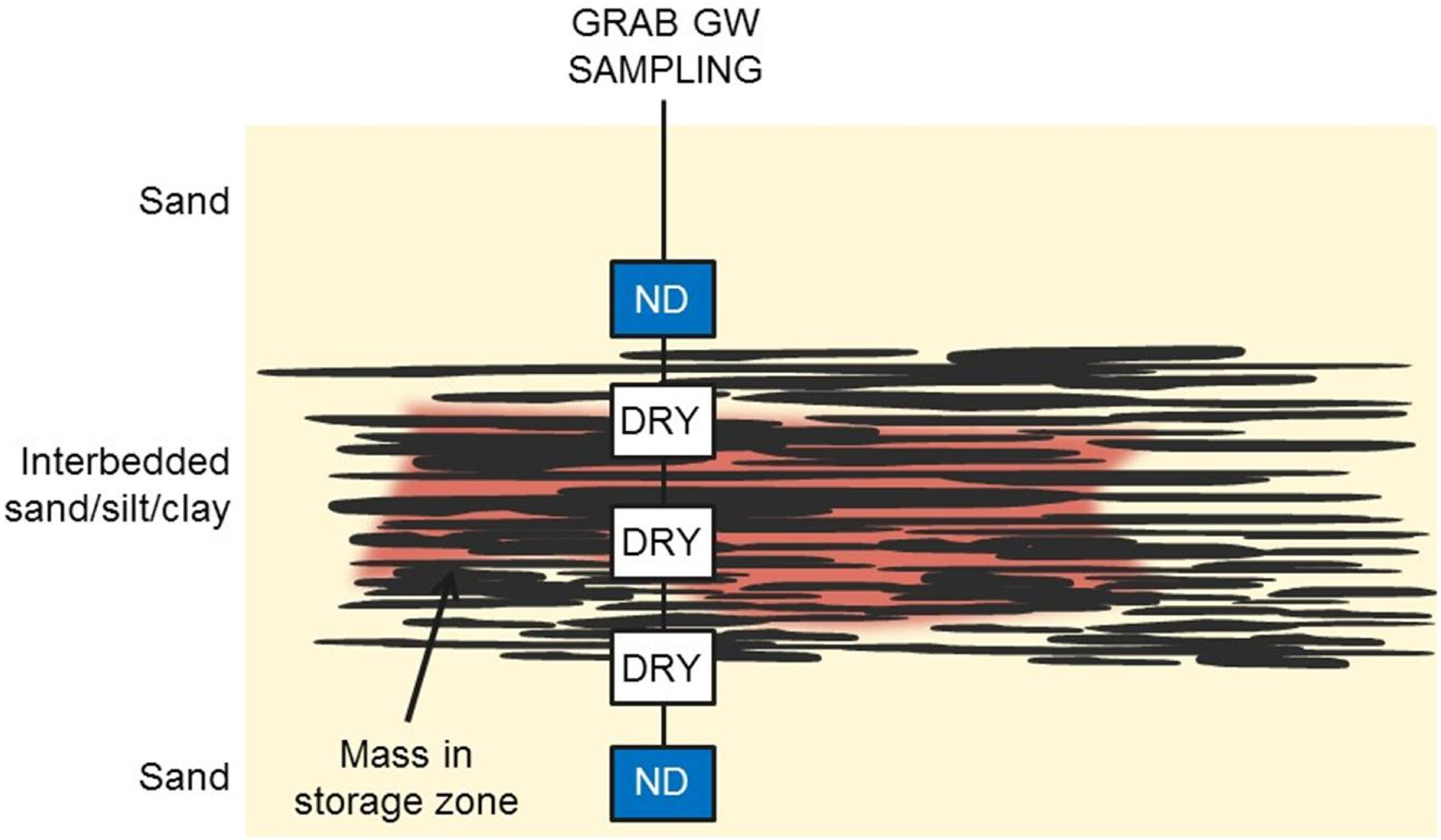


Mobile Lab Whole-Core Soil TCE Concentration, PPM

Positive NAPL result

How do you see mass in storage zones?





GRAB GW SAMPLING

Sand

ND

DRY

Interbedded sand/silt/clay

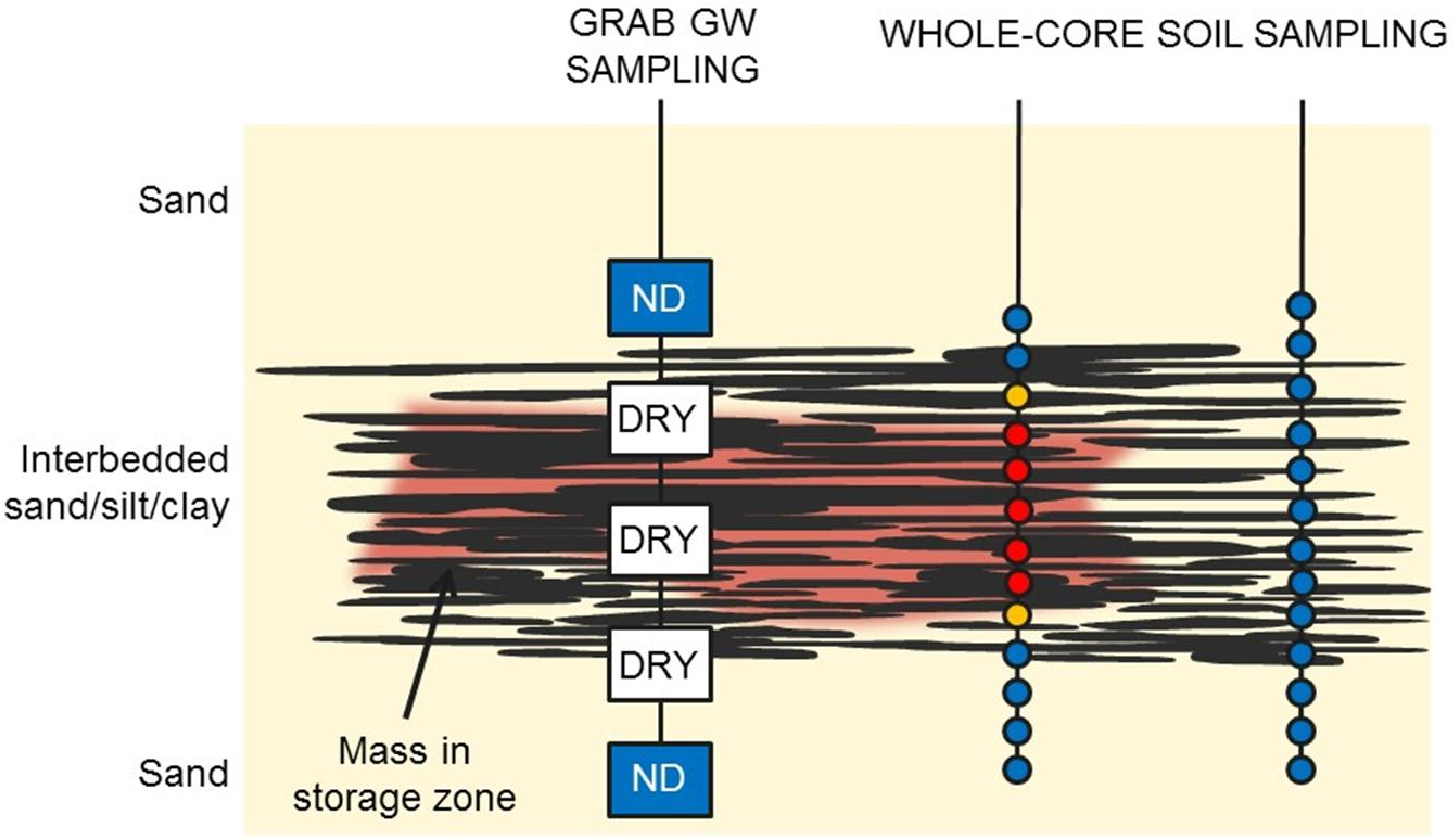
DRY

DRY

Mass in storage zone

Sand

ND



What is it?

High-resolution, saturated soil samples

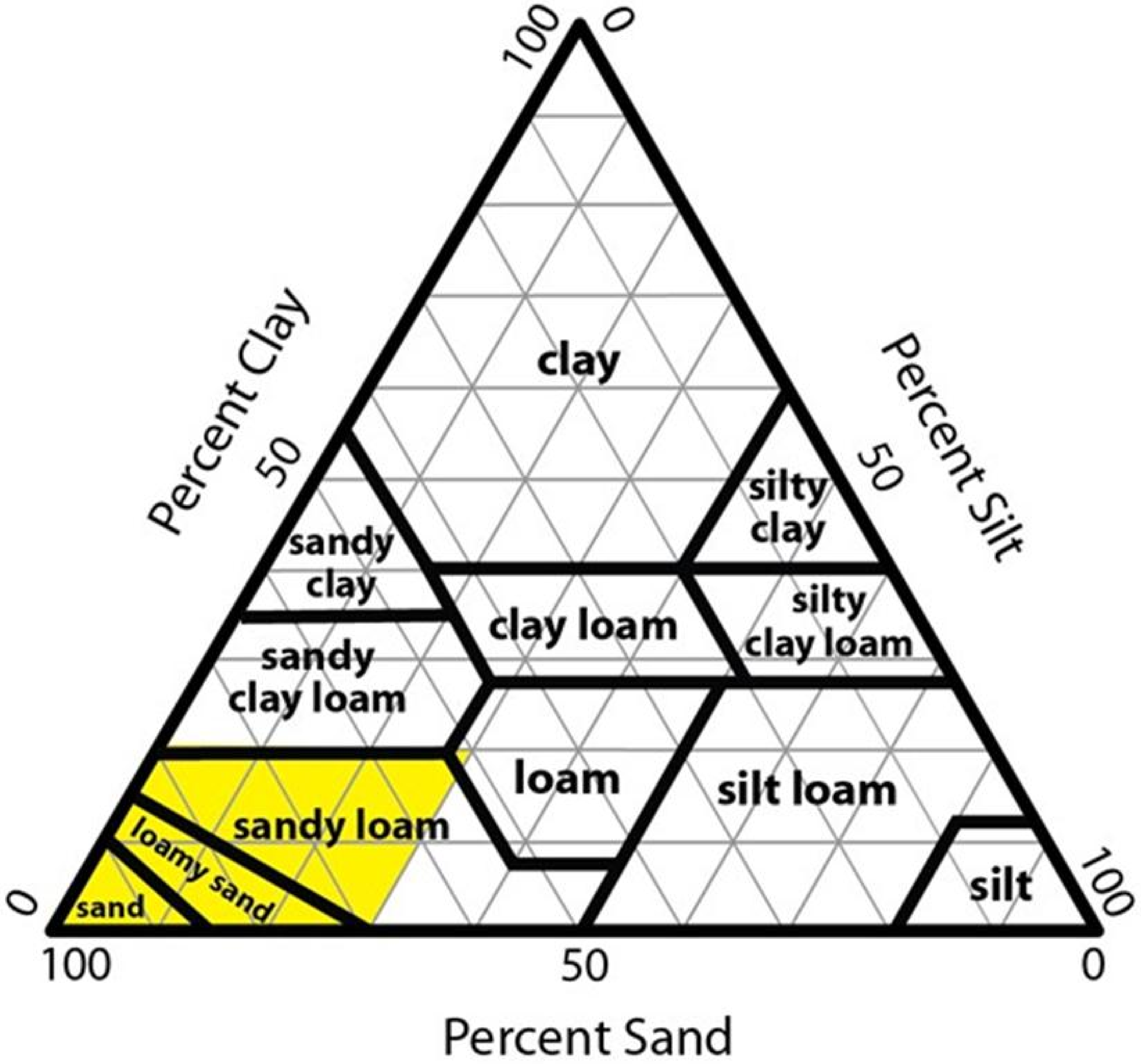
Analyzed like a typical soil sample

Stratigraphic Flux

Where the Groundwater Flows…

Most soil types are not aquifer material

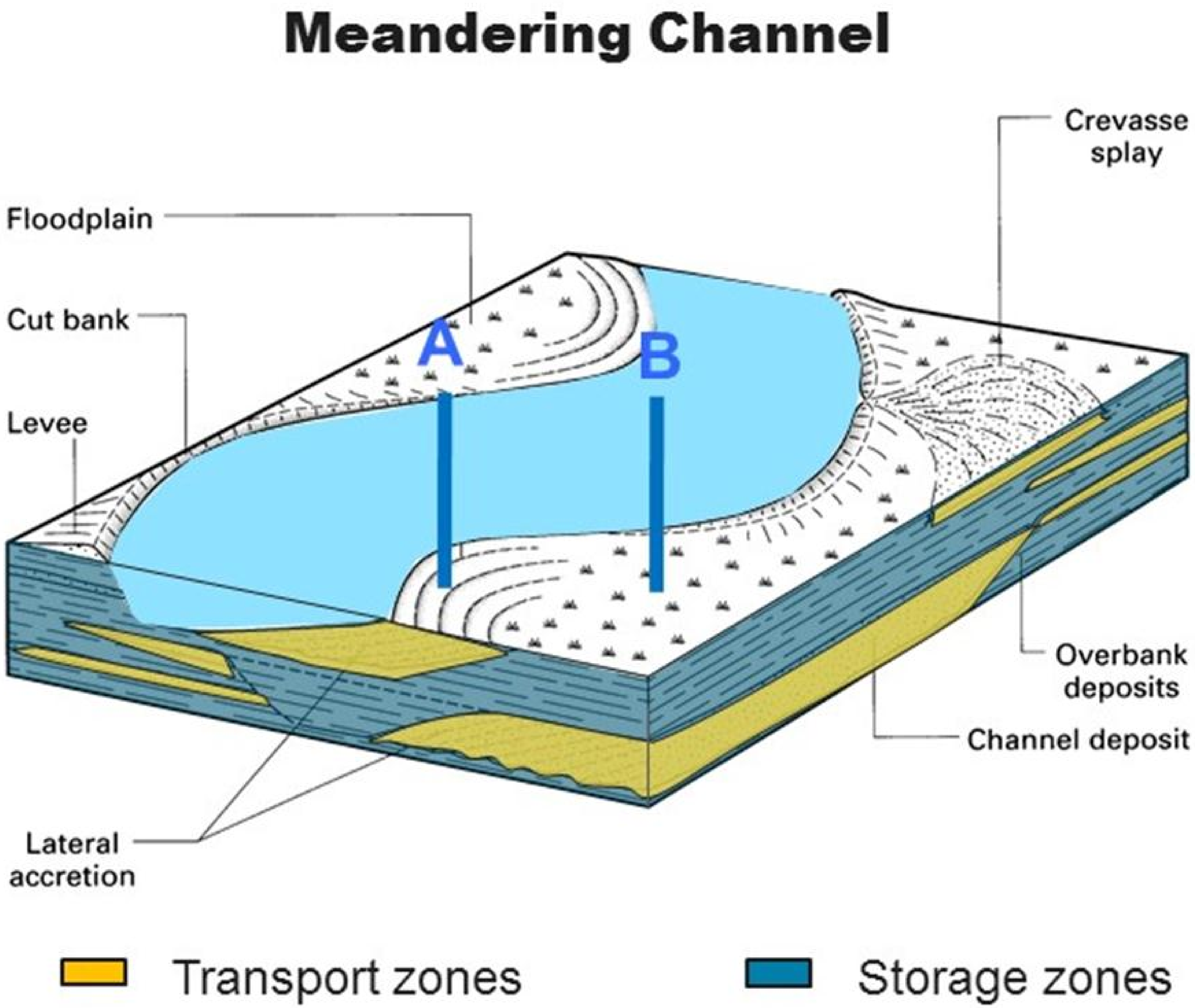
- The aquifer matrix is laid down in high-energy environments
- High-energy environments are heterogeneous and anisotropic



Stratigraphic Flux

Link mass flux analysis with classical geological interpretation to describe the 3-D aquifer architecture

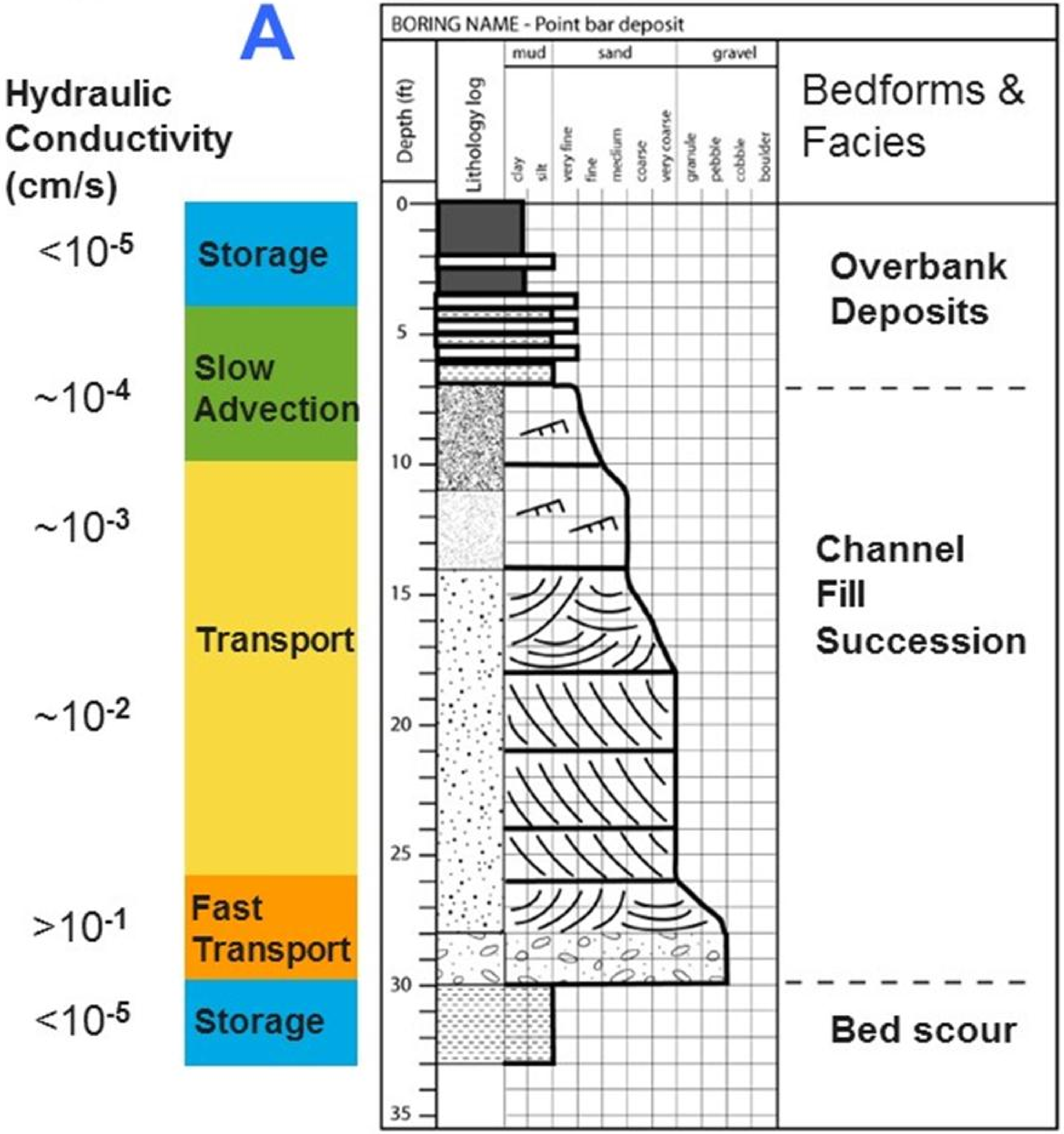
- Focus evaluation on zones that matter
- Helps prioritize remediation efforts



Facies and Permeability

Detailed soil descriptions key:

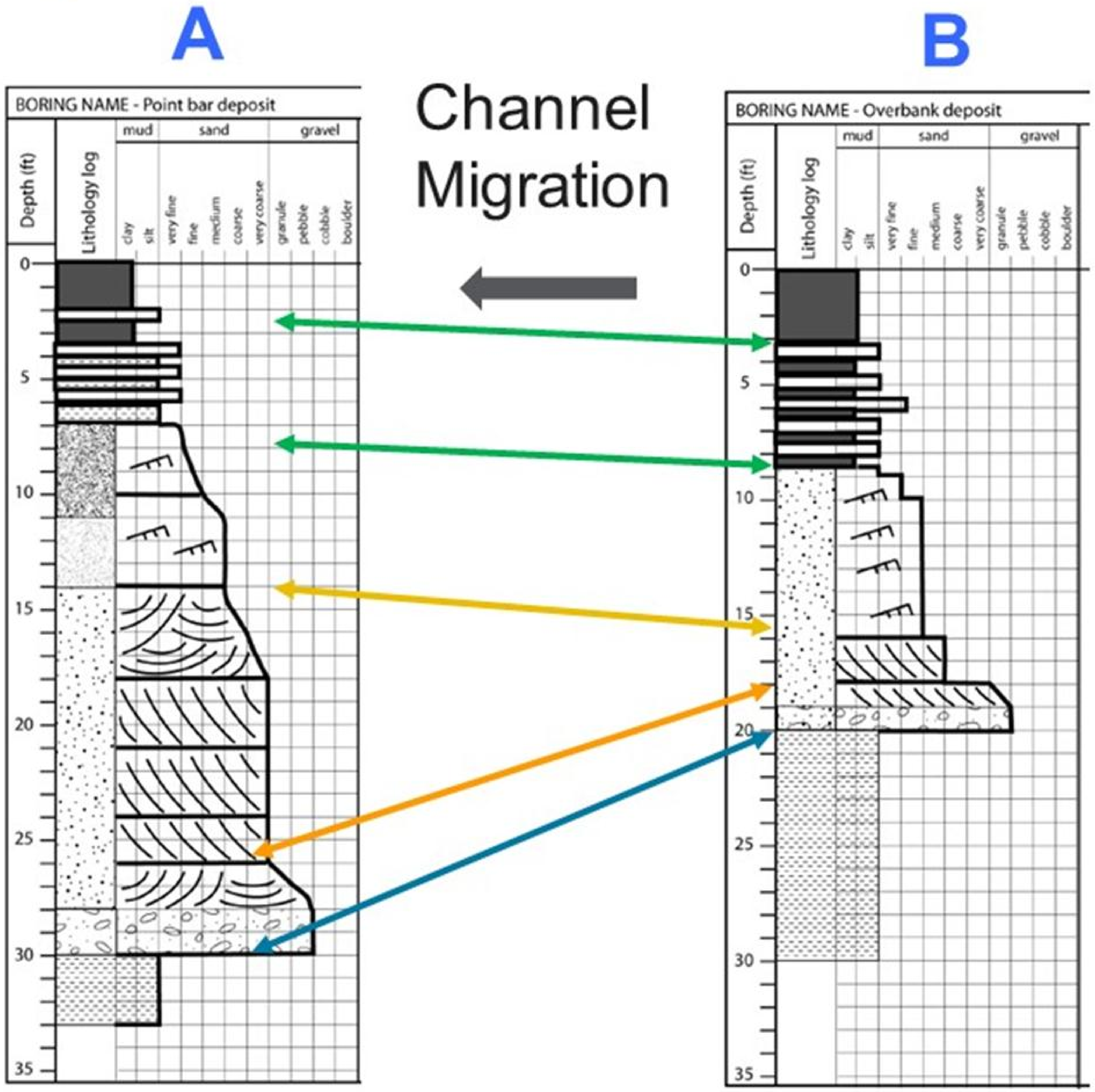
- High permeability, coarse grained at base
- Decreasing permeability & grain size toward top
- 5+ orders of magnitude variability in K



Basis for Interpolating Borings

Accretion from right to left:

