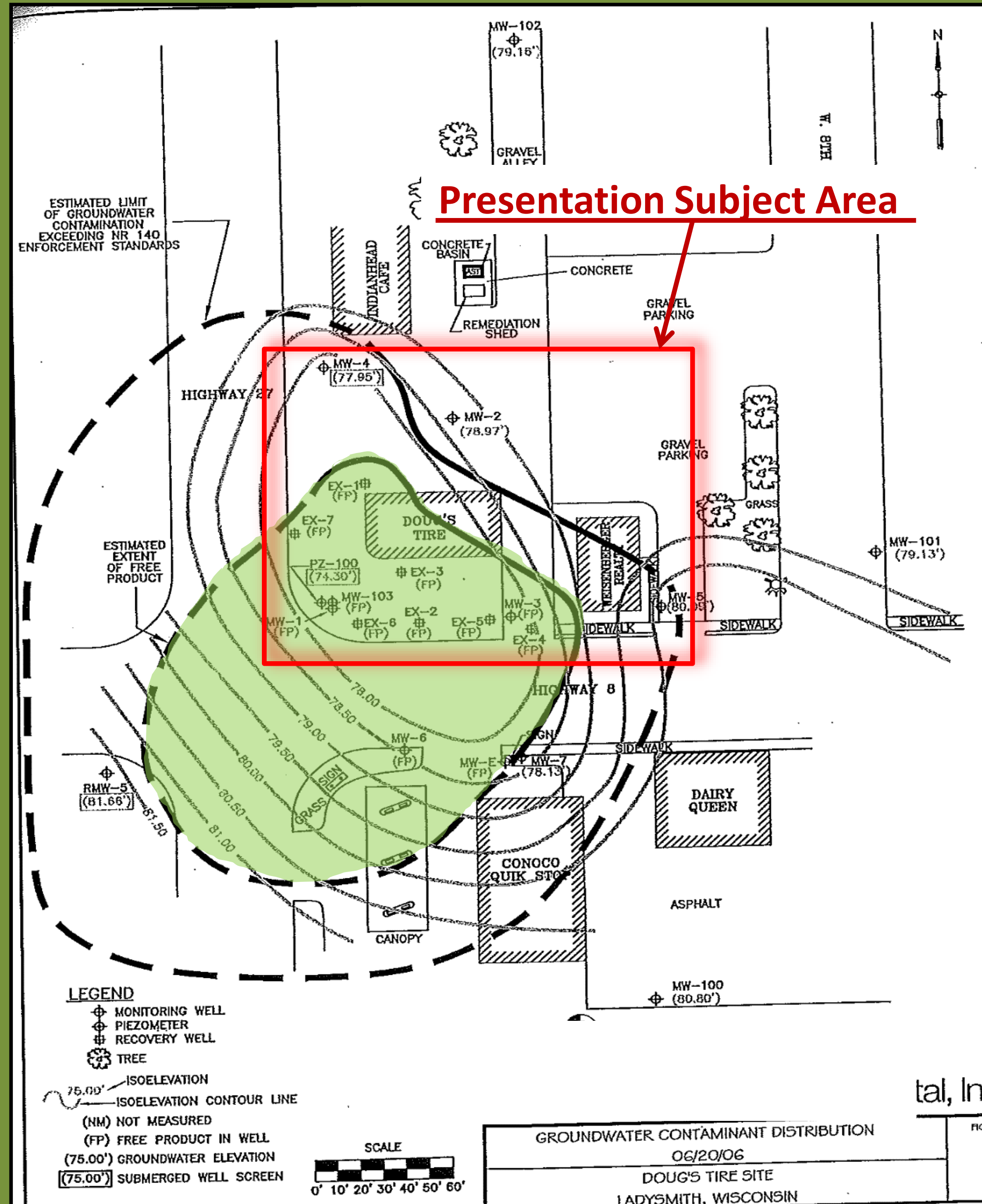
Pre-Assessment

2006 LNAPL Distribution
(one of three adjacent sites)

- 7-Well Extraction System
- Compressed Air Pumps
- Operated 2003-07
- Extracted Diesel and Gasoline
- 7K gals. LNAPL reportedly removed
- Relative water proportion uncertain (IMO)
- $670K reimbursed (PECFA)
- MWs contain 2-4 ft. LNAPL post-remedy