- Depositional environment allows for better interpretation between borings
- Provides first basis for the interpretation of stratigraphic flux – transport vs storage

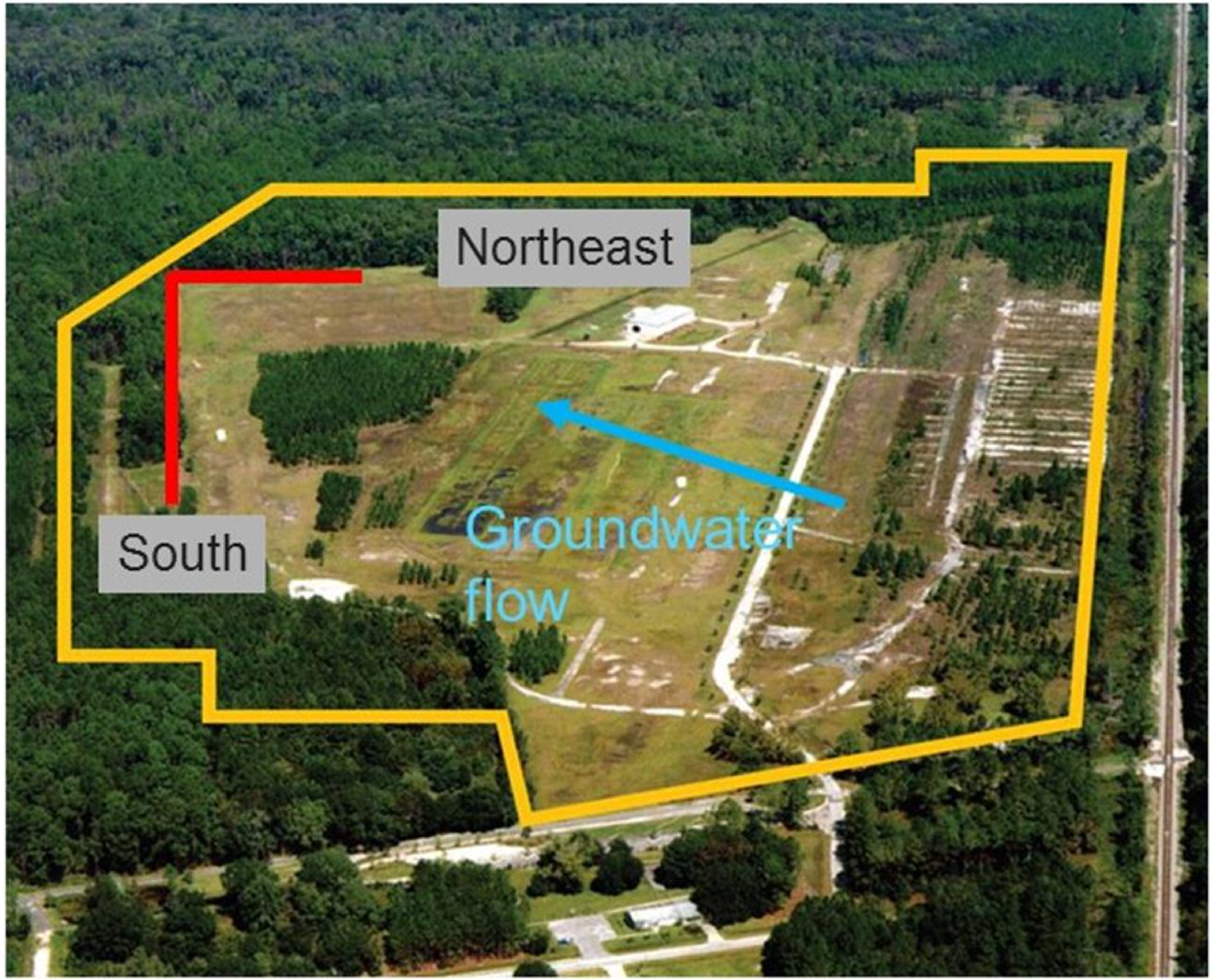


Case Study: Flux Based Optimization of P&T System

Scope

Optimize capture of existing P&T system

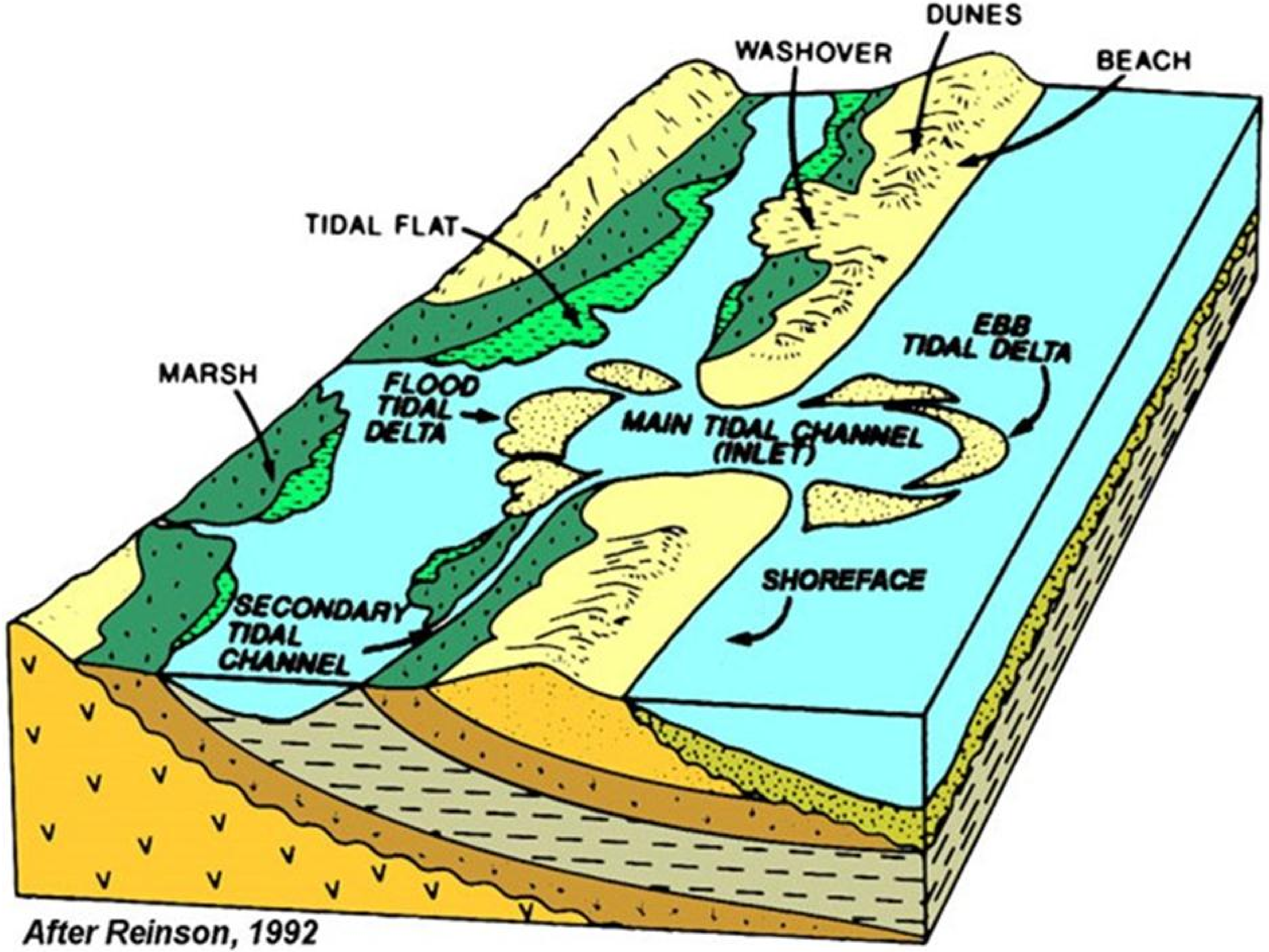
- Stratigraphic flux transect around northwest corner of property
- HPT for relative K
- Vertical aquifer profiling for concentration



Geologic Setting

Sea Island Section of Atlantic Coastal Province:

- barrier islands
- salt marsh deposits
- streams

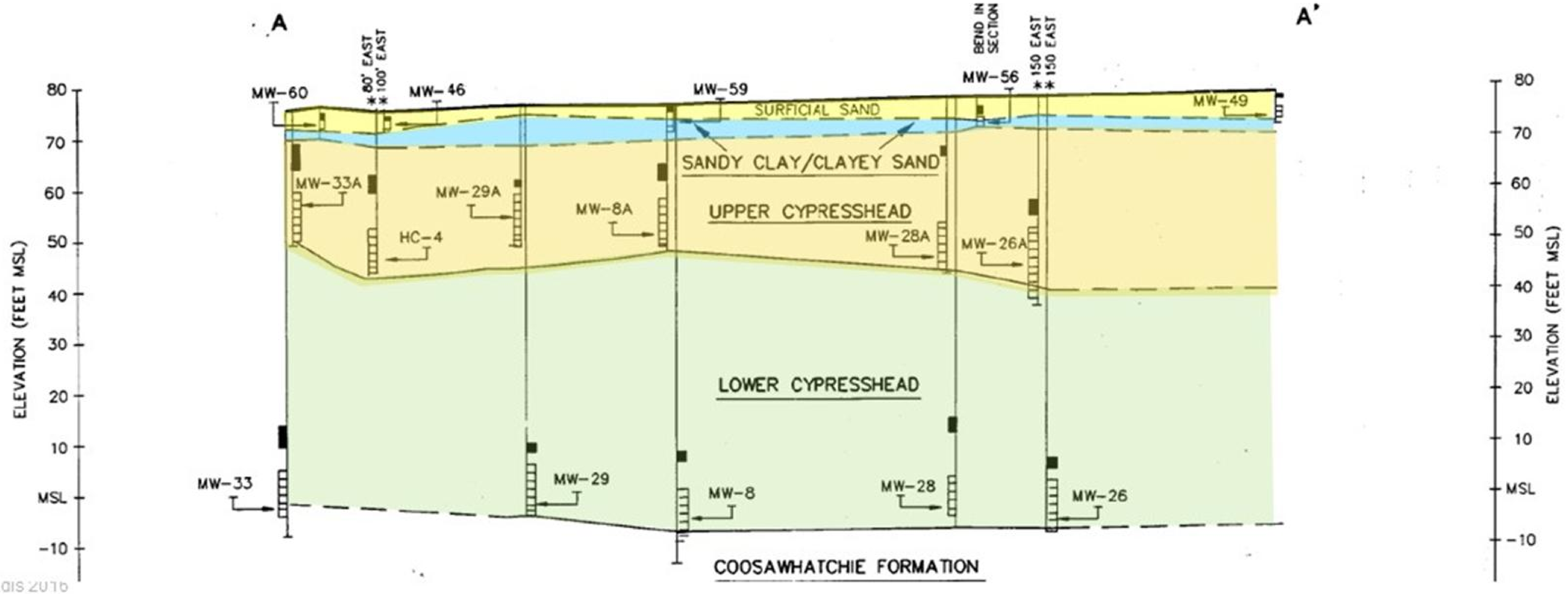


After Reinson, 1992

Geologic Setting

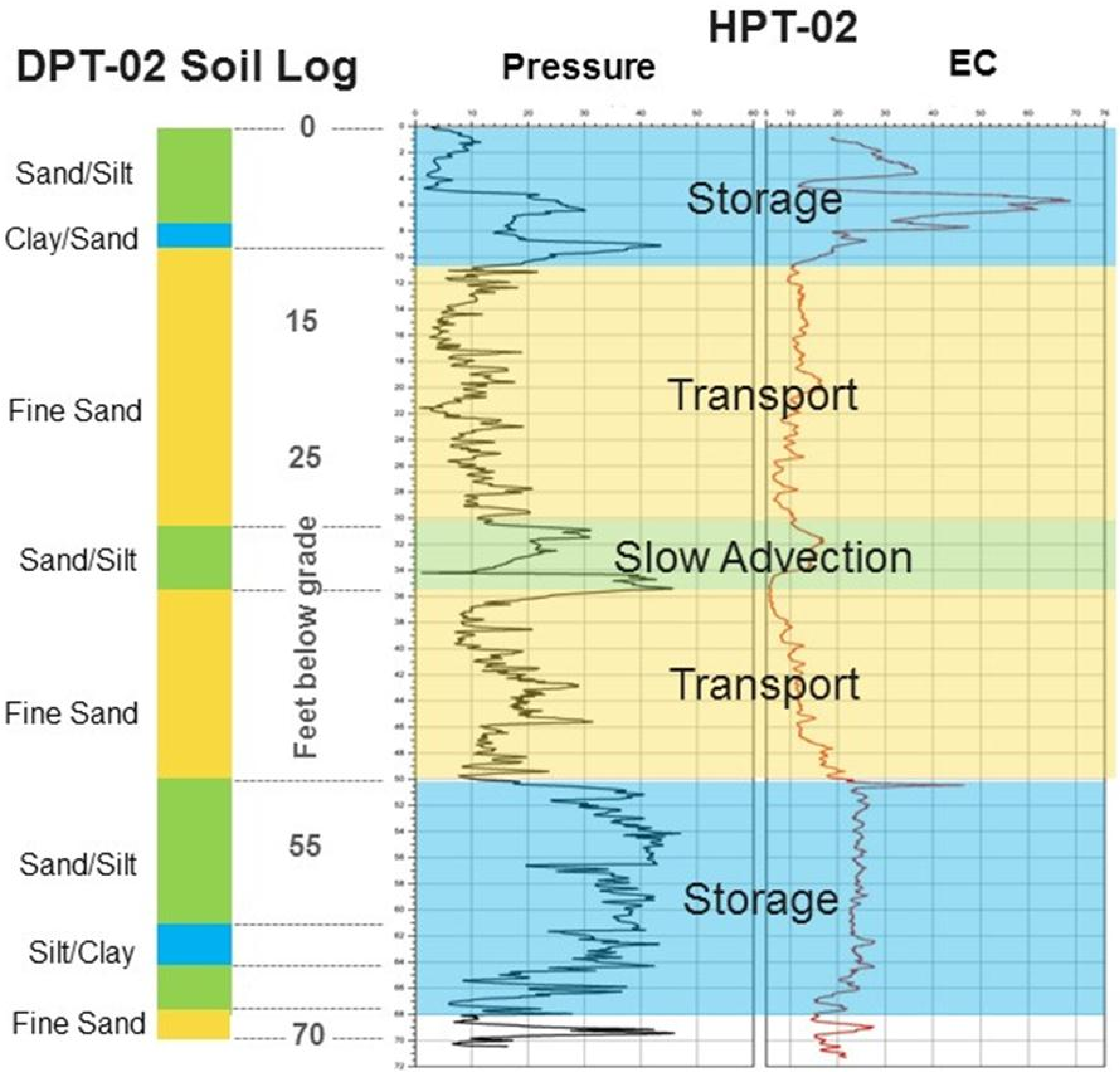
Cypresshead Formation:

- Upper – “massively bedded” fine sand
- Lower- greater clay and silt fraction



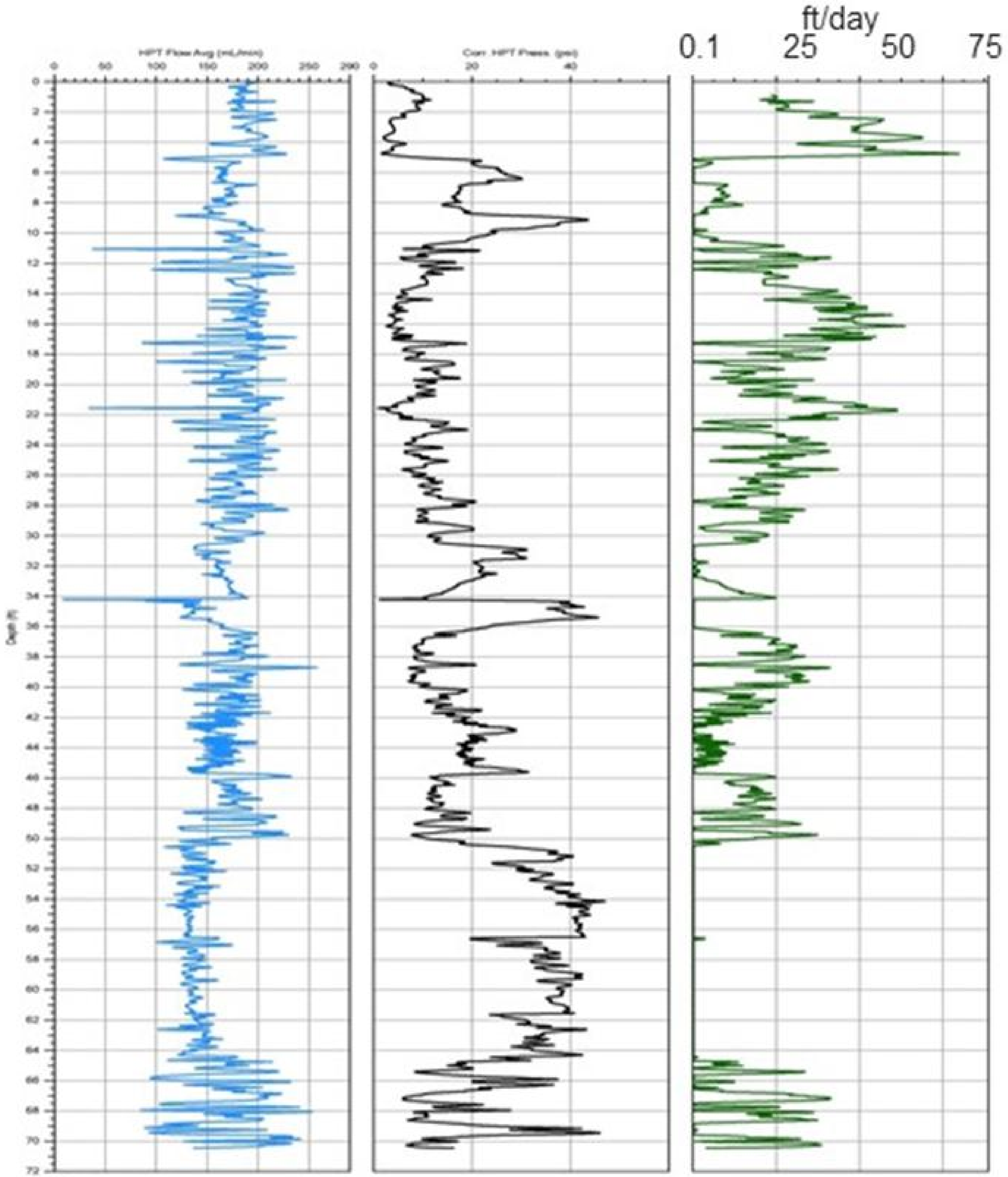
Hydraulic Profiling

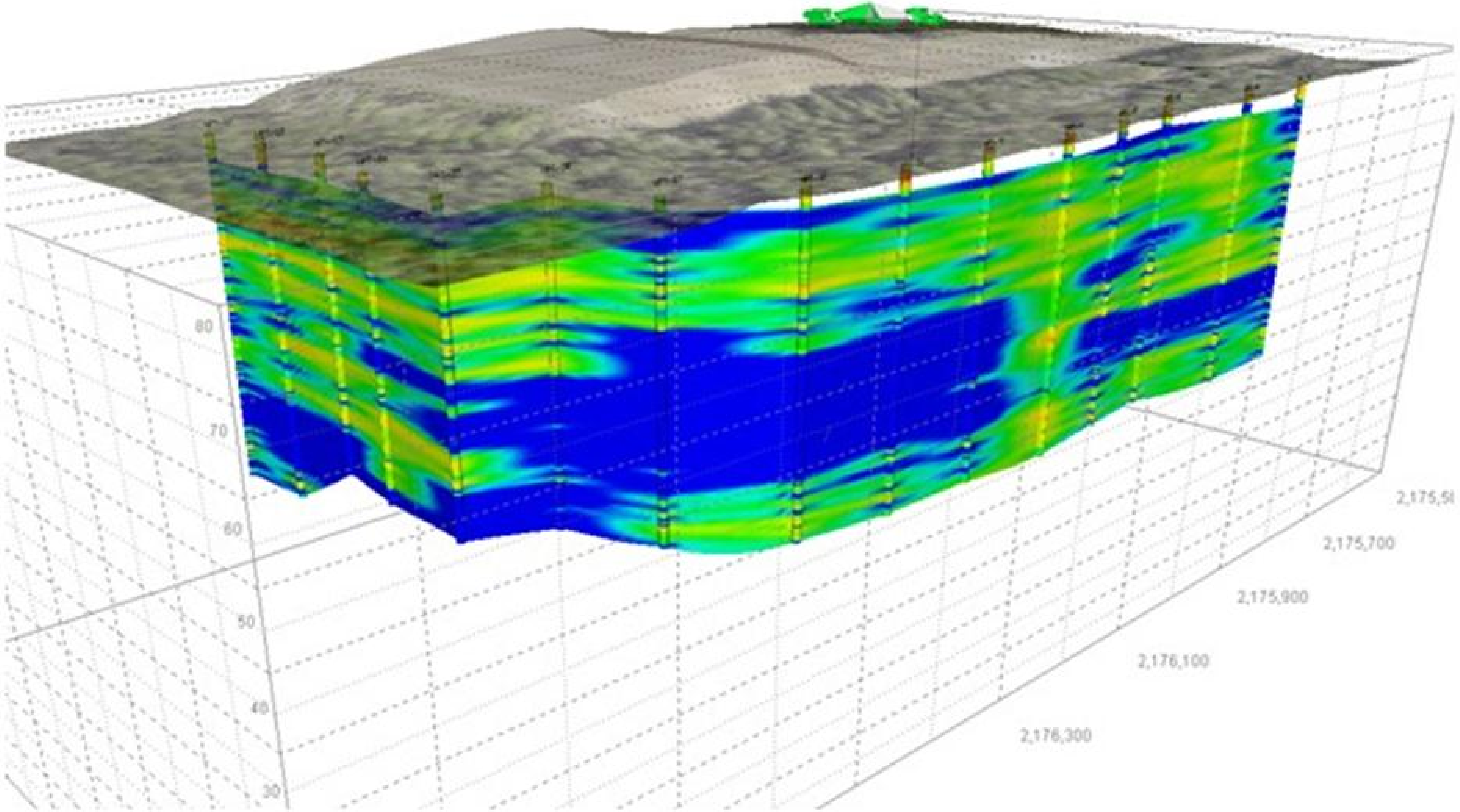
Geoprobe® HPT Tool



Relative K

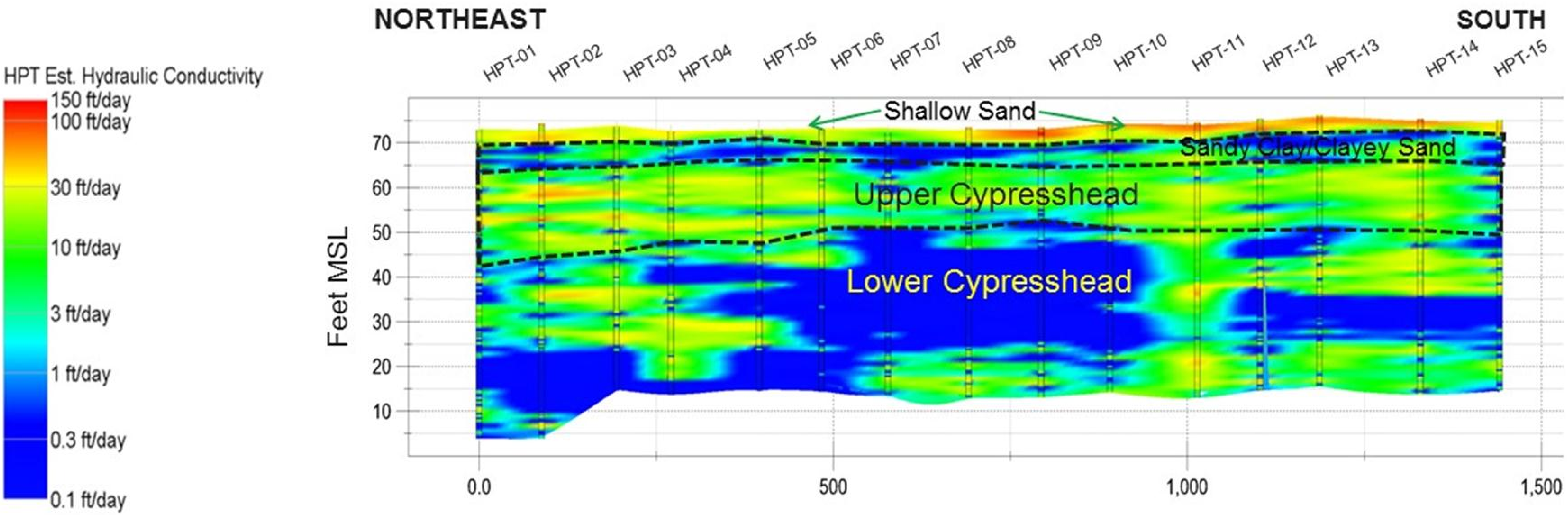
Flow (Q) / Pressure (P) = Est. K (Q/P)





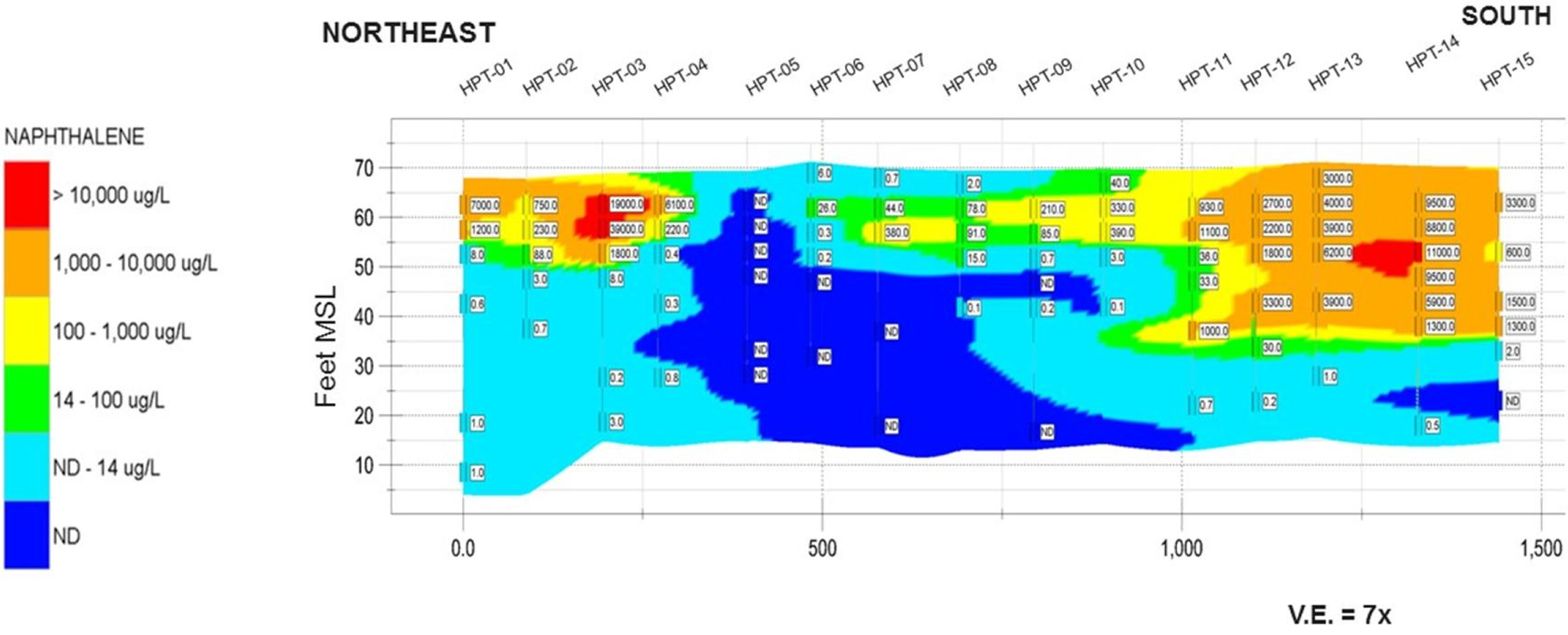
- Q/P corrected based on empirical relationship with slug test data developed by Geoprobe

Stratigraphic Correlation



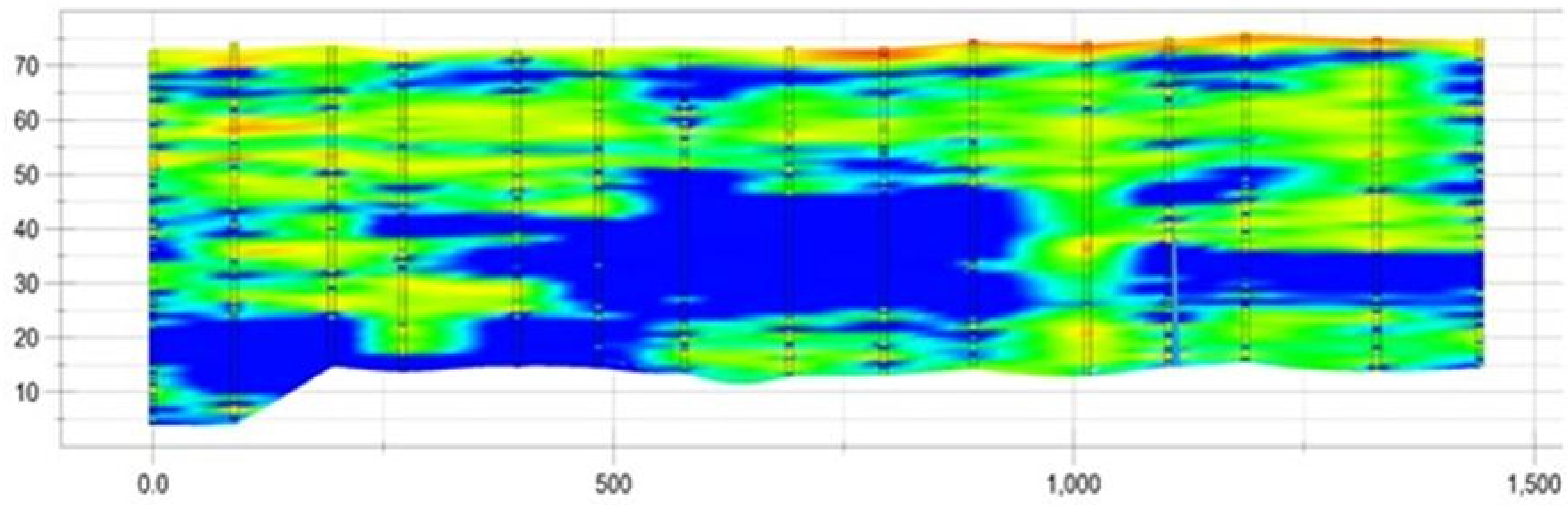
V.E. = 7x

Naphthalene (ppb)



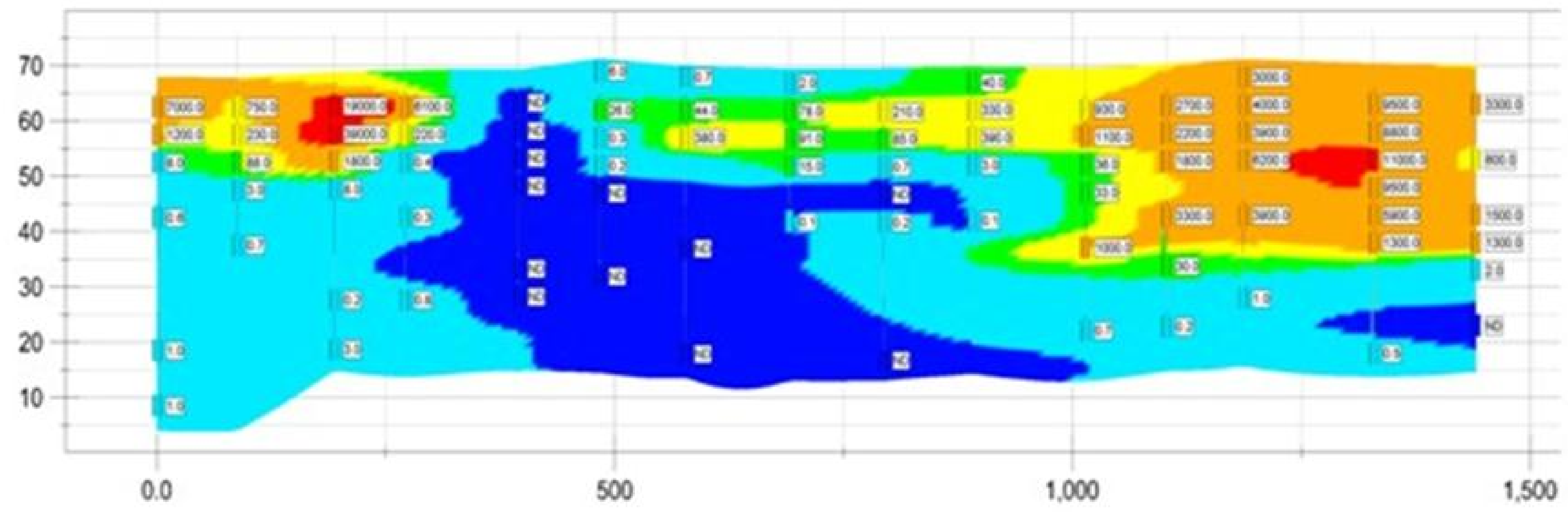
Stratigraphic Flux

Hydraulic Conductivity (K)



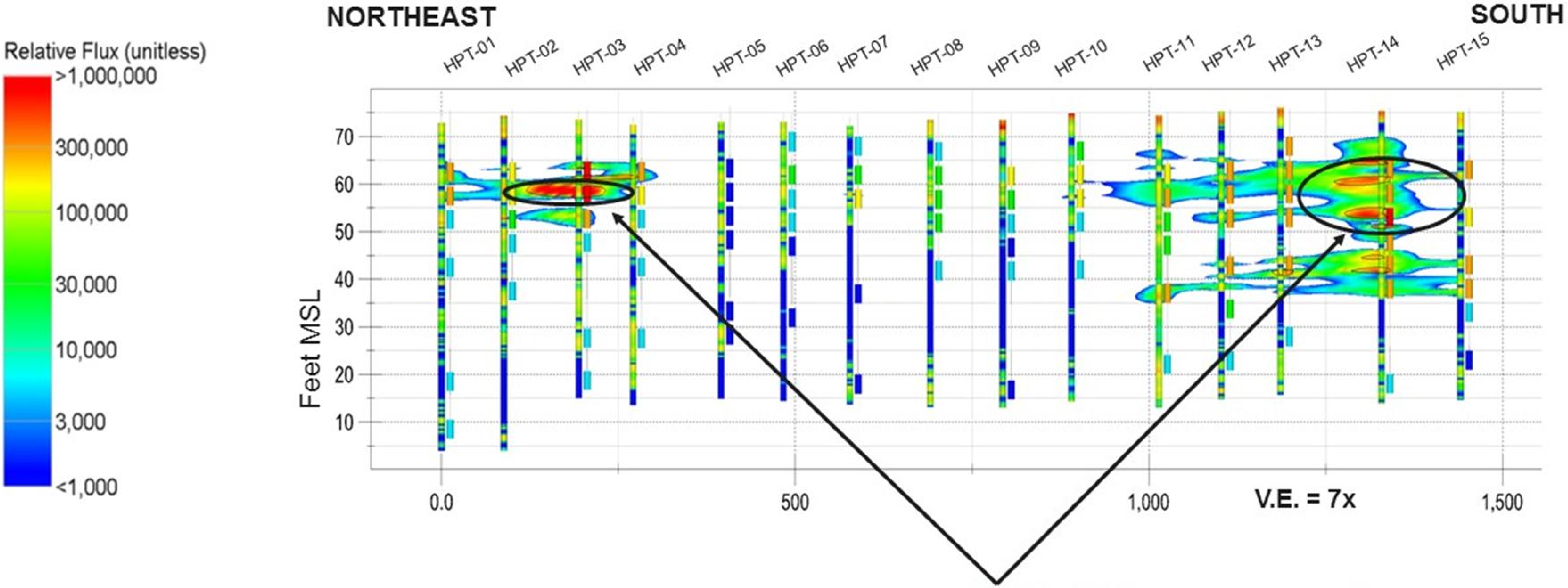
X

Concentration (C)



=

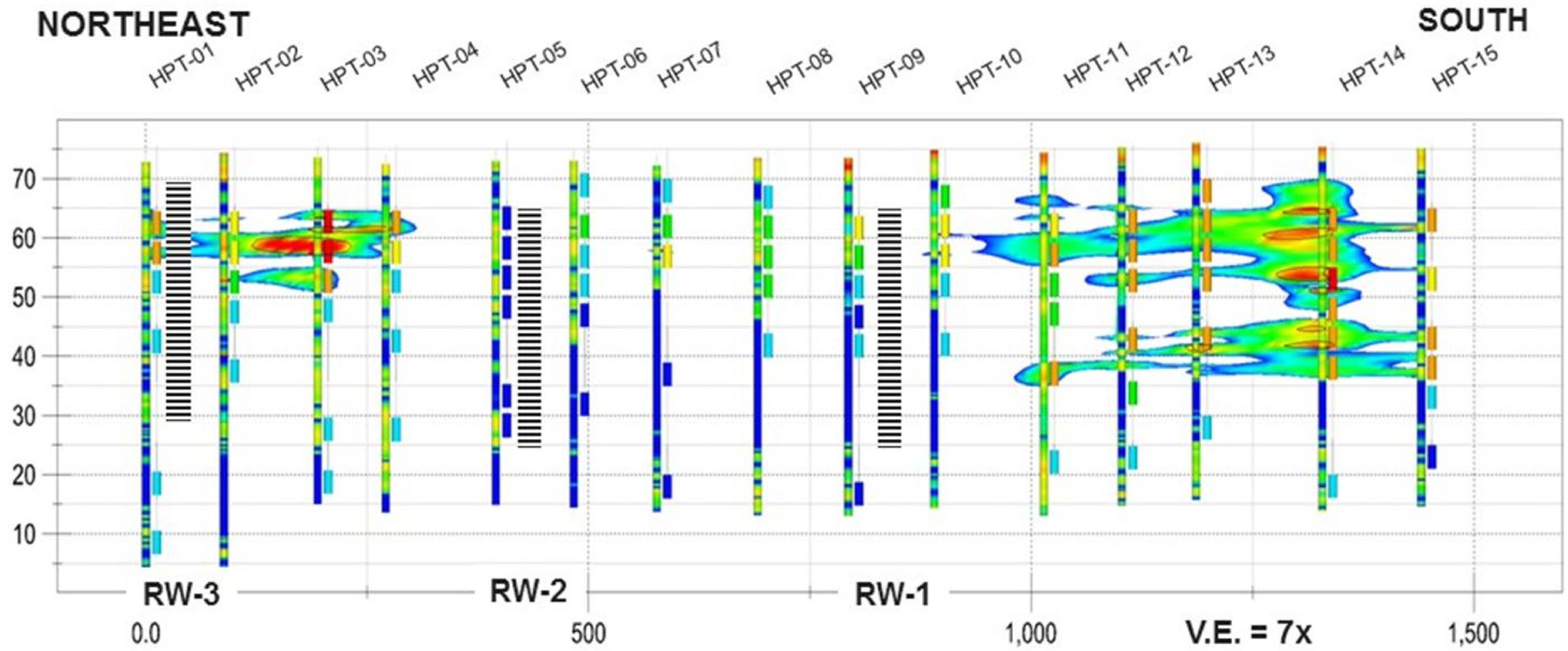
Stratigraphic Flux



90% of flux occurs in 10% of cross-section

Stratigraphic Flux

- Focused flux enables optimization with new options
- Existing recovery wells not co-located with flux



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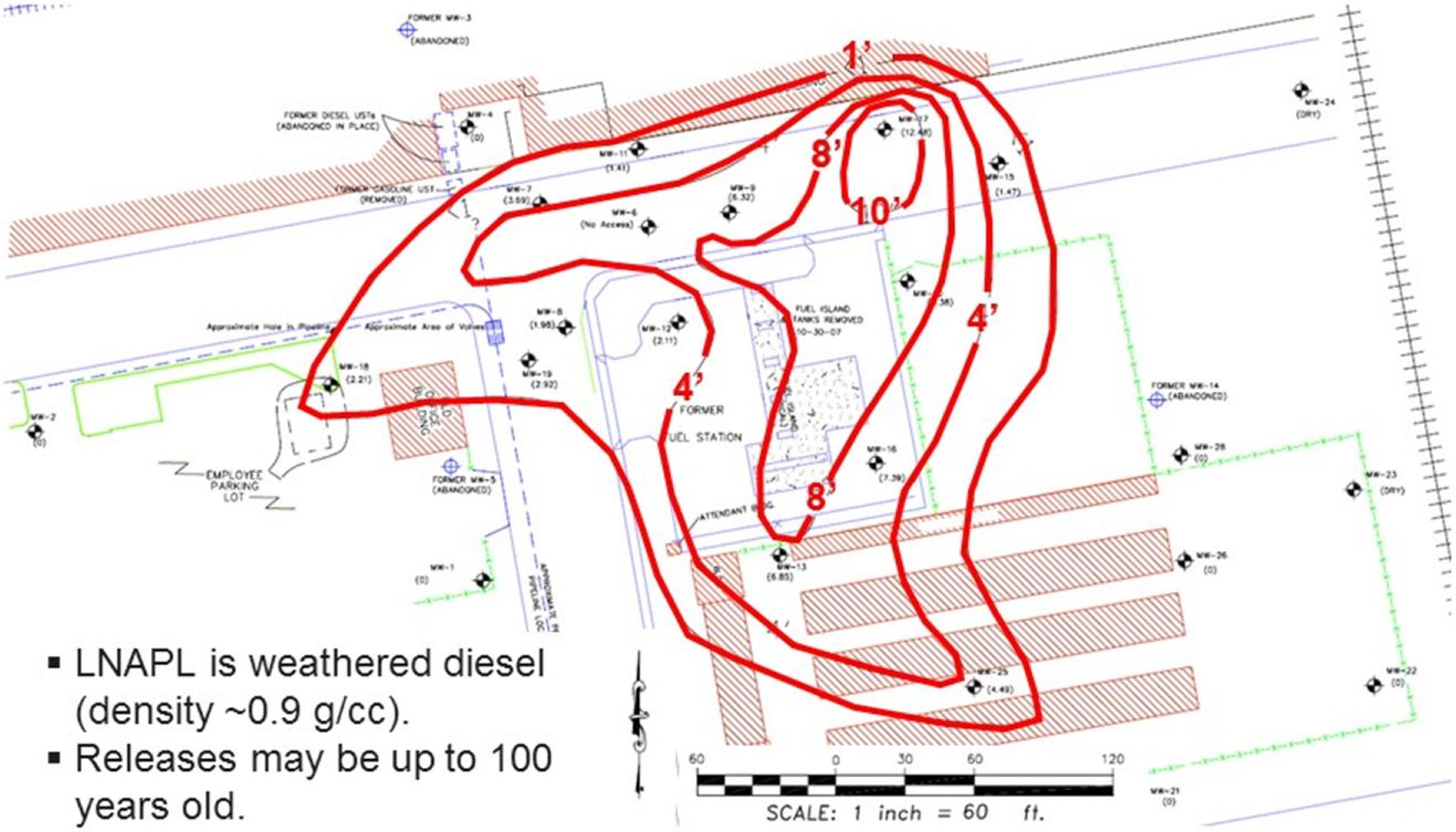
Case Study: Stratigraphic Based Site Strategy Improvement