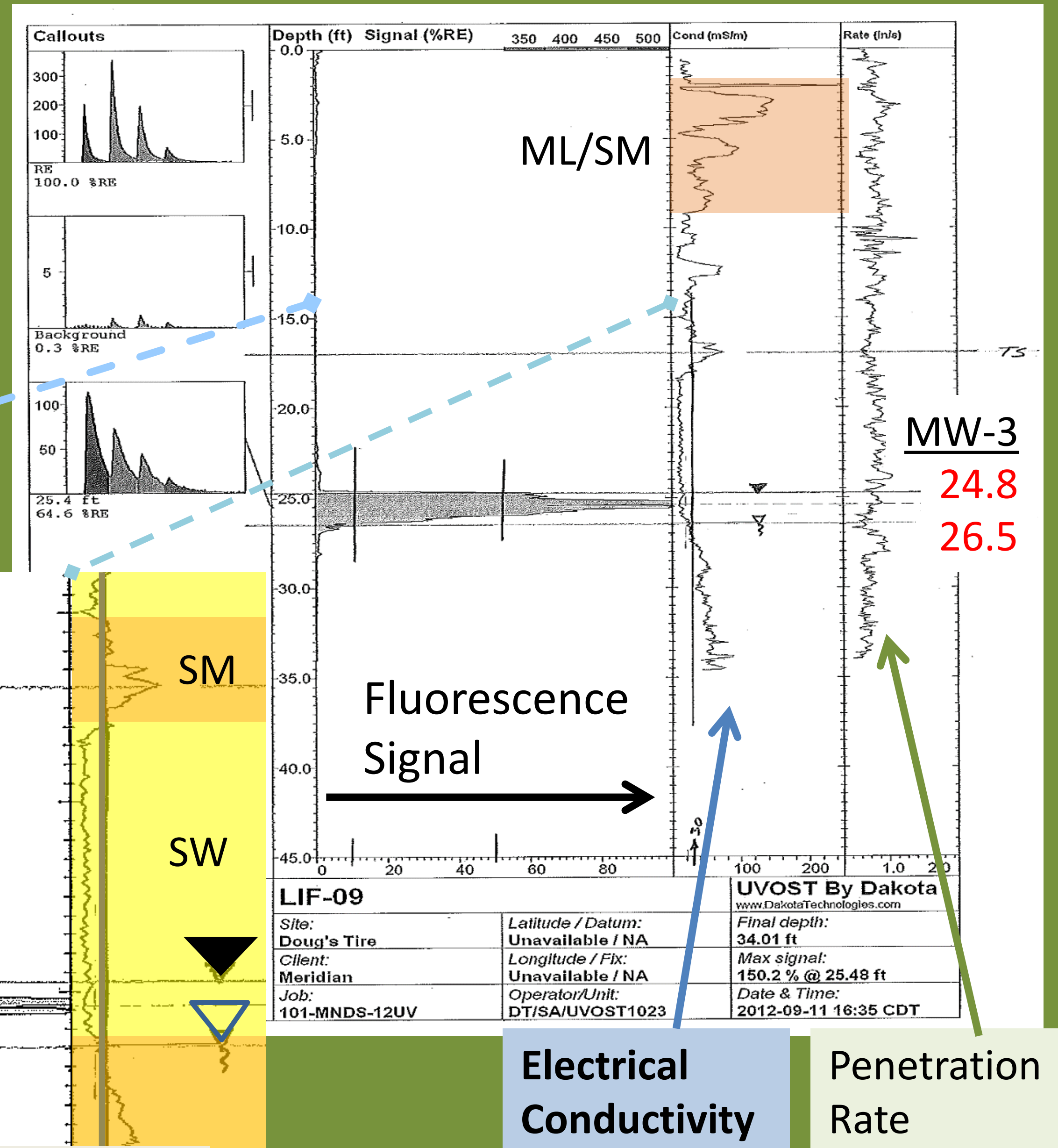


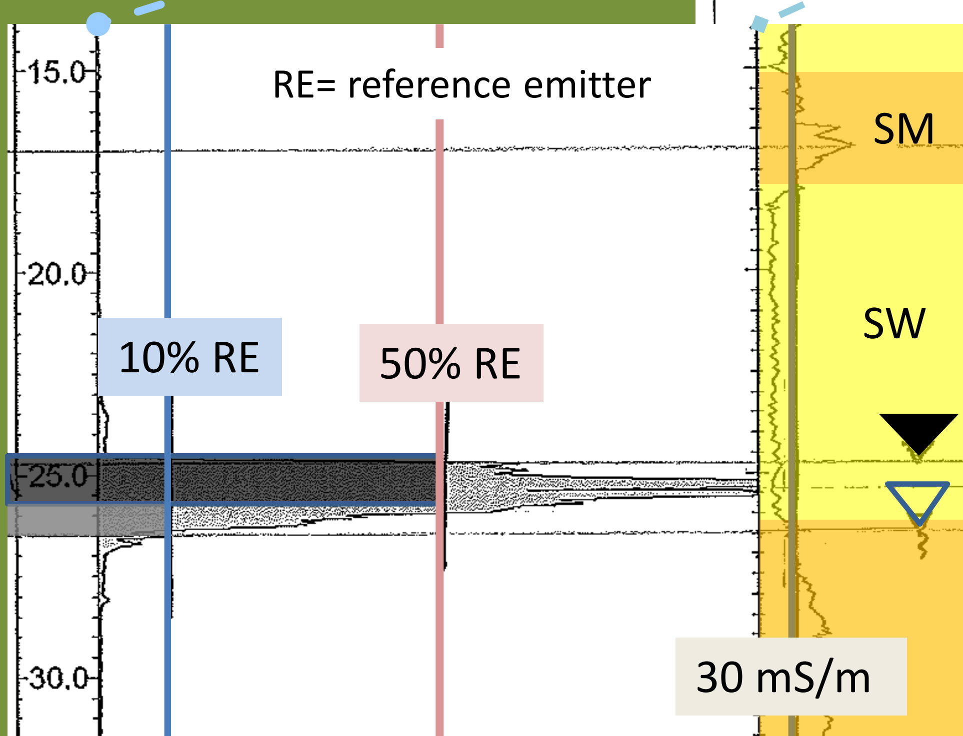
LNAPL Assessments conducted during 2011-12 on all three adjacent corner PECFA sites

- Significant LNAPL volumes remained on-site (3) and beneath the ROW.
- No modern assessments attempted.
- Active treatments (2) had effectively ended 4-5 years earlier.
- Remaining product was obviously “potent” (relatively un-weathered)
- Coordinated groundwater sampling showed a significant dissolved plume, including heavily impacted piezometers

Laser Induced Fluorescence (LIF) Survey Logs

(geophysical tools needing interpretation)