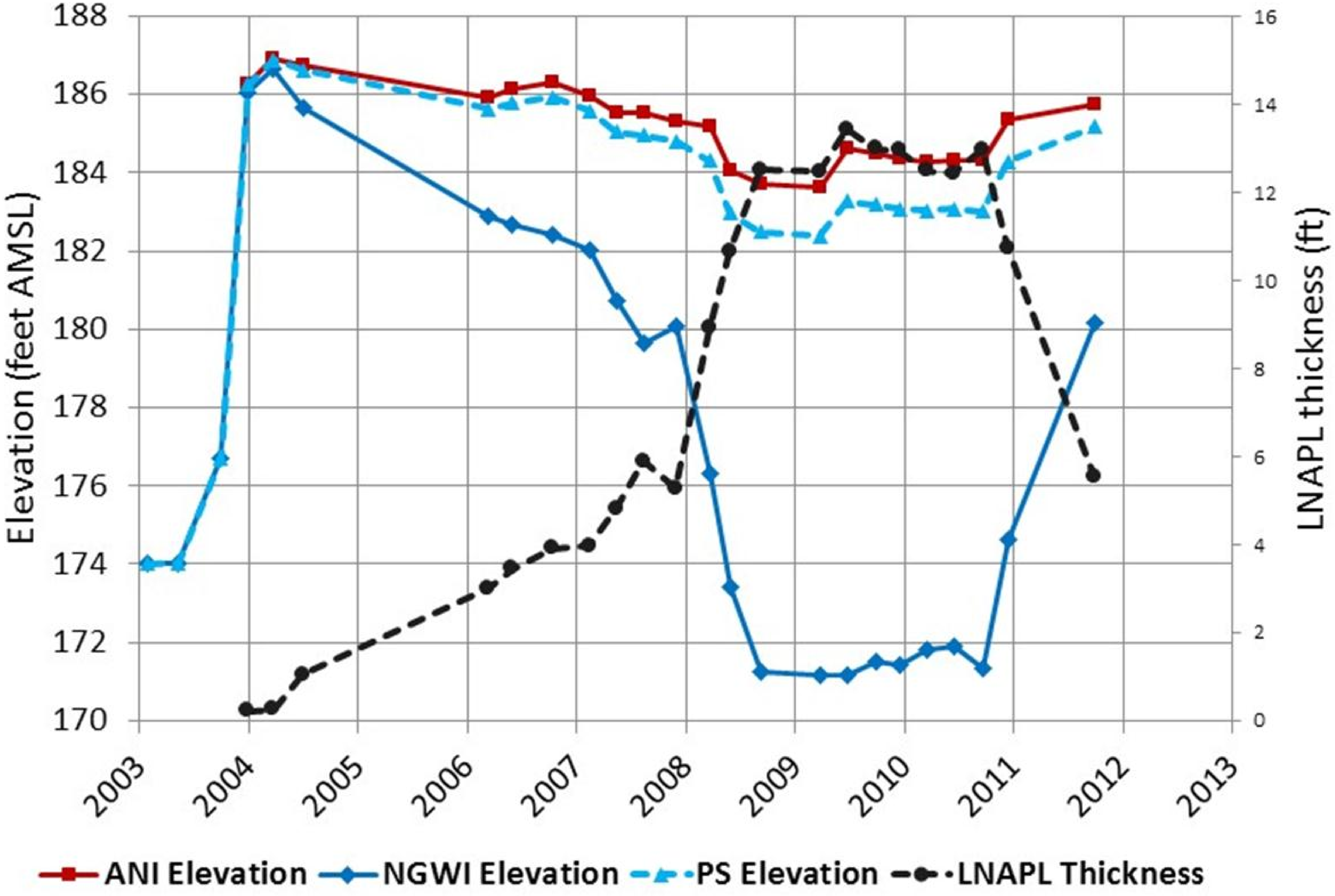
“Free Product” Map



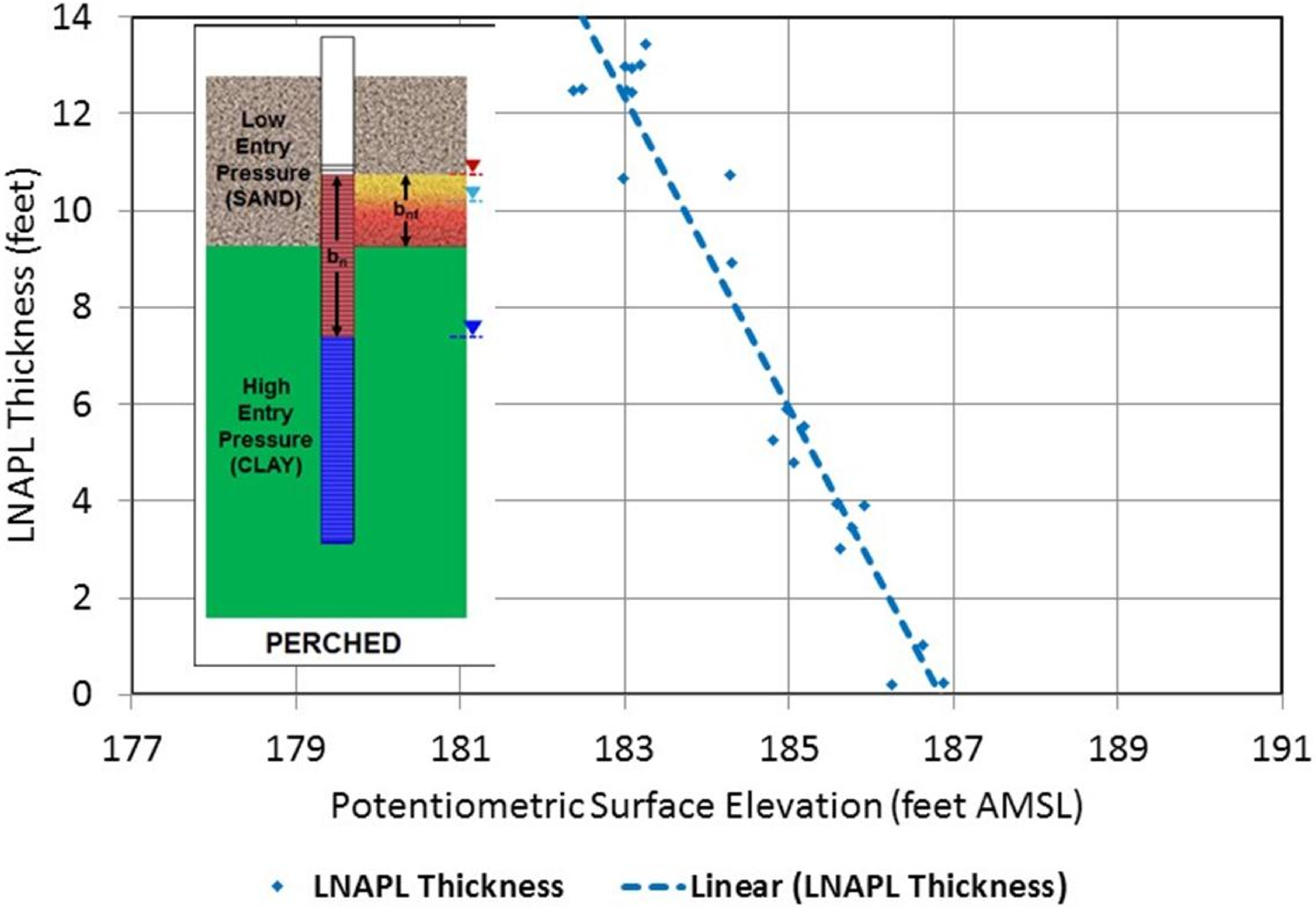
- LNAPL is weathered diesel (density ~0.9 g/cc).
- Releases may be up to 100 years old.

Presumptive remedy = Multiphase Extraction

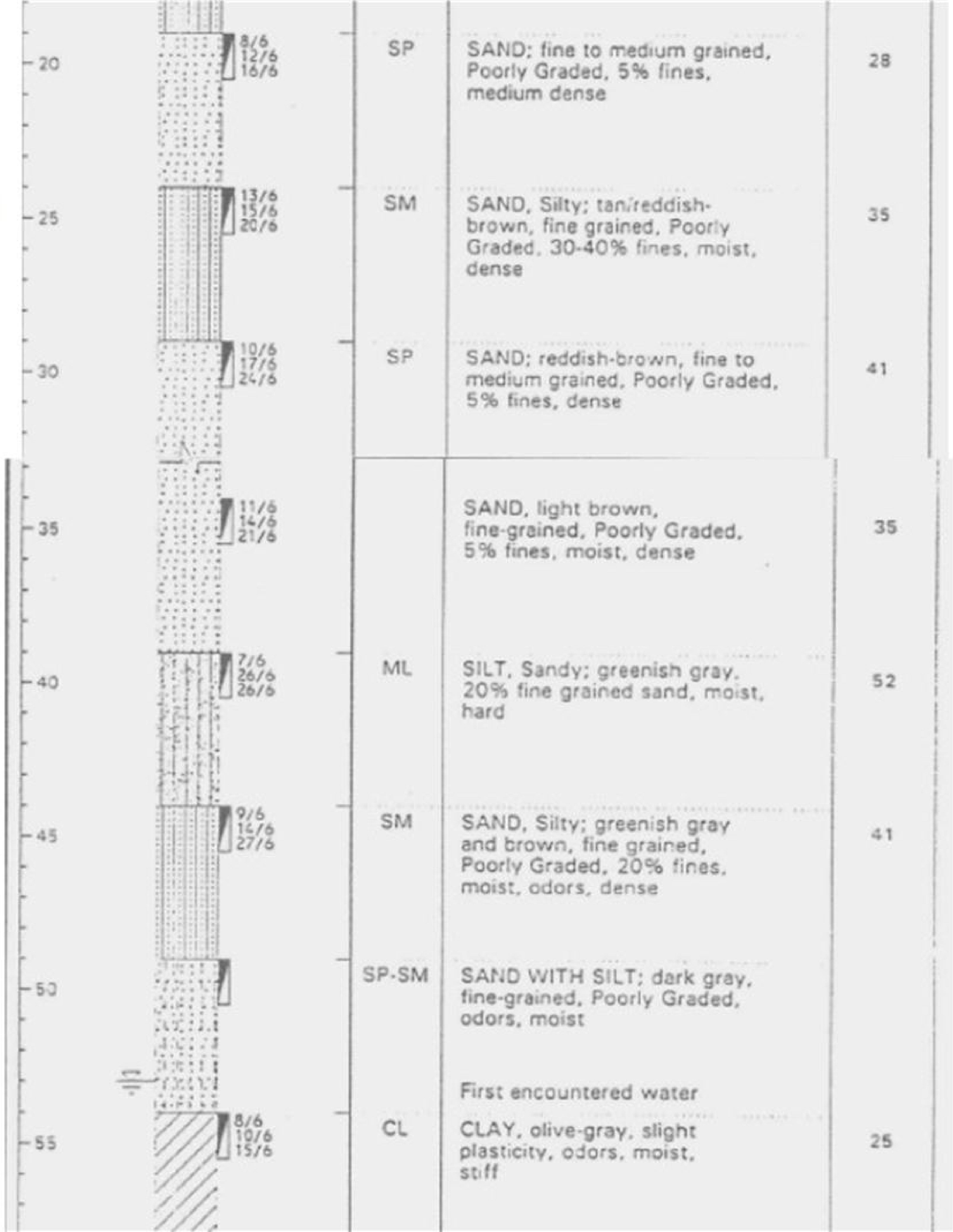
MW-17 Hydrograph



MW-17 Diagnostic Gauge Plot



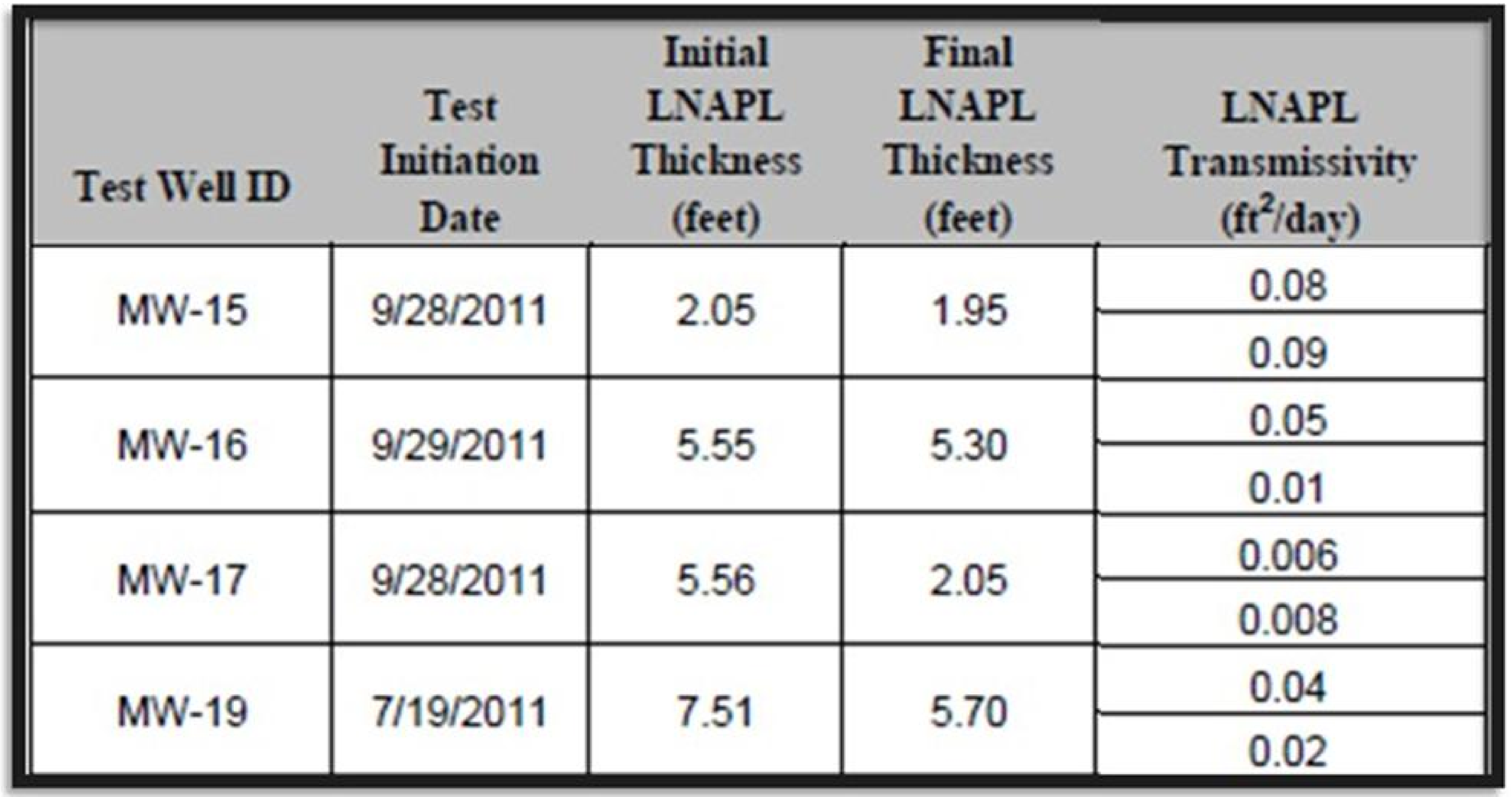
Review Boring Logs



20	8/6 12/6 16/6	SP	SAND; fine to medium grained, Poorly Graded, 5% fines, medium dense	28
25	13/6 15/6 20/6	SM	SAND, Silty; tan/reddish-brown, fine grained, Poorly Graded, 30-40% fines, moist, dense	35
30	10/6 17/6 24/6	SP	SAND; reddish-brown, fine to medium grained, Poorly Graded, 5% fines, dense	41
35	11/6 14/6 21/6		SAND, light brown, fine-grained, Poorly Graded, 5% fines, moist, dense	35
40	7/6 26/6 26/6	ML	SILT, Sandy; greenish gray, 20% fine grained sand, moist, hard	52
45	9/6 14/6 27/6	SM	SAND, Silty; greenish gray and brown, fine grained, Poorly Graded, 20% fines, moist, odors, dense	41
50		SP-SM	SAND WITH SILT; dark gray, fine-grained, Poorly Graded, odors, moist First encountered water	
55	8/6 10/6 15/6	CL	CLAY, olive-gray, slight plasticity, odors, moist, stiff	25

Soil texture change at every sample interval

LNAPL Transmissivity Evaluation



Test Well ID	Test Initiation Date	Initial LNAPL Thickness (feet)	Final LNAPL Thickness (feet)	LNAPL Transmissivity (ft^2/day)
MW-15	9/28/2011	2.05	1.95	0.08
				0.09
MW-16	9/29/2011	5.55	5.30	0.05
				0.01
MW-17	9/28/2011	5.56	2.05	0.006
				0.008
MW-19	7/19/2011	7.51	5.70	0.04
				0.02

LNAPL Recovery Impractical < 0.1 to 0.8 ft2/day

Updated LNAPL CSM

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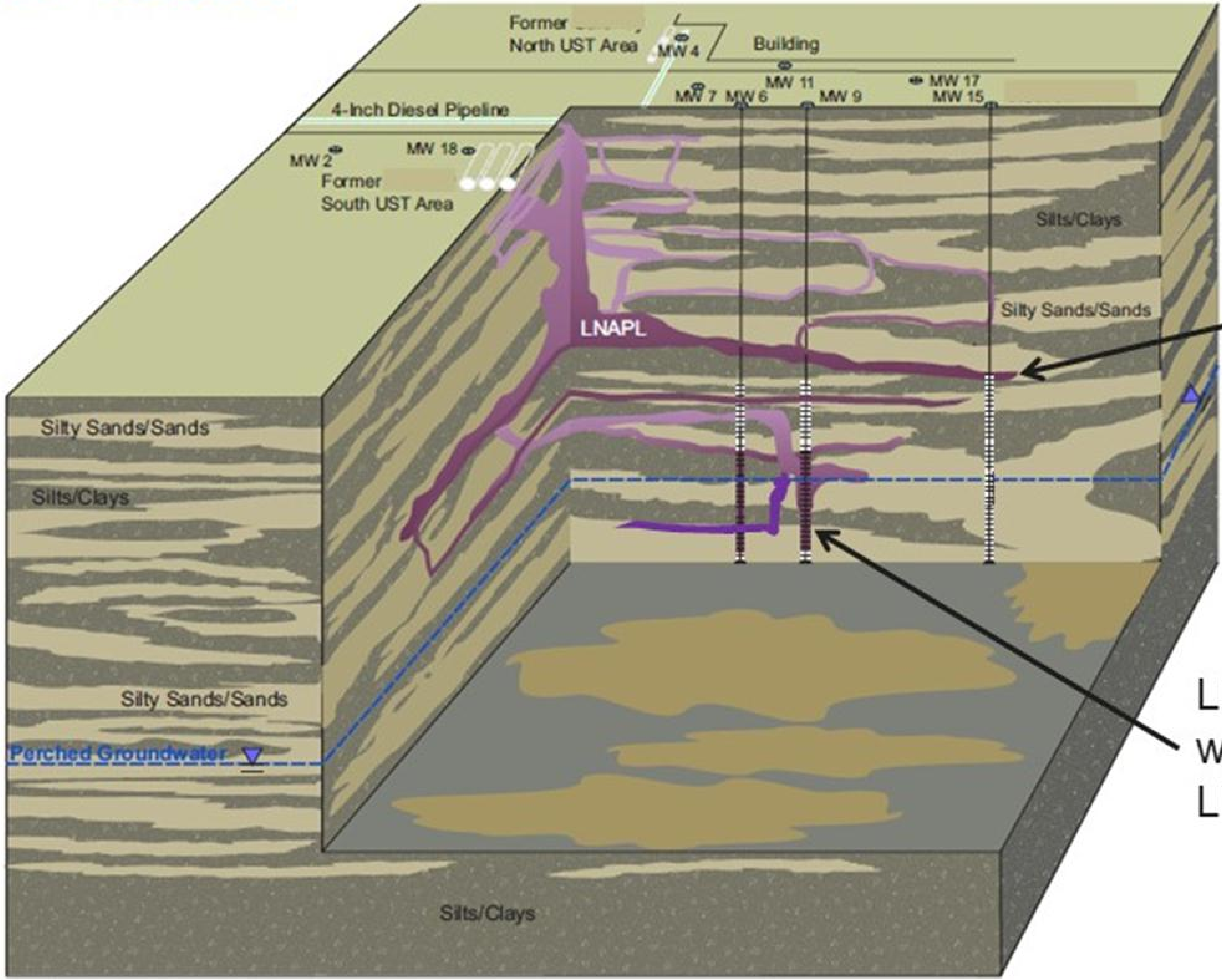
MPE not practical because LNAPL Mobility too low.

Use bioventing to enhance natural depletion of LNAPL



Stratigraphy controls LNAPL mobility & recoverability

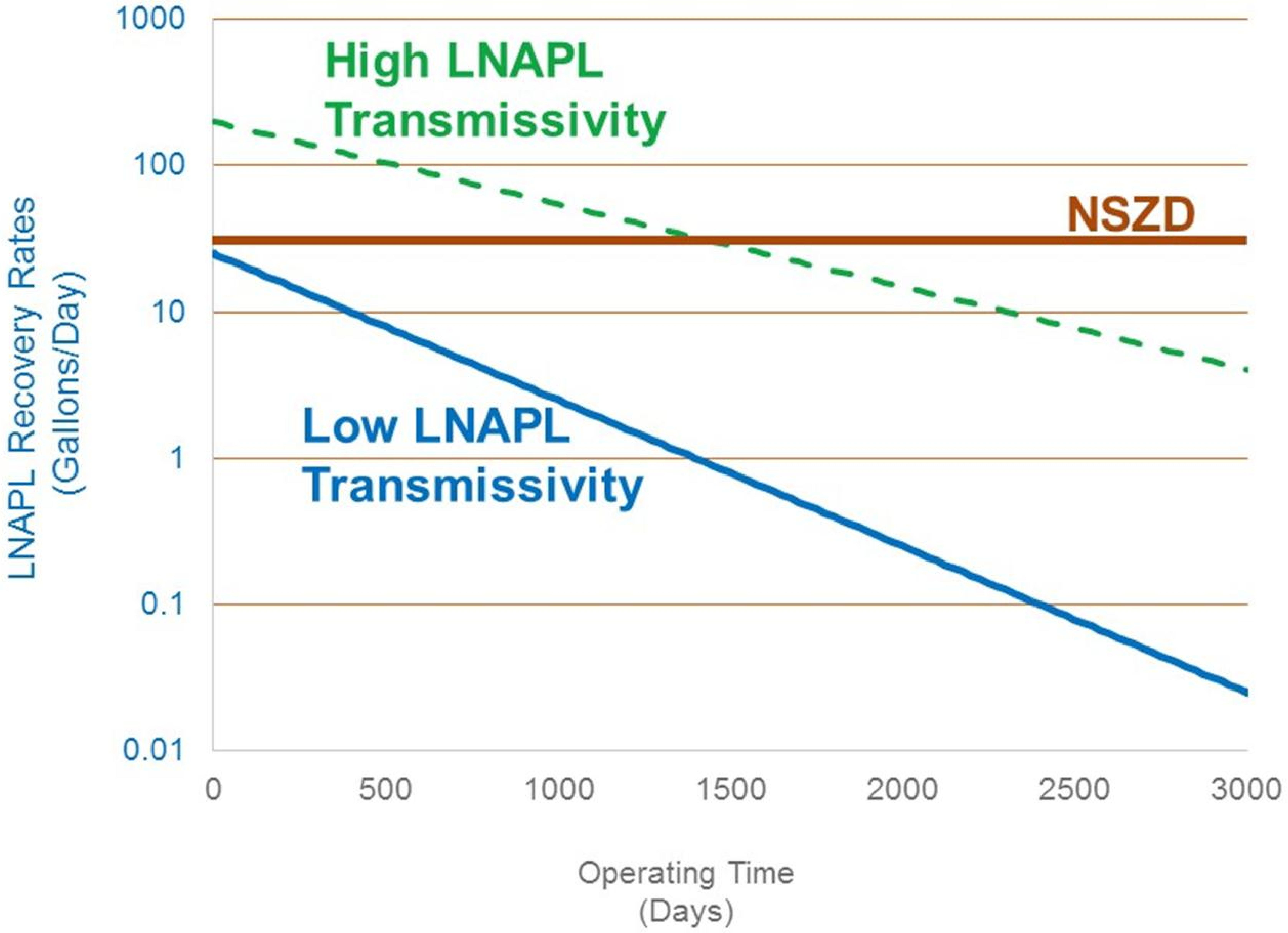
LNAPL accumulates in wells from perched LNAPL zones

Interpret all data, then choose right characterization tool

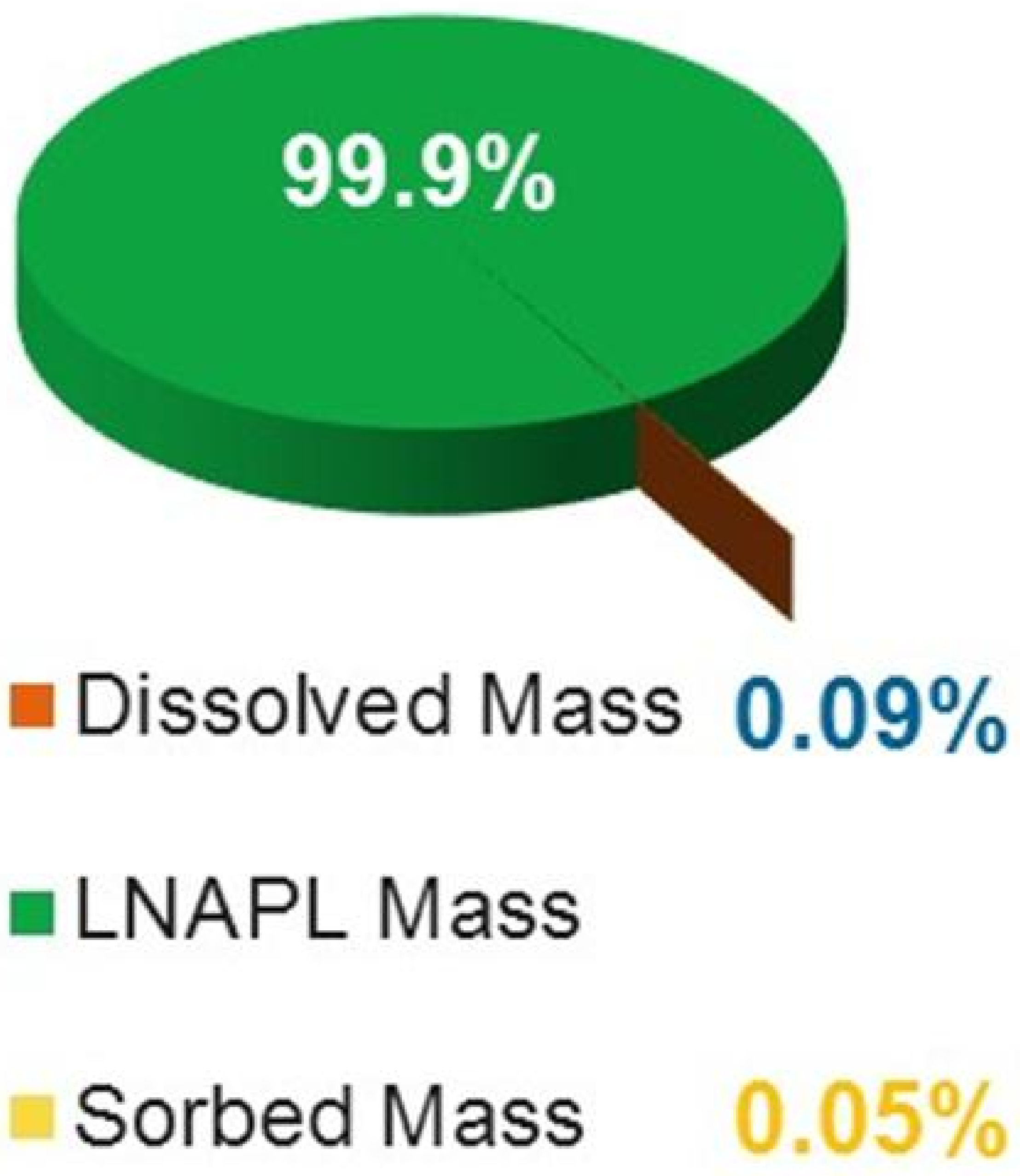
Questions?

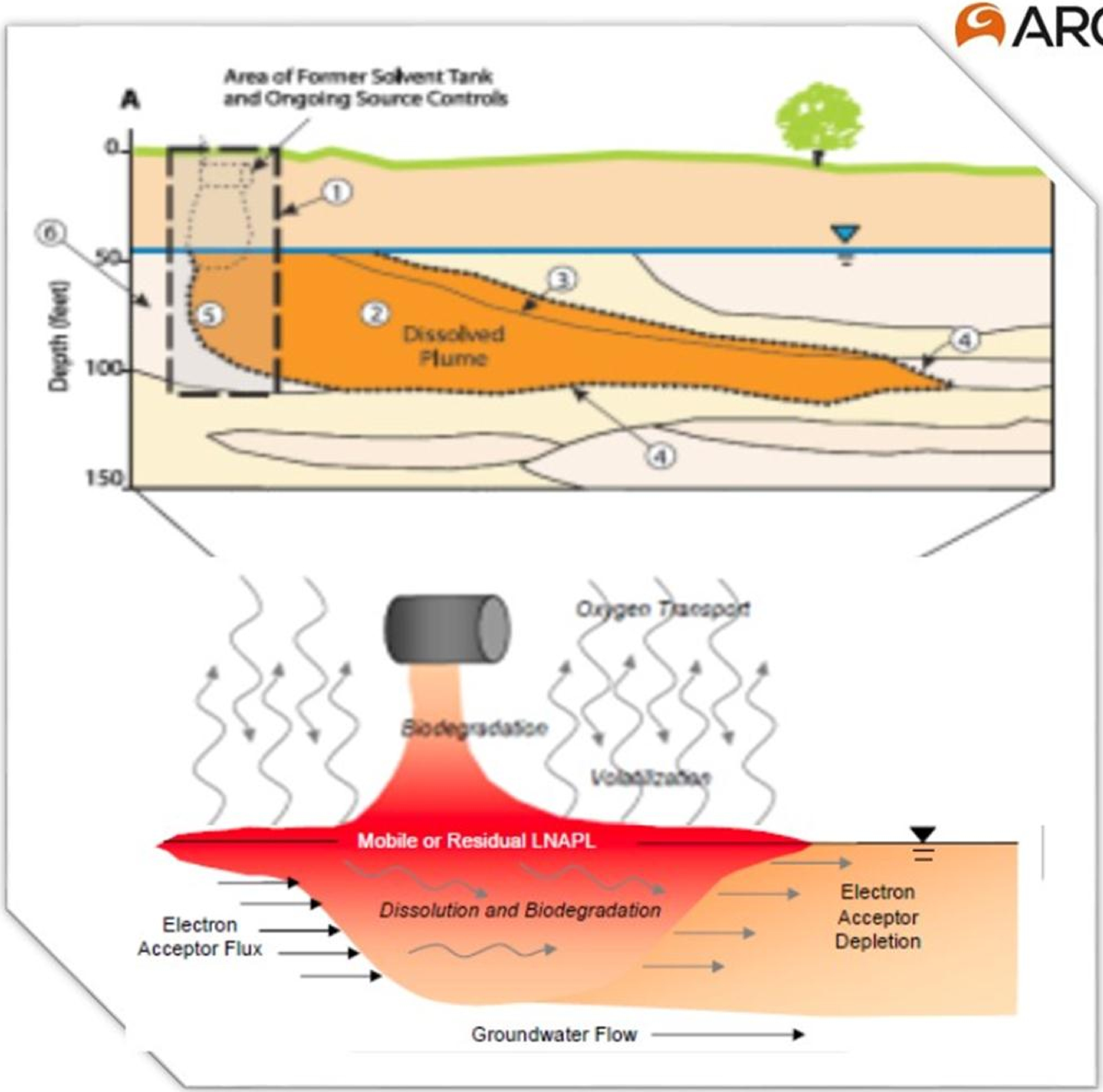
Natural Source Zone Depletion (NSZD)

NSZD vs LNAPL Recovery



NSZD is not MNA

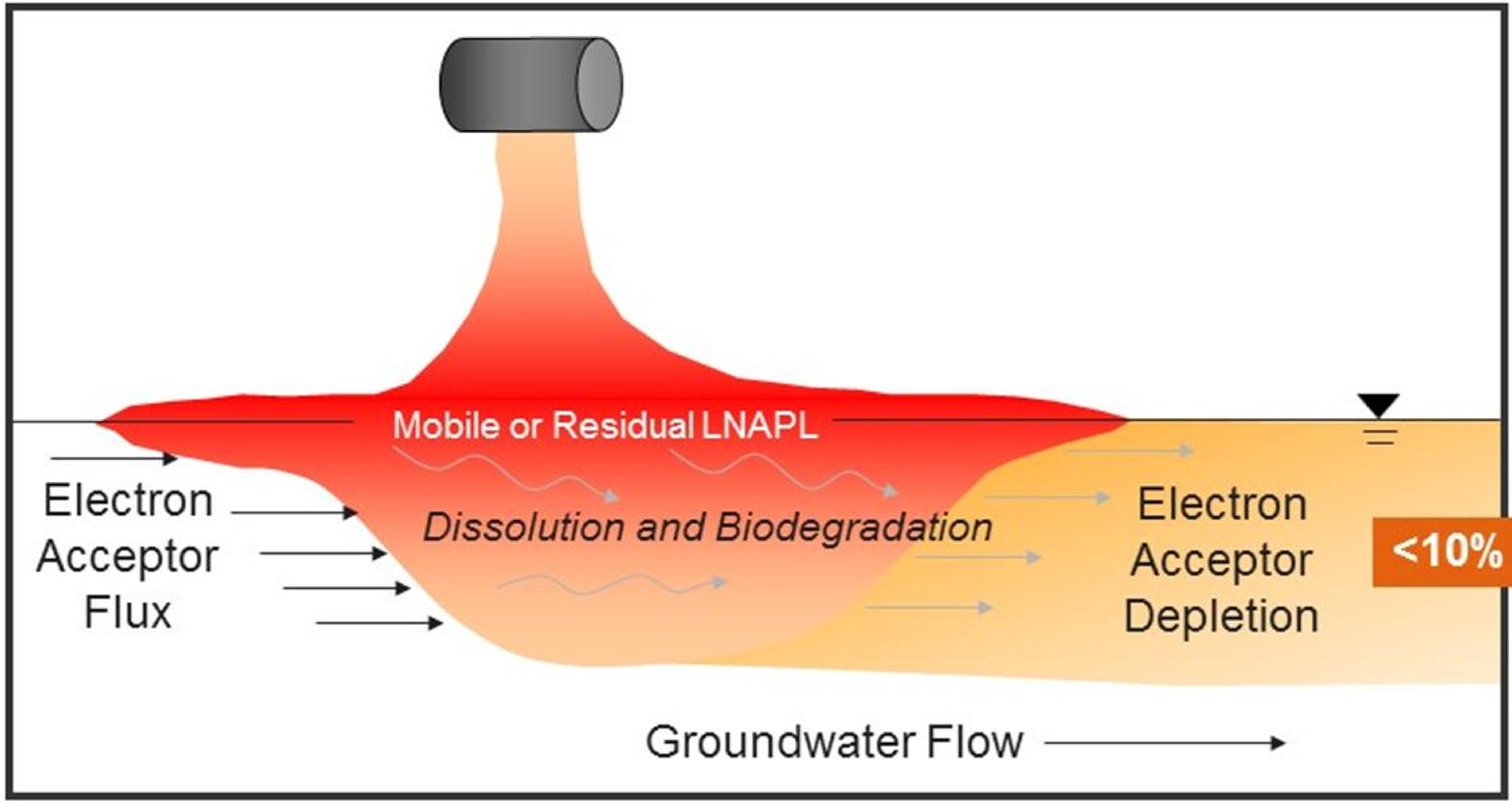




- MNA for dissolved phase <u>plumes</u>
- NSZD for LNAPL <u>source zones</u>

NSZD Processes in Groundwater

or… What do wells tell us about NSZD?



<10% of total NSZD

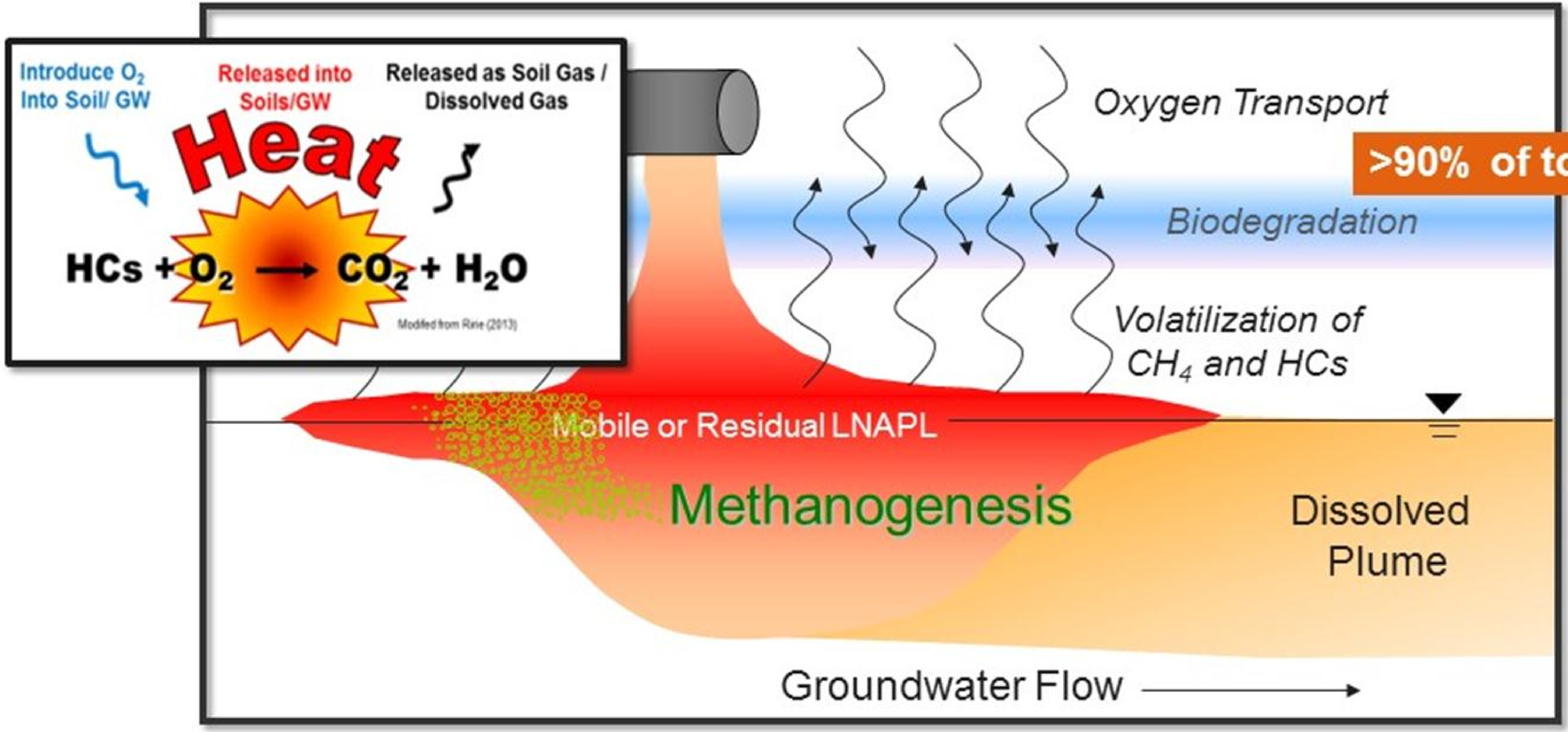
Courtesy ITRC, 2010

Mass loss occurs from:

Dissolution: Estimated from flow and concentration data
Biodegradation: Estimated from geochemical data

NSZD Processes in the Vadose Zone

or… What don't wells tell us about NSZD?

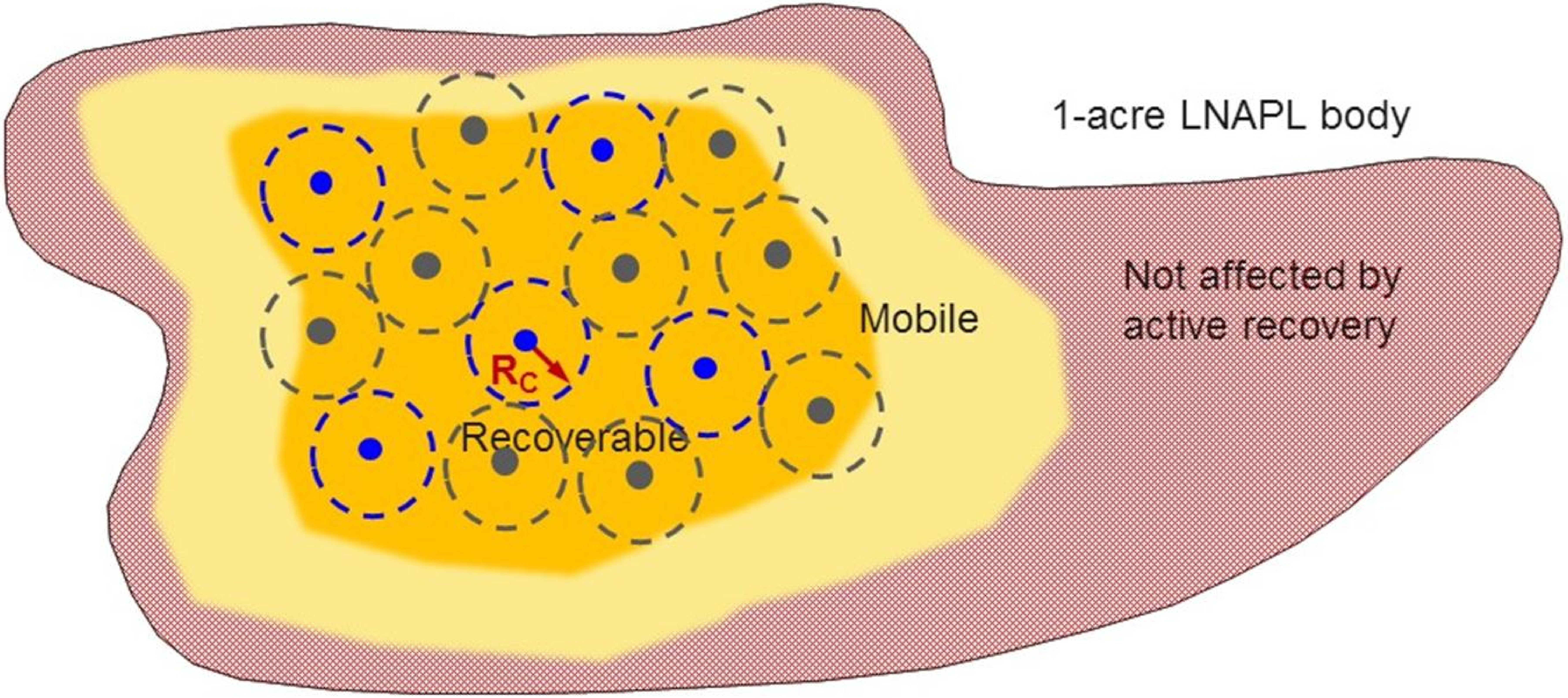


Modified from ITRC, 2010 and Ririe, 2013

Mass loss occurs from:

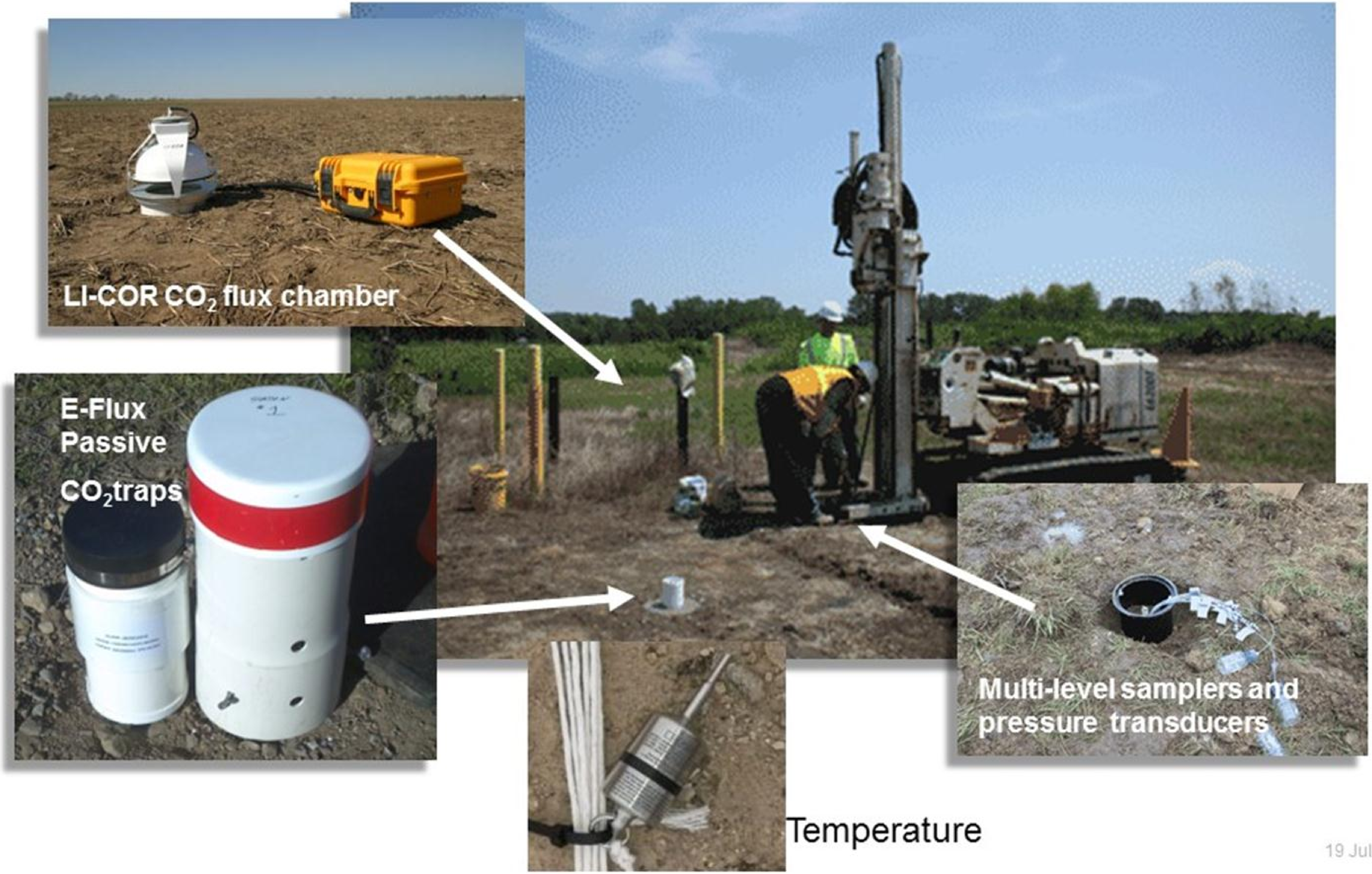
Volatilization: Estimated from soil gas concentration data
Biodegradation: Estimated from soil gas efflux, soil gas depth profiles, or temperature anomalies

NSZD Rates in Perspective

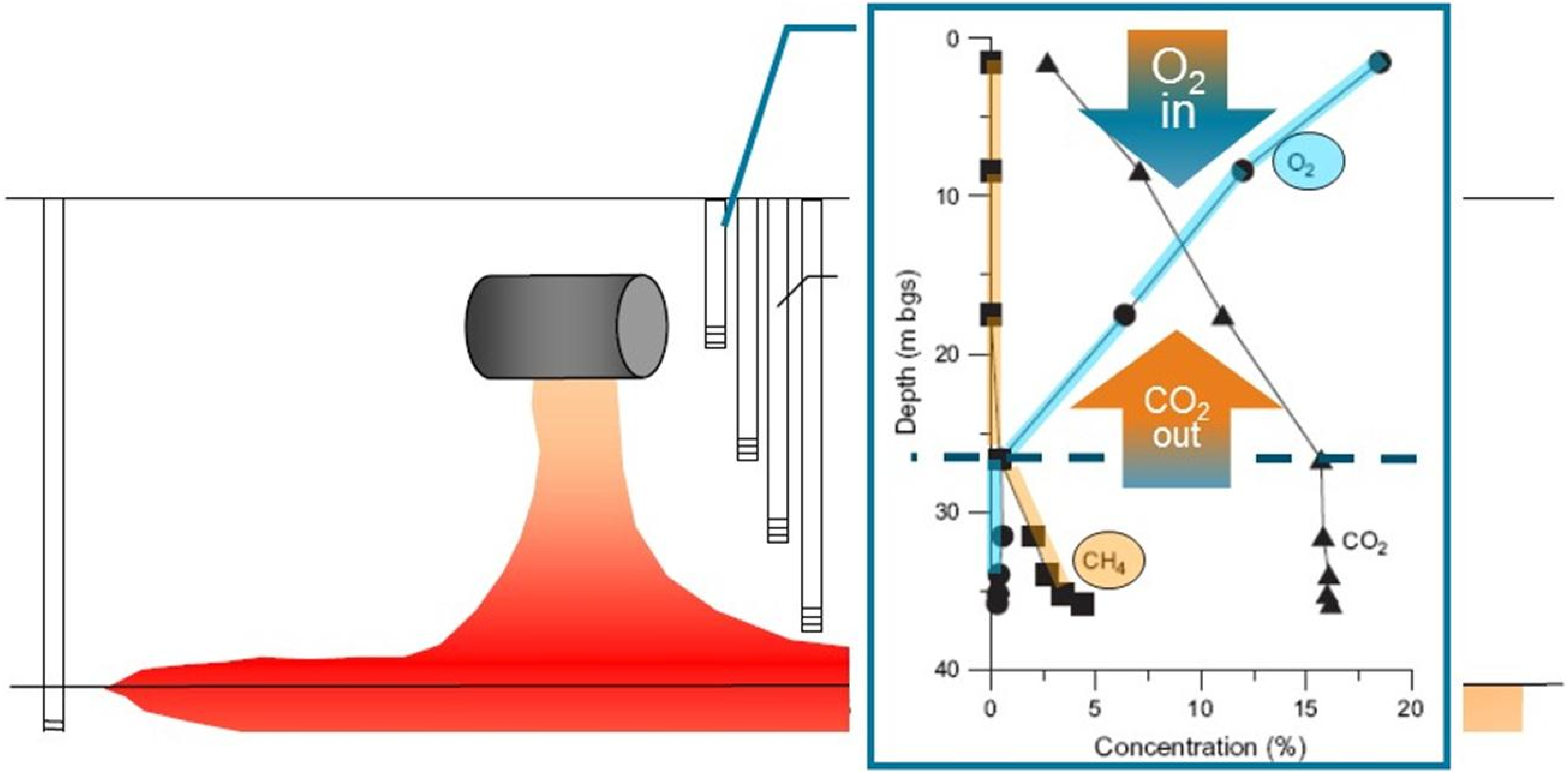


- NSZD (1,000 gal/acre/yr)
  - Acts on 100% of LNAPL Body (mobile and residual)
- Five Skimmers with 20 ft ROI
  - Acts on 14% of LNAPL Body
  - Average LNAPL thickness = 1 ft
  - Average T_n = 0.1 ft^2/d
  - 370 gal/yr