Lessons Learned

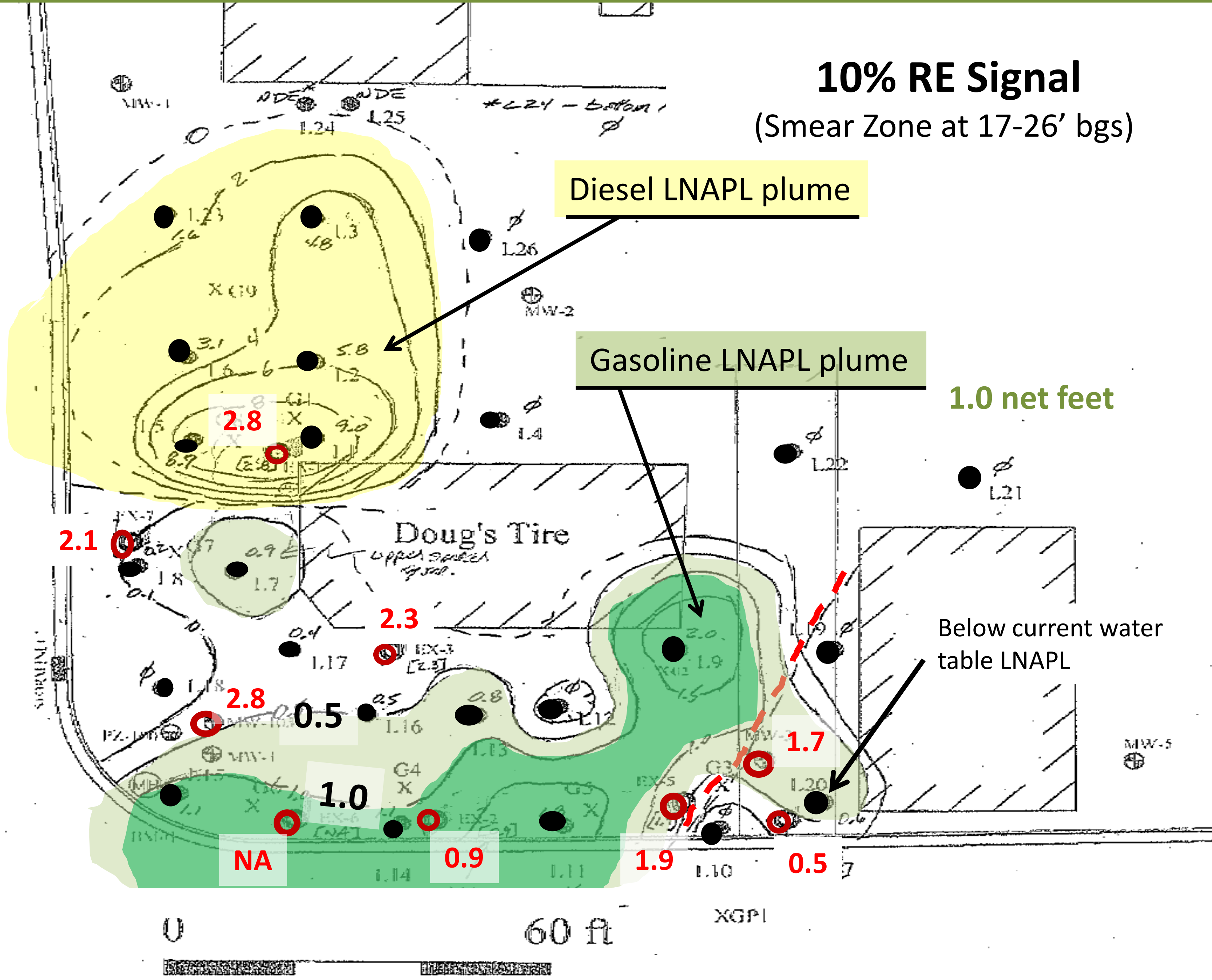
LIF Survey Log results need to be ***interpreted and integrated***:

- They cost >>$
- Fluorescence results provide thickness maps independent of wells. They also distinguish between products.
- Conductivity results provide detailed smear zone geology.
- Integrated results show LNAPL distributions that are far more detailed than any prior effort using boring log data.

Additional Hint:
Well LNAPL thicknesses should be measured the same day/start of survey.
LNAPL plume expression may not be obvious on LIF logs (e.g. LNAPL below water table, vadose zone contamination, plume changes over short distances, etc.).