Methods for Quantifying NSZD



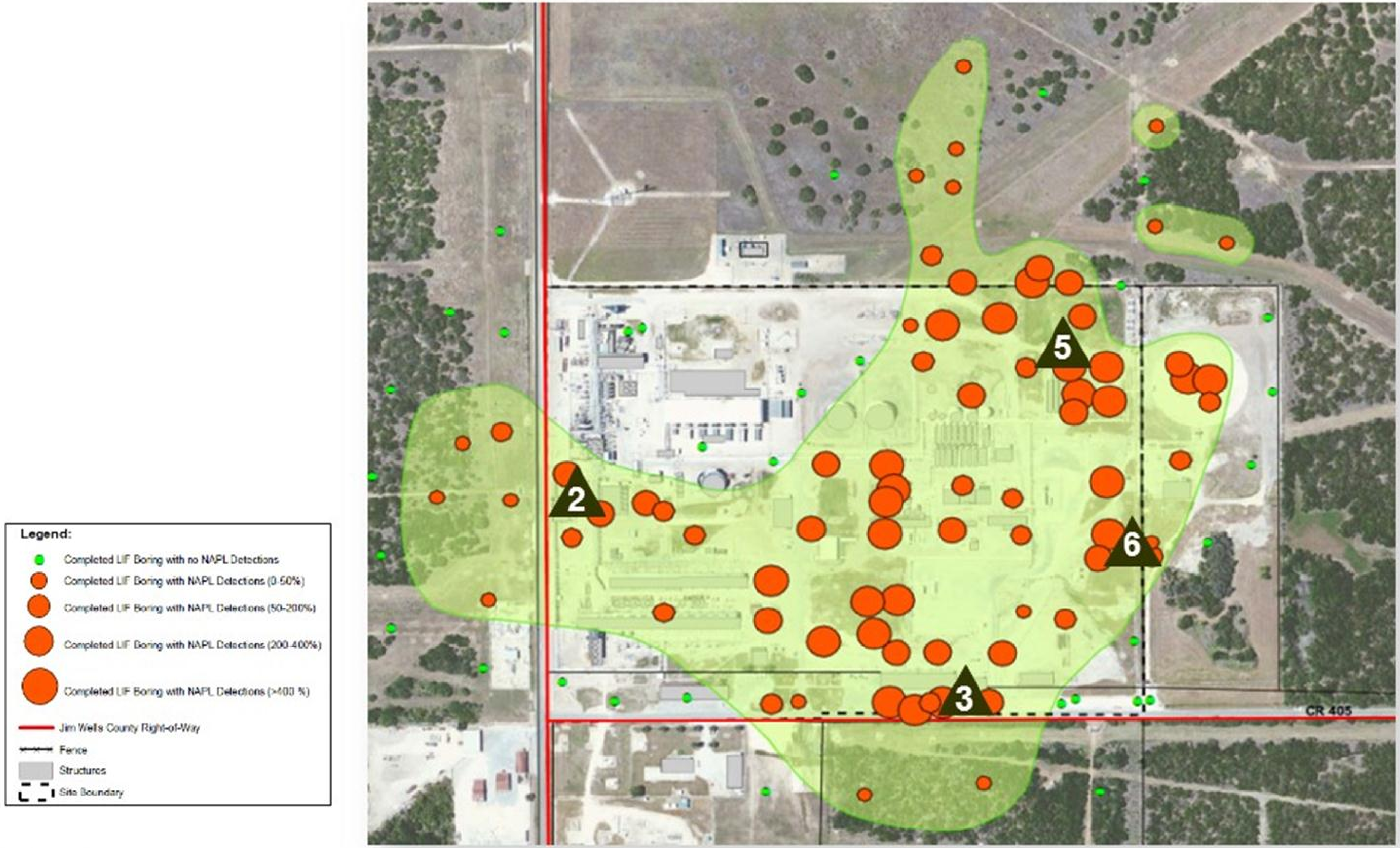
Gradient Method



Source: Evaluating Natural Source Zone Depletion at Sites with LNAPL, Interstate Technology & Regulatory Council – LNAPLs Team, April 2009.

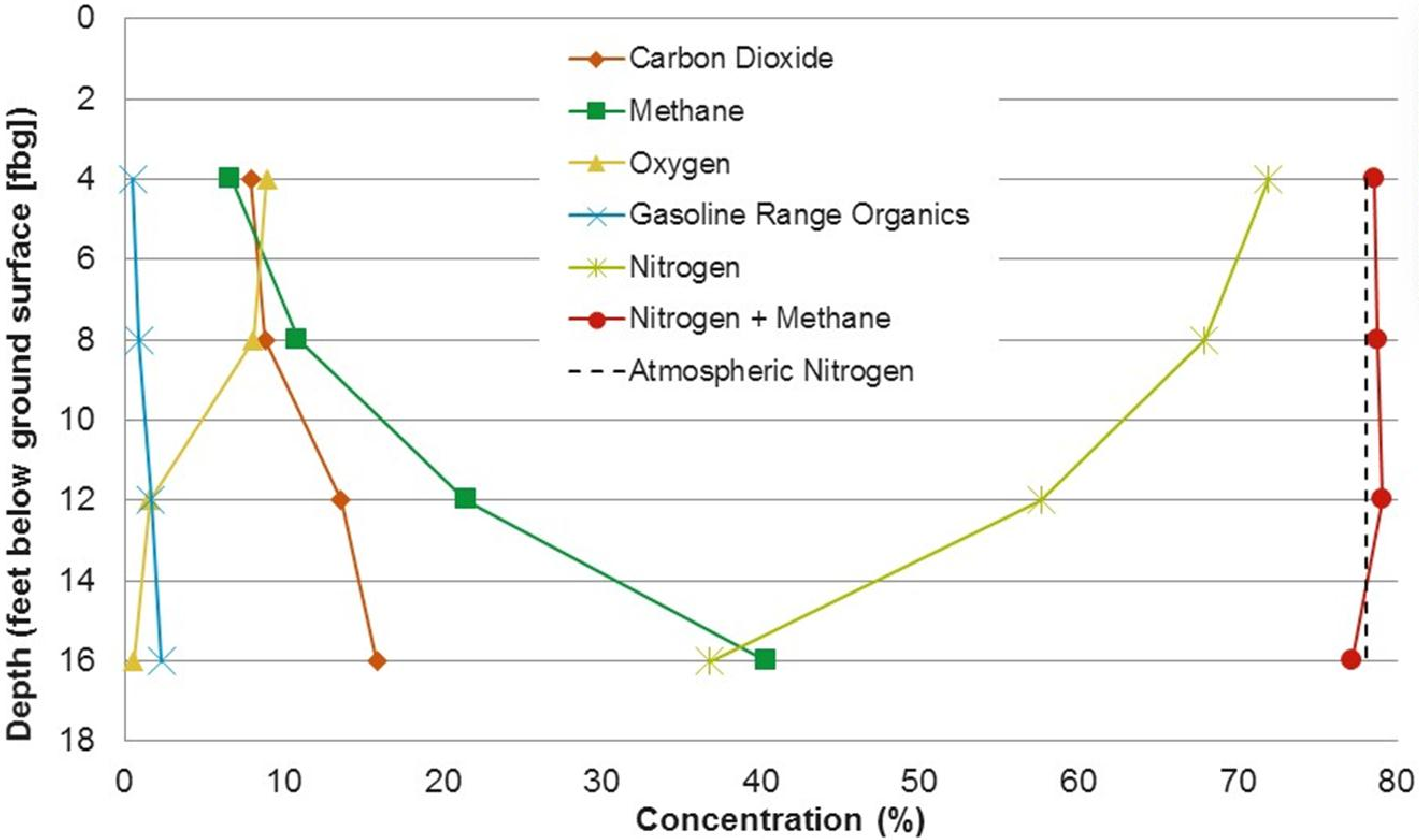
Gradient Method

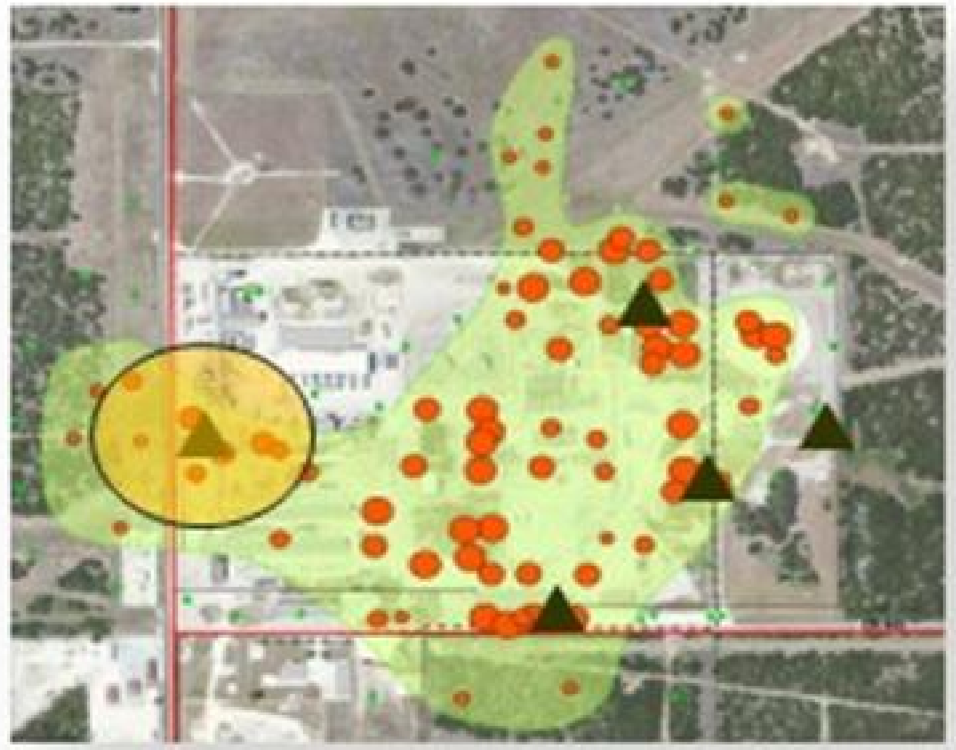
NSZD Case Study #1



Soil Gas Profile

NSZD Case Study #1

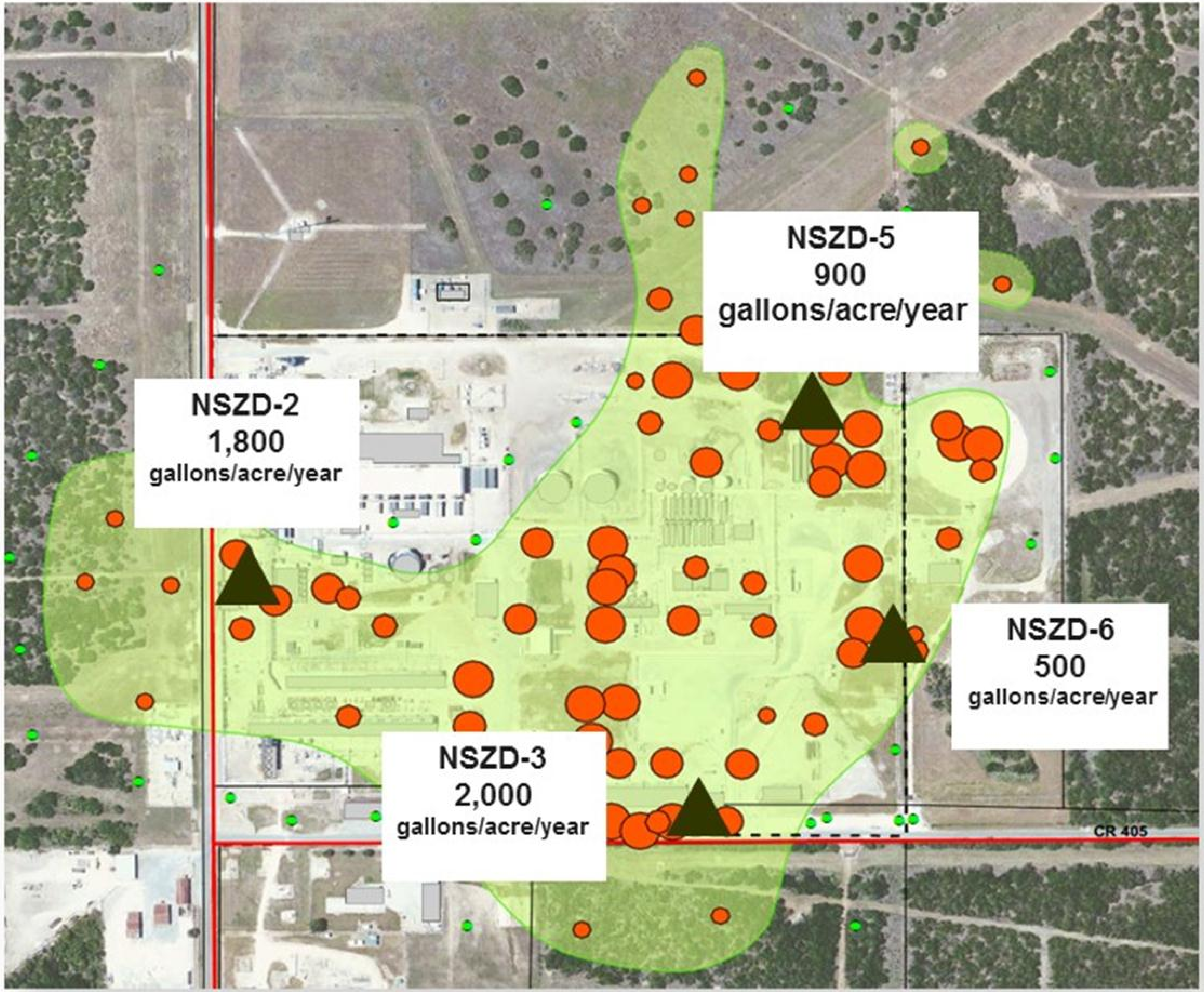




Results

NSZD Case Study #1

Site Wide Average
1,300
gallons/acre/year



Legend:

- ● Completed LIF Boring with no NAPL Detections
- ● Completed LIF Boring with NAPL Detections (0-50%)
- ● Completed LIF Boring with NAPL Detections (50-200%)
- ● Completed LIF Boring with NAPL Detections (200-400%)
- ● Completed LIF Boring with NAPL Detections (>400 %)
- — Jim Wells County Right-of-Way
- -x-x- Fence
- ▨ Structures
- ⌐ ¬ Site Boundary

CO_2 Flux: Instantaneous

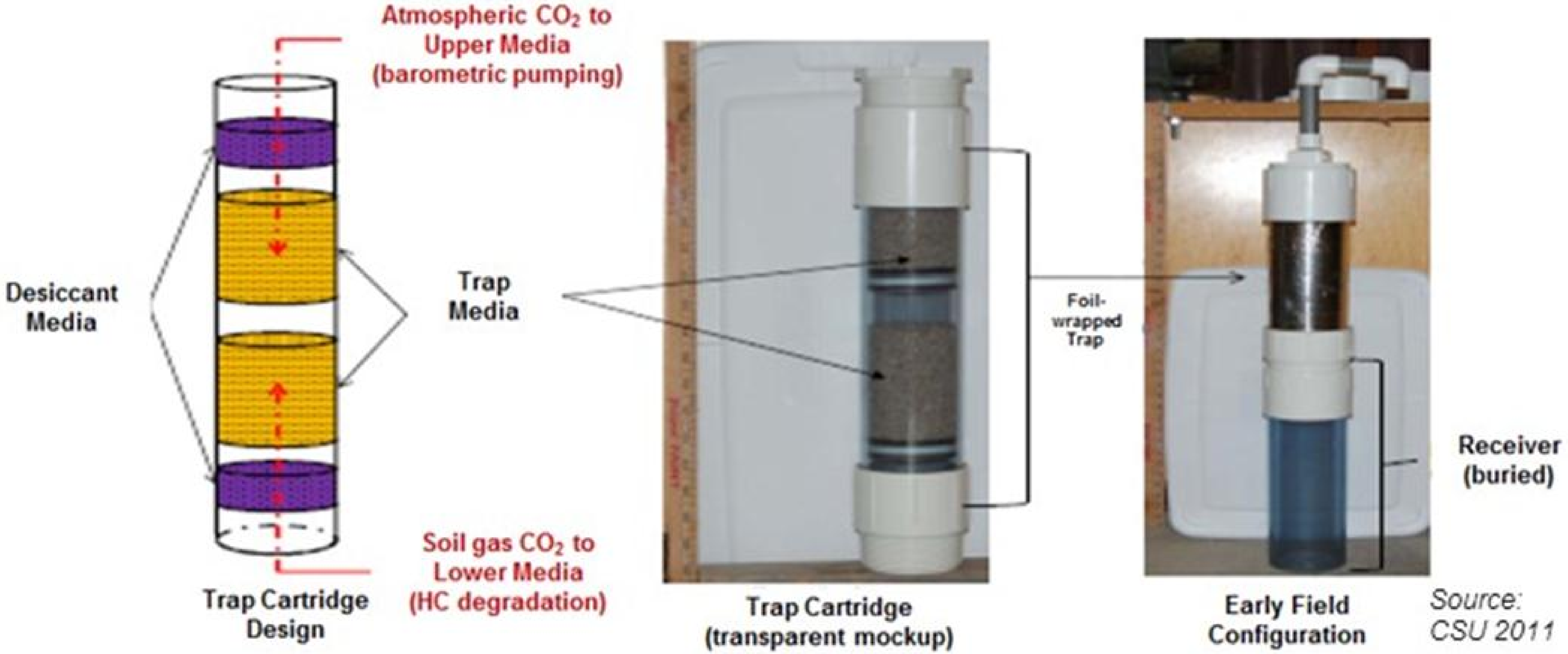
Instrument measures build-up of CO_2 concentration over short duration (~30 seconds per measurement) using infrared gas analyzer to calculate flux

Collected data across known LNAPL extent and in upgradient (“background”) areas.

CO_2 Surface Flux: Time-Integrated

CO_2 sorbent canisters placed on in-ground receiver

- Deploy CO_2 traps at eight locations for semi-annual monitoring
- Soil gas samples for analysis of CH_4 to capture losses associated with incomplete mineralization to CO_2



Trap Cartridge Design

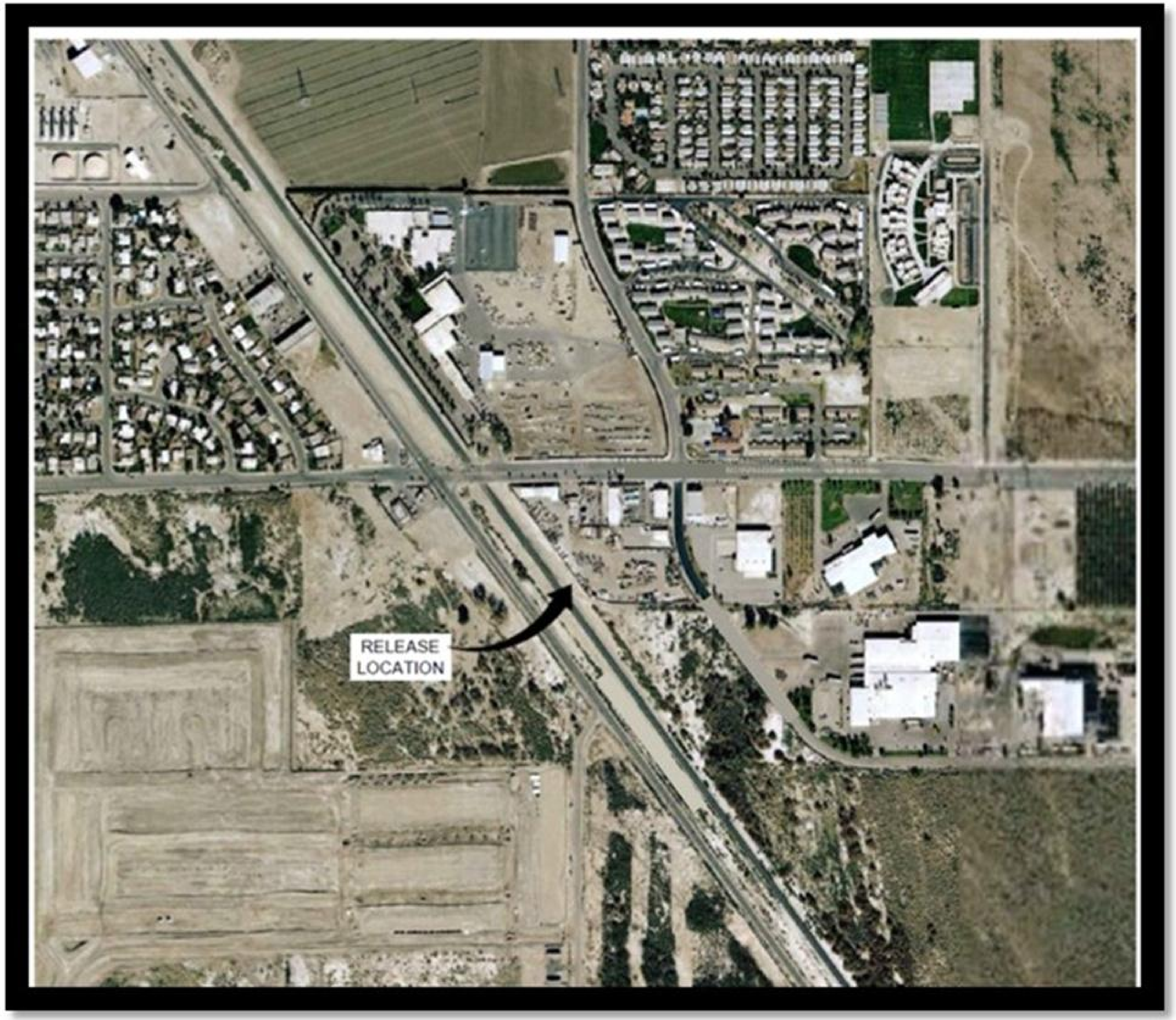
Trap Cartridge (transparent mockup)

Early Field Configuration

Source: CSU 2011

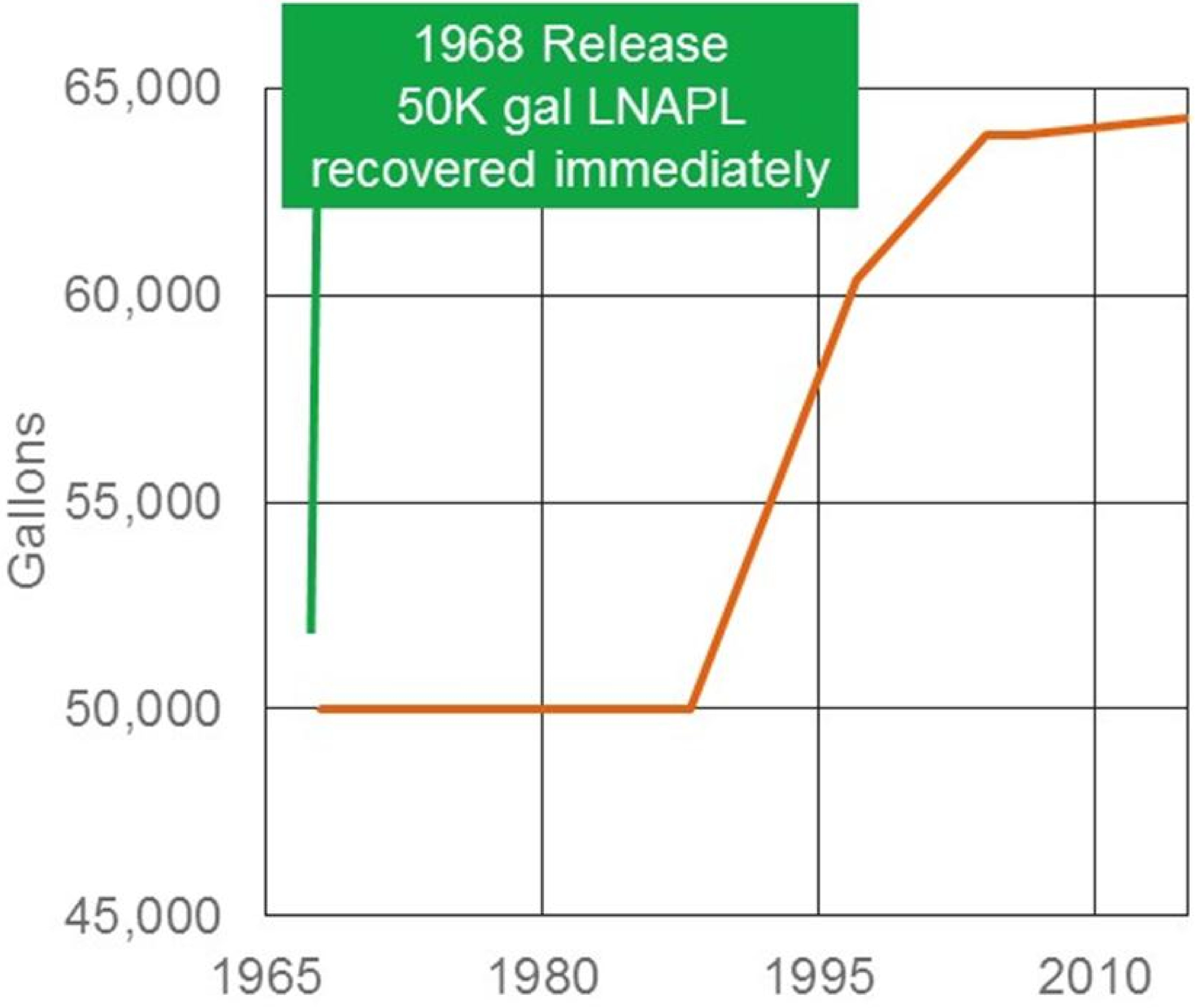
NSZD Case Study #2

Pipeline Release Site



Remediation History

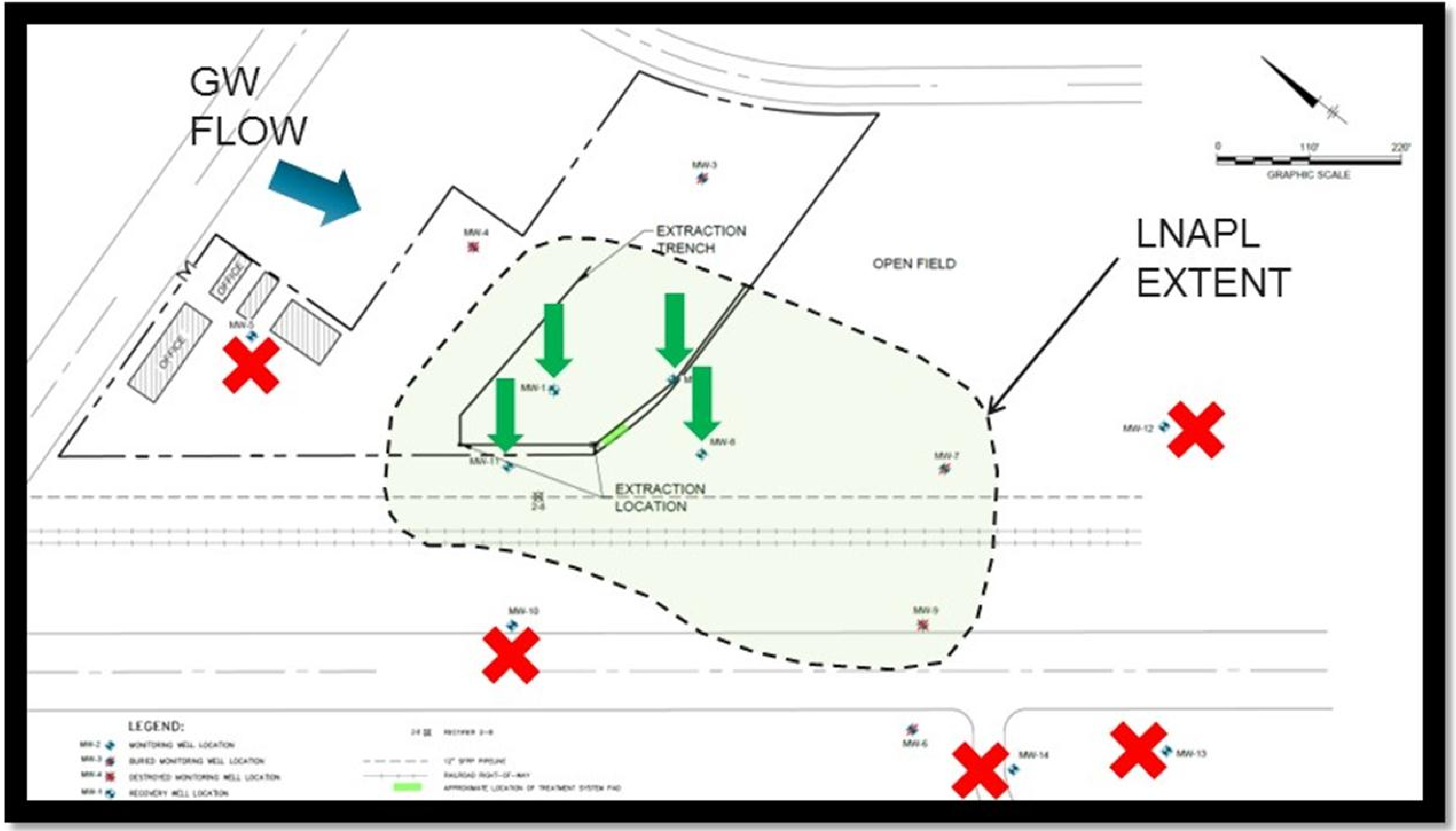
NSZD Case Study #2


1968 Release
50K gal LNAPL
recovered immediately

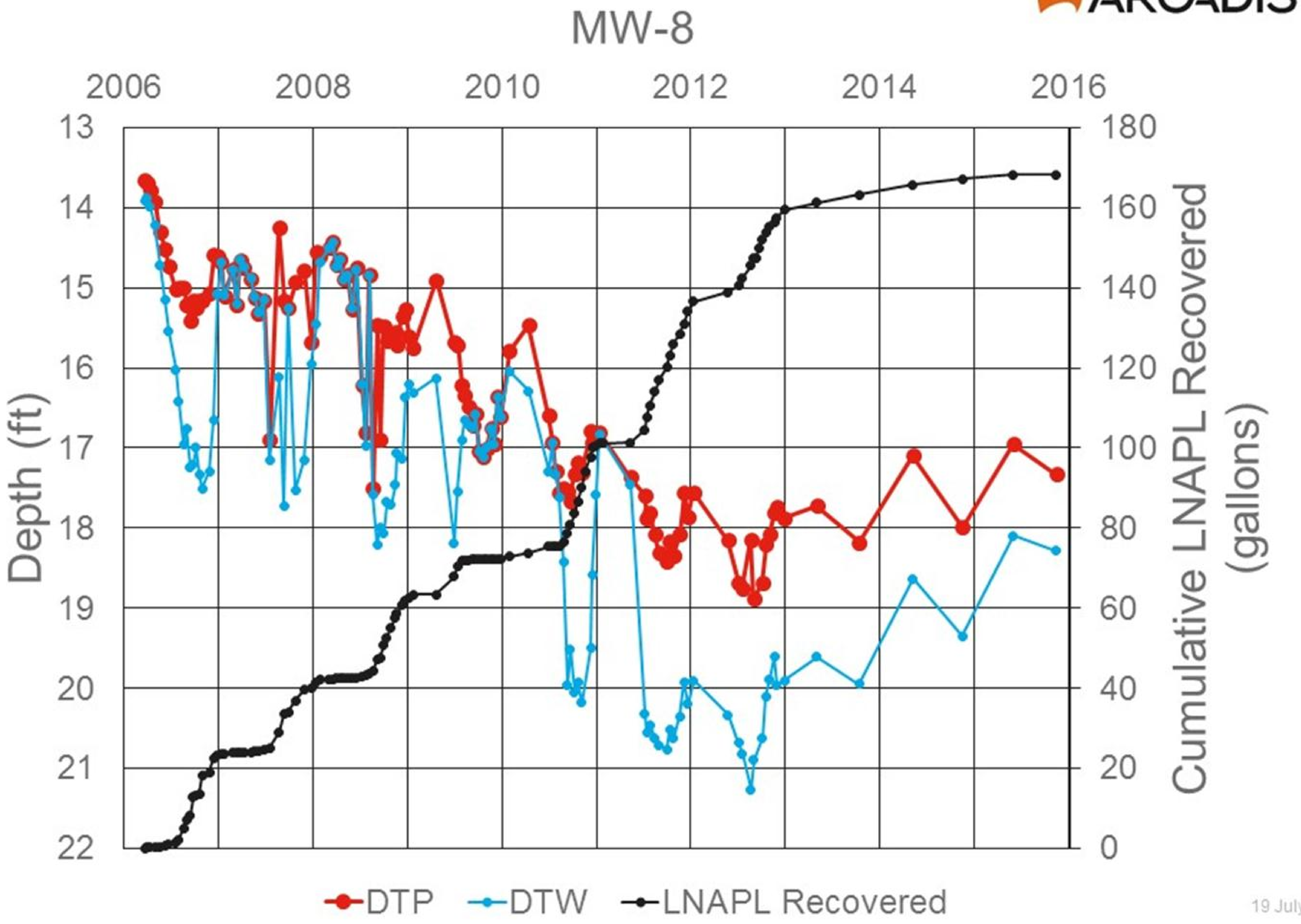
Declining Recovery

NSZD Case Study #2

LNAPL in Monitoring Wells

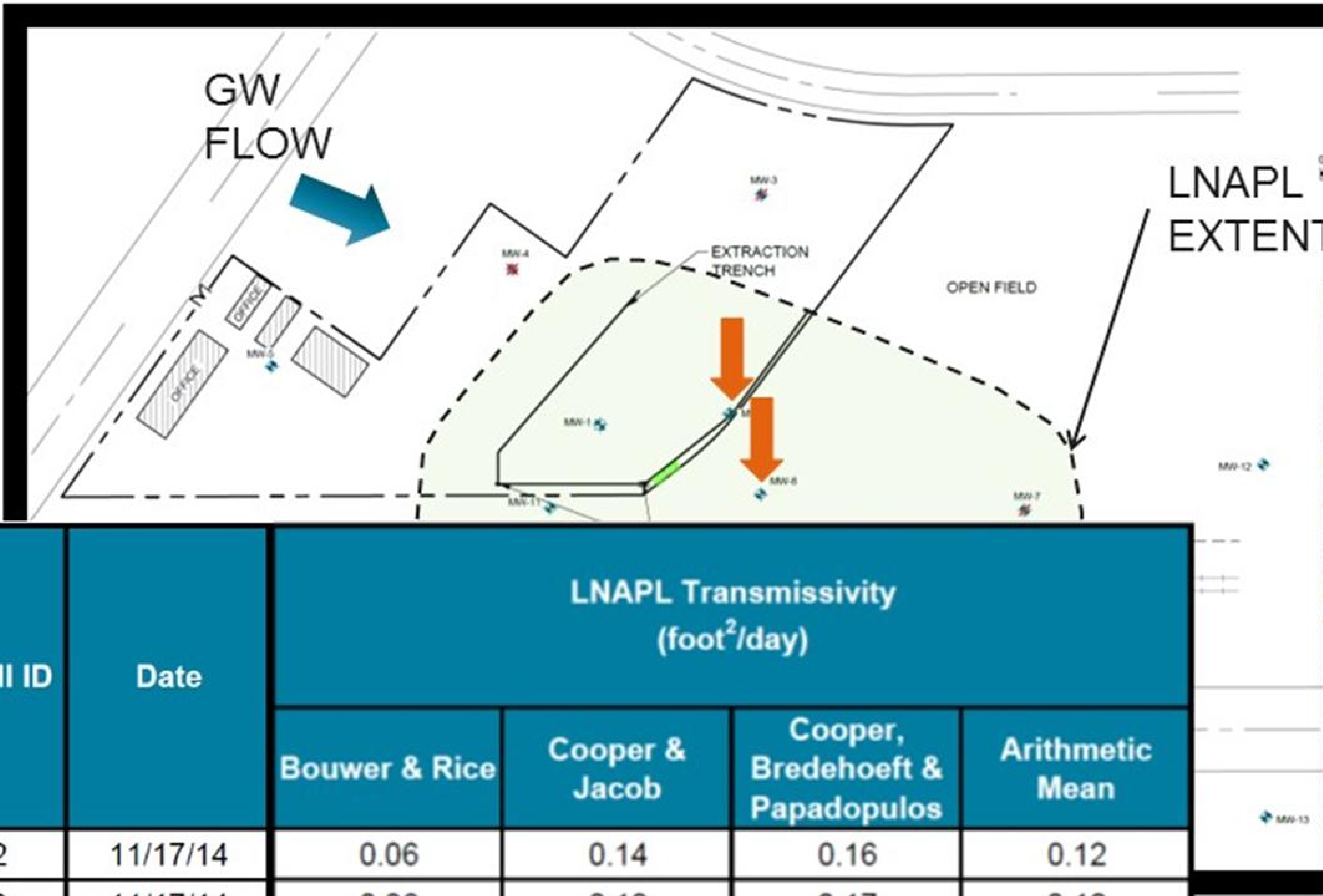


NSZD Case Study #2



LNAPL Baildown Test

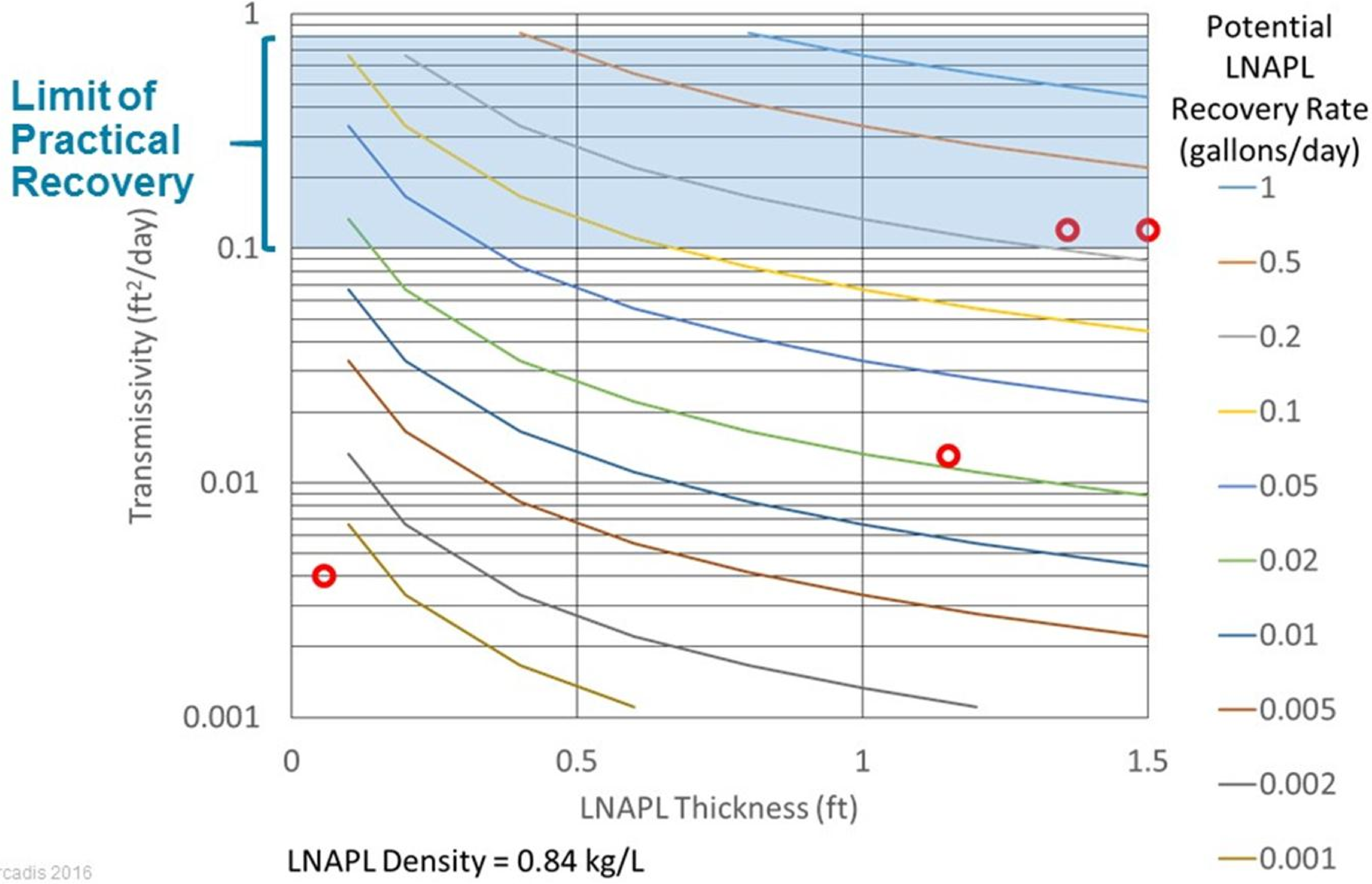
NSZD Case Study #2



Test Well ID	Date	LNAPL Transmissivity (foot^2/day)			
		Bouwer & Rice	Cooper & Jacob	Cooper, Bredehoeft & Papadopulos	Arithmetic Mean
MW-2	11/17/14	0.06	0.14	0.16	0.12
MW-8	11/17/14	0.06	0.13	0.17	0.12
MW-2	6/1/15	0.0005	0.00	0.01	0.004
MW-8	6/1/15	0.0002	0.02	0.02	0.013