10% RE Signal

(Smear Zone at 17-26' bgs)



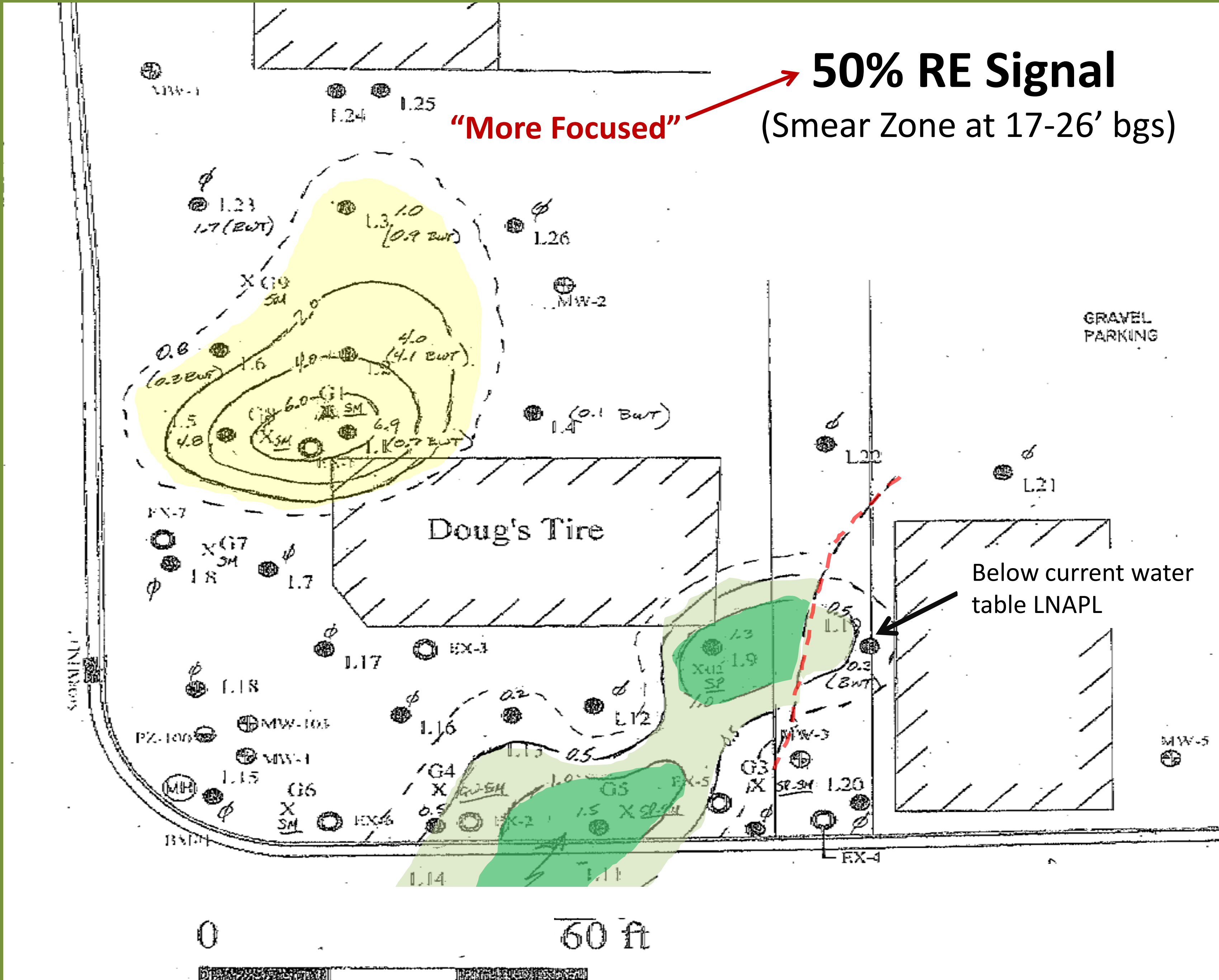
Lessons Learned

LIF results can show disconnect between true LNAPL plume thickness/distribution and that suggested by well data.

Well data is subject to artifacts related to vertical LNAPL movement (i.e., drainage and imbibition effects in the near wellbore environment).