Potential LNAPL Recoverability

NSZD Case Study #2



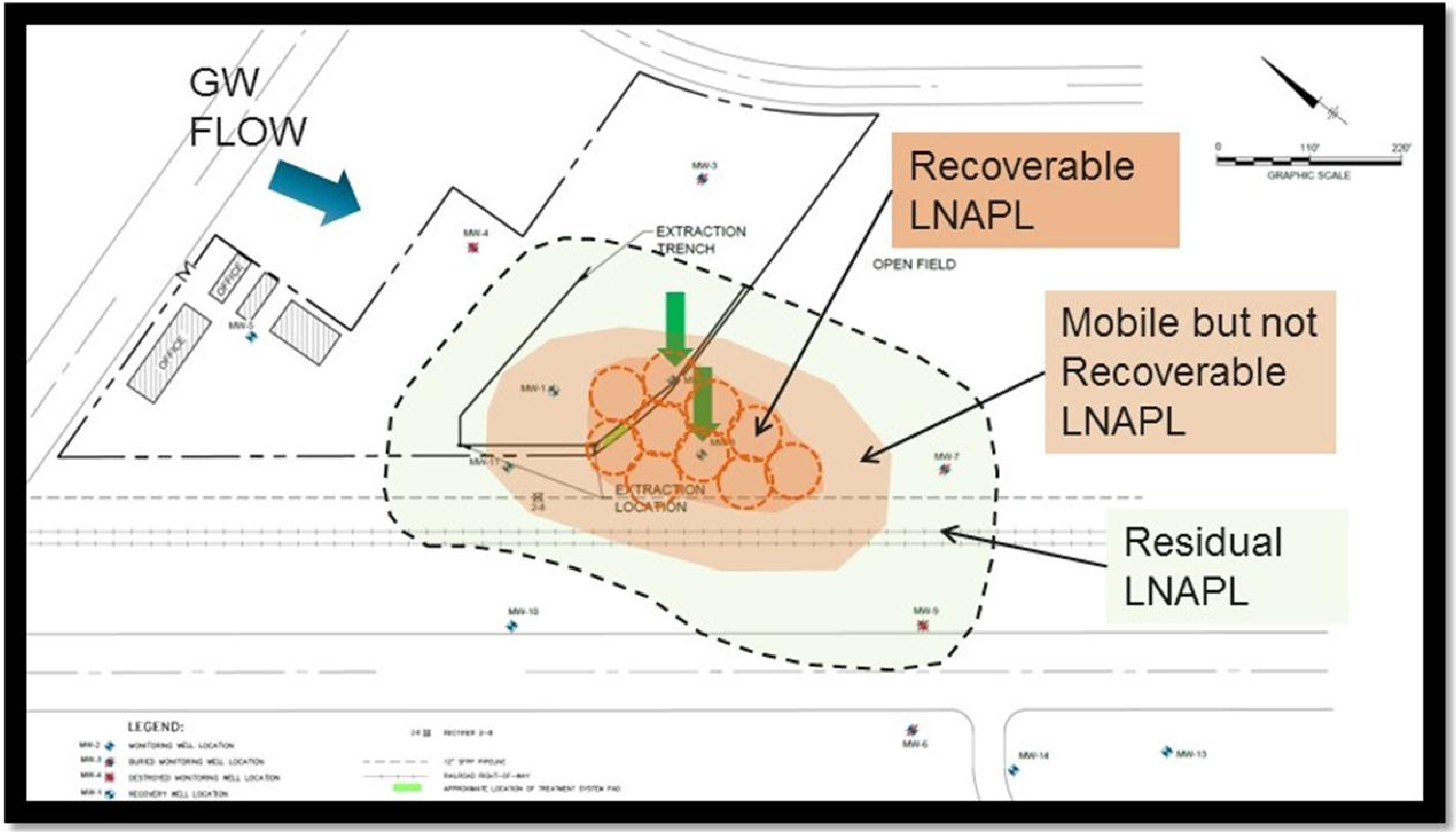
LNAPL Density = 0.84 kg/L

$$T_n = \frac{Q_n \ln\left(\frac{R_{oi}}{r_w}\right)}{2\pi s_n}$$

ASTM E2856

Speculative LNAPL Recovery

NSZD Case Study #2



Recoverable LNAPL

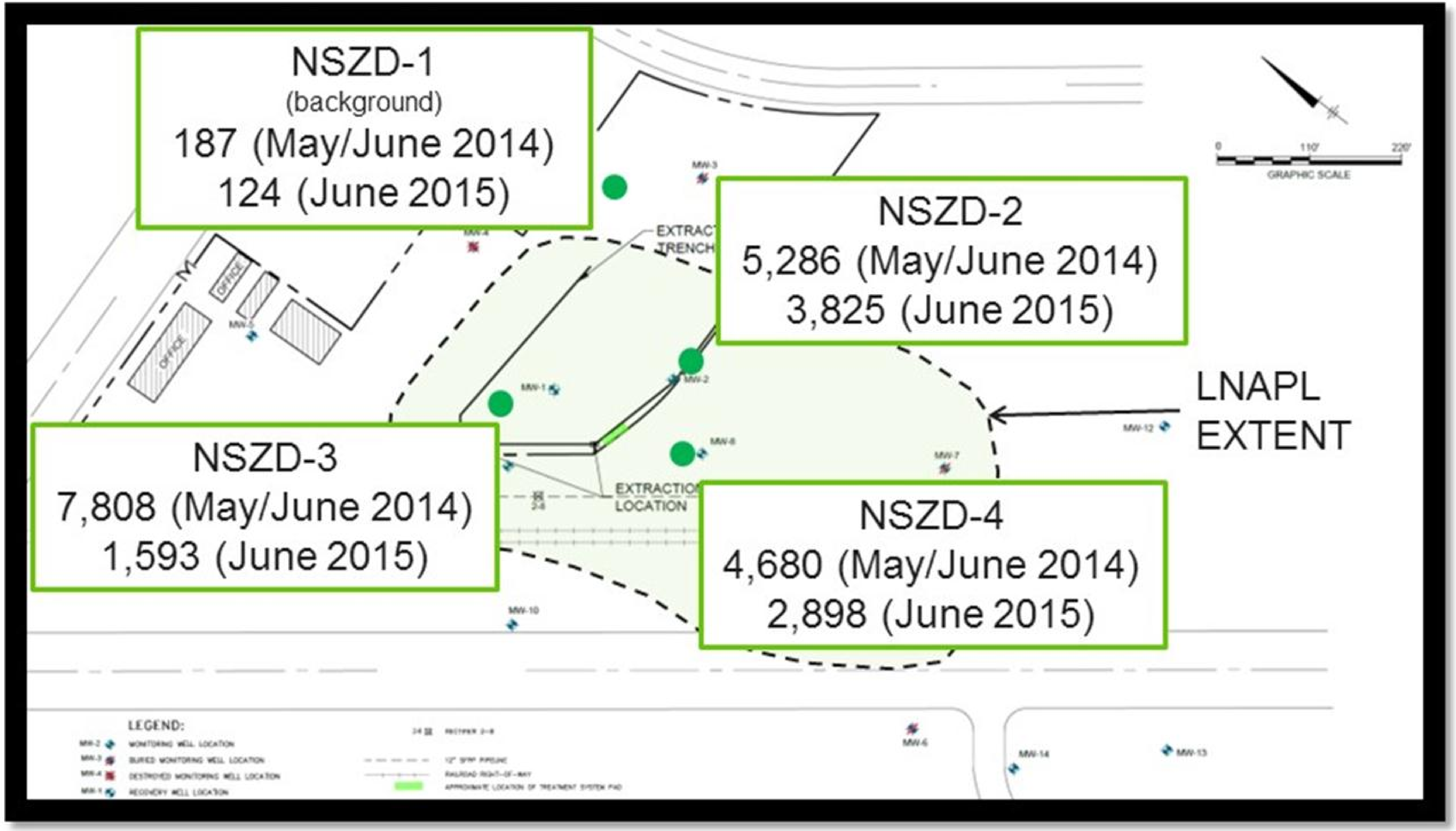
Mobile but not Recoverable LNAPL

Residual LNAPL

10 Wells might produce about 100 gal/yr… but for how long?

NSZD Rate from CO_2 Traps

NSZD Case Study #2



NSZD-1
(background)
187 (May/June 2014)
124 (June 2015)

NSZD-2
5,286 (May/June 2014)
3,825 (June 2015)

LNAPL EXTENT

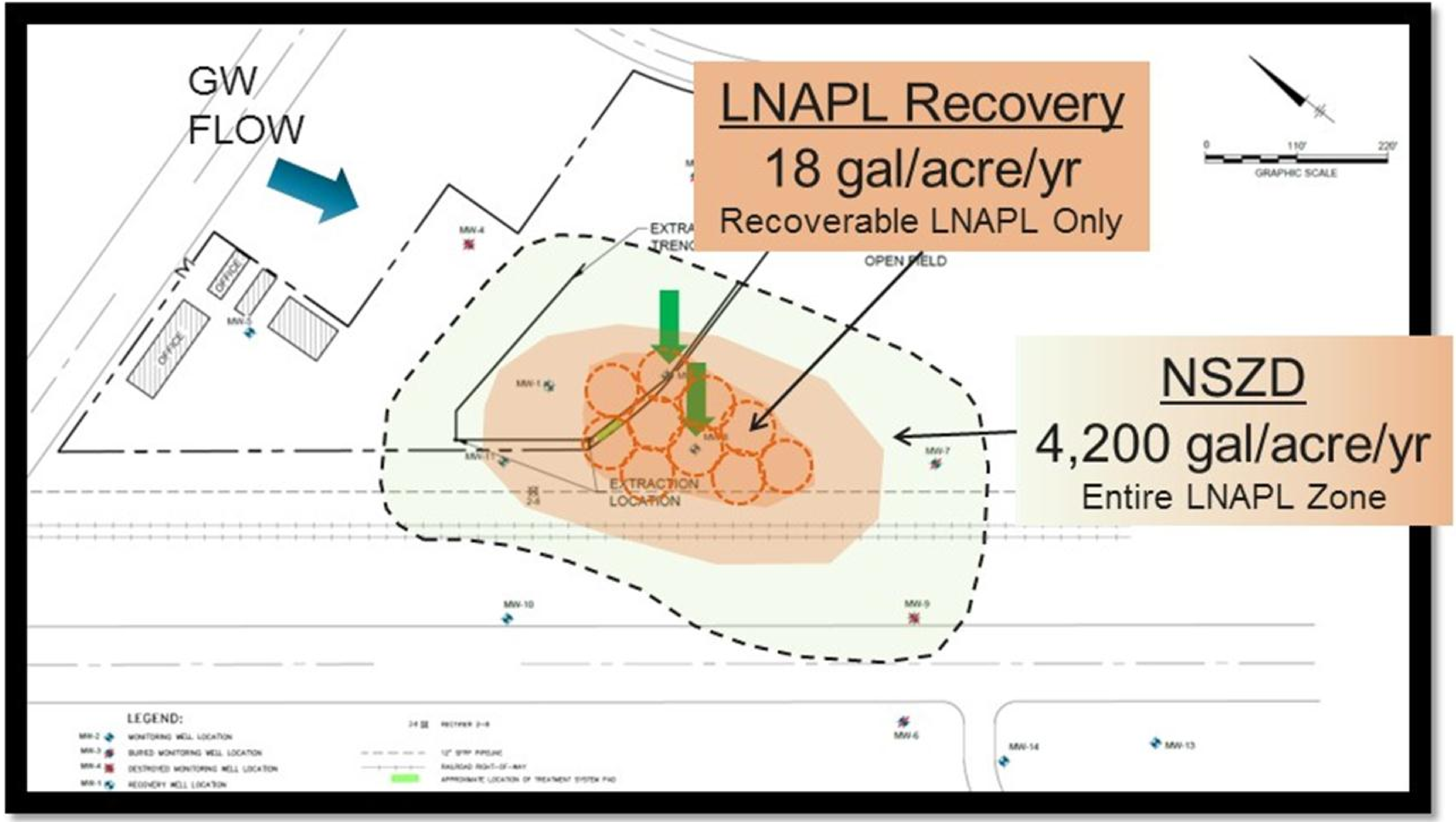
NSZD-3
7,808 (May/June 2014)
1,593 (June 2015)

NSZD-4
4,680 (May/June 2014)
2,898 (June 2015)

NSZD rates in gallons per acre per year

LNAPL Recovery vs. NSZD

NSZD Case Study #2



LNAPL Recovery

18 gal/acre/yr

Recoverable LNAPL Only

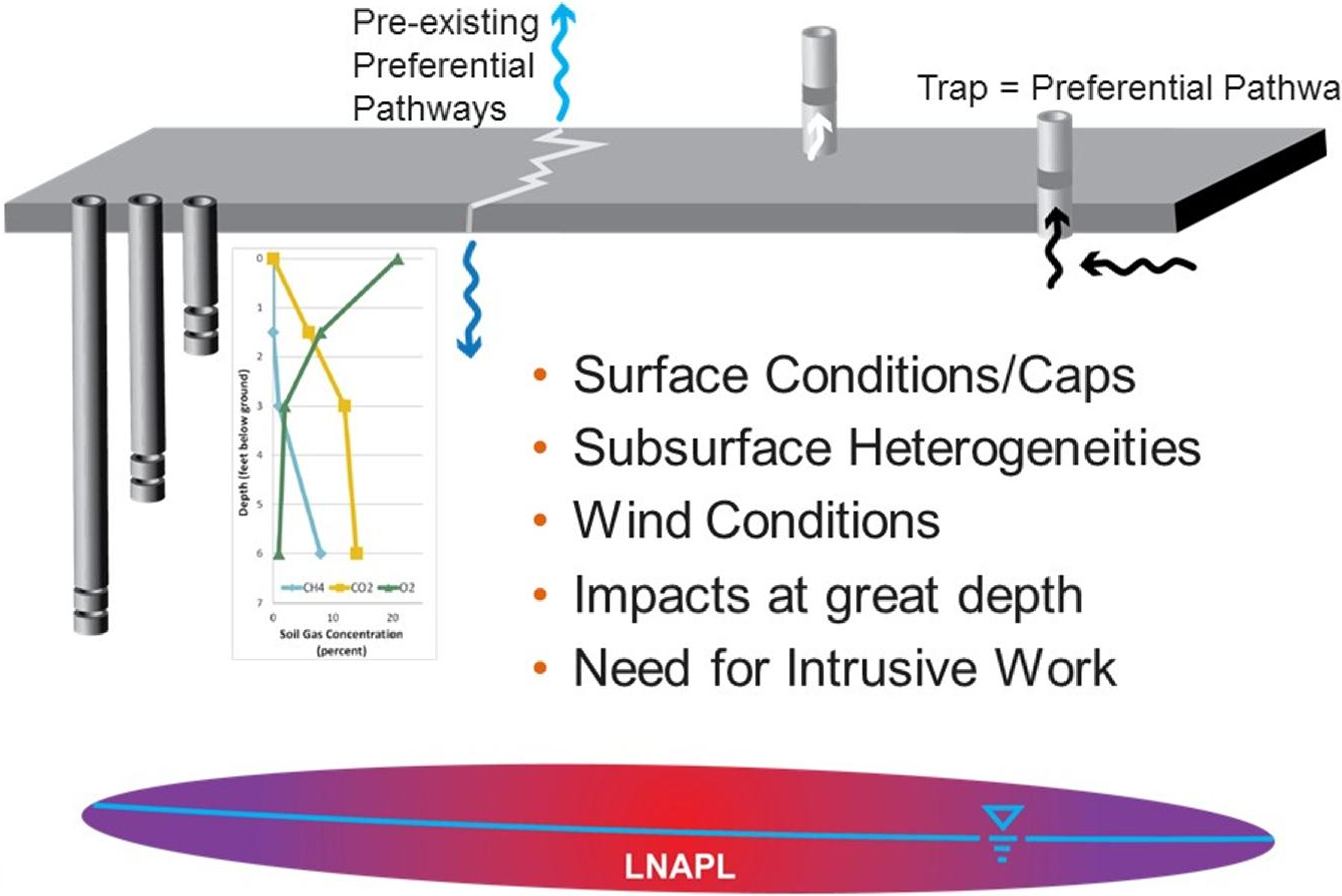
NSZD

4,200 gal/acre/yr

Entire LNAPL Zone

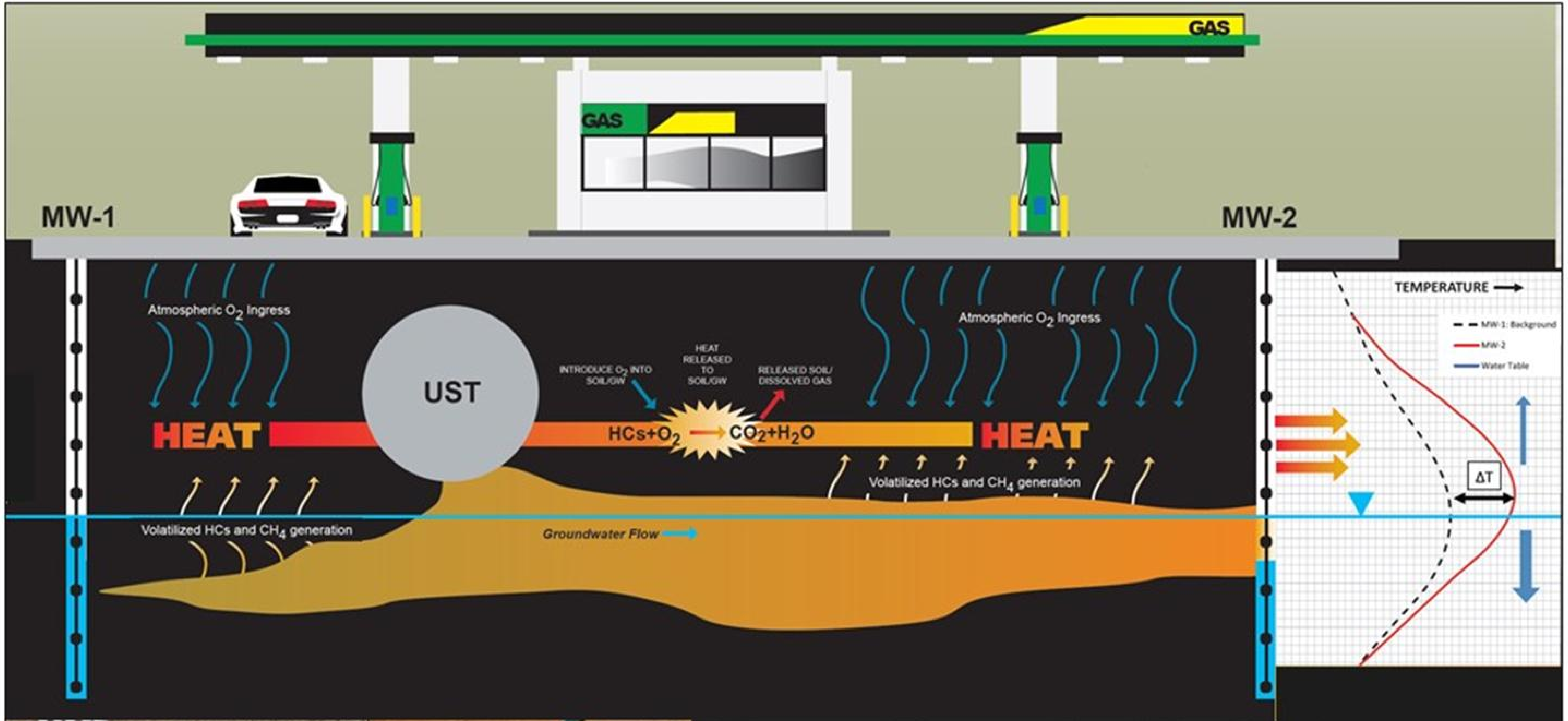
NSZD is >200x More Effective than LNAPL Recovery

Challenges with Soil Gas Methods



- Surface Conditions/Caps
- Subsurface Heterogeneities
- Wind Conditions
- Impacts at great depth
- Need for Intrusive Work

Temperature-Based NSZD Concept

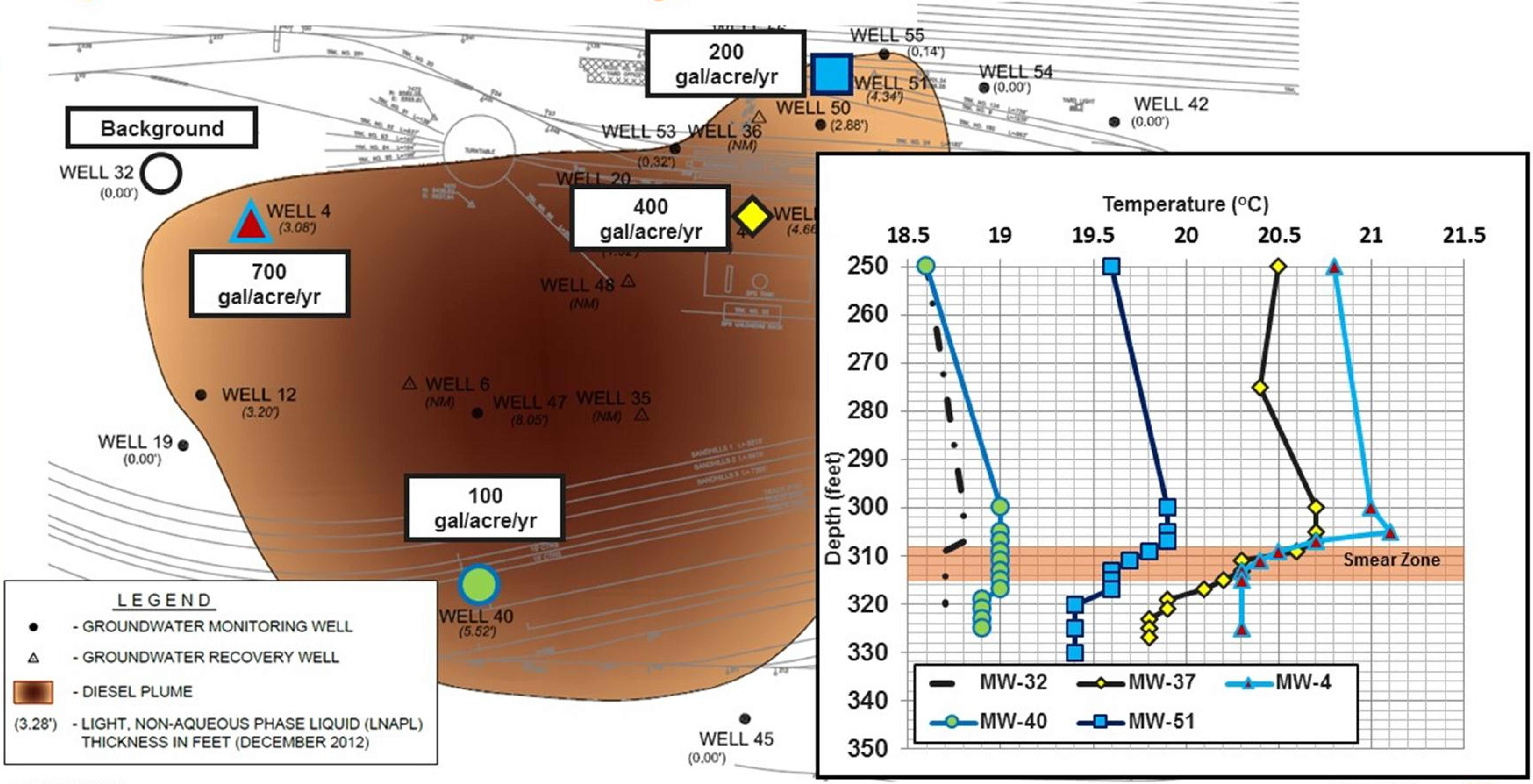


Thermal Anomalies Identified by Measuring Temperature Distribution Down Existing Wells

- "Snapshot" Data by Lowering Thermocouple / Temperature Probe, or
- Over Longer Time Periods Using Data Loggers Placed at Different Depths

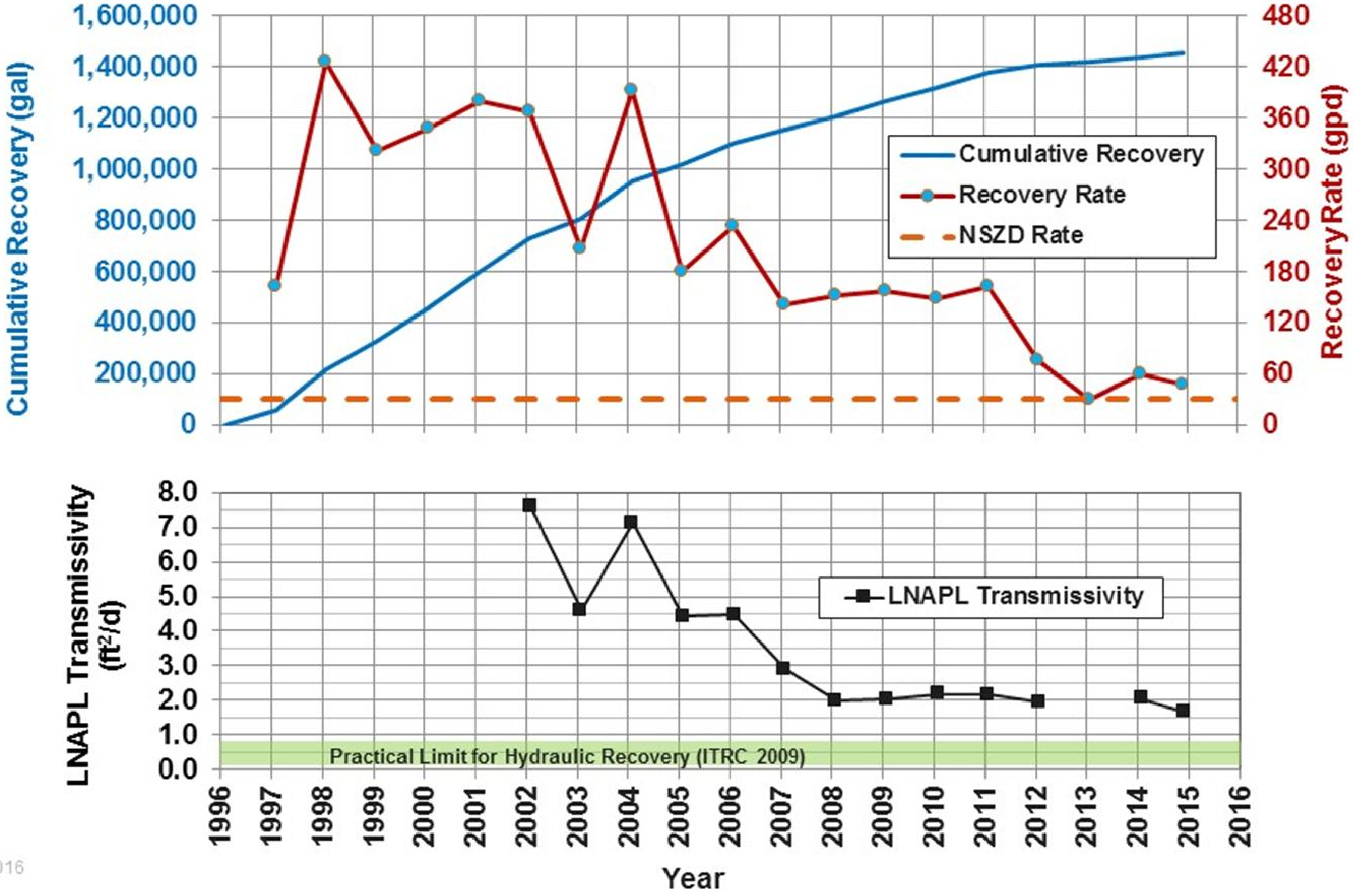
Temperature Case Study

NSZD Case Study #3



LNAPL Recovery vs. NSZD

NSZD Case Study #3



Questions?