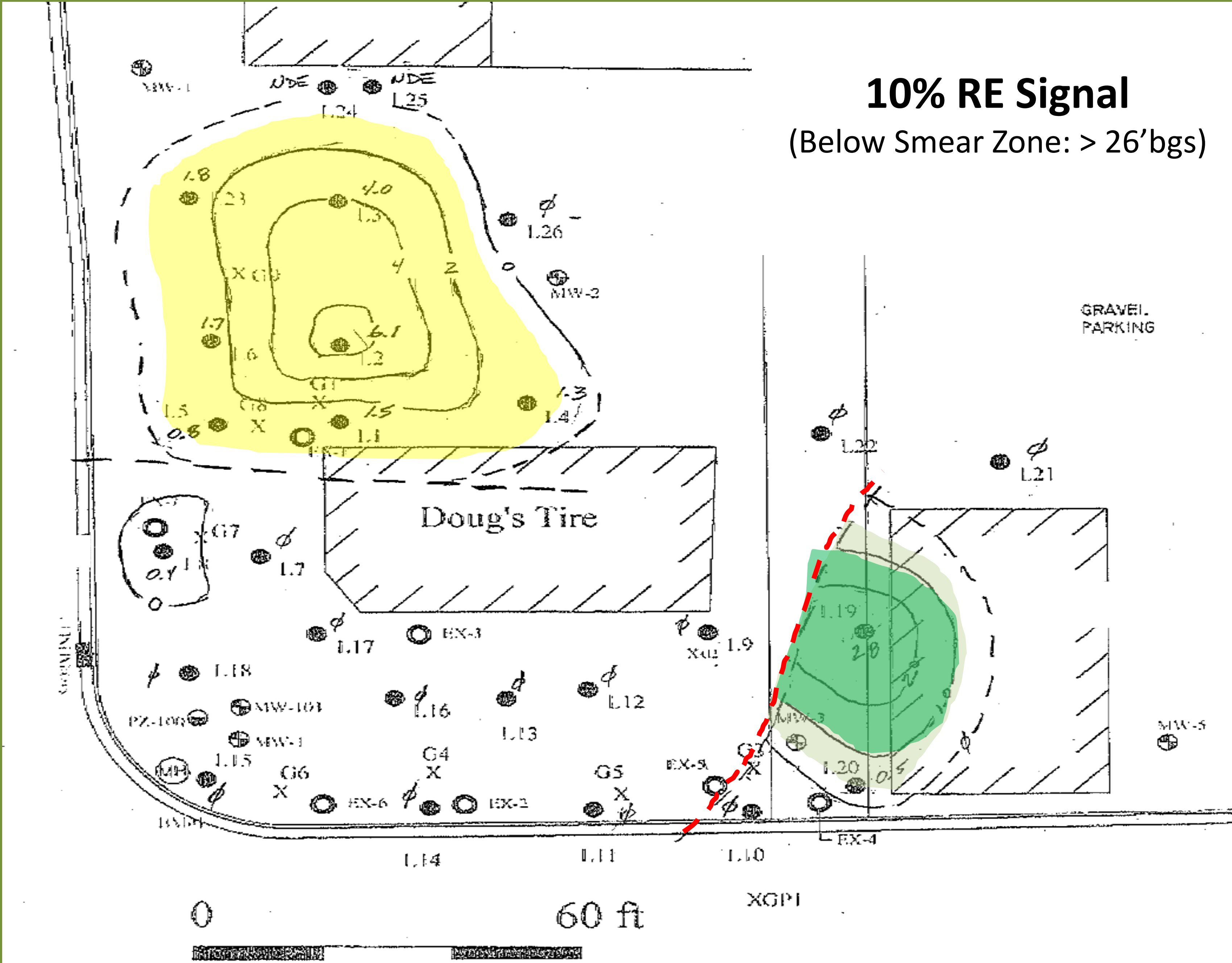
50% RE Signal

(Smear Zone at 17-26' bgs)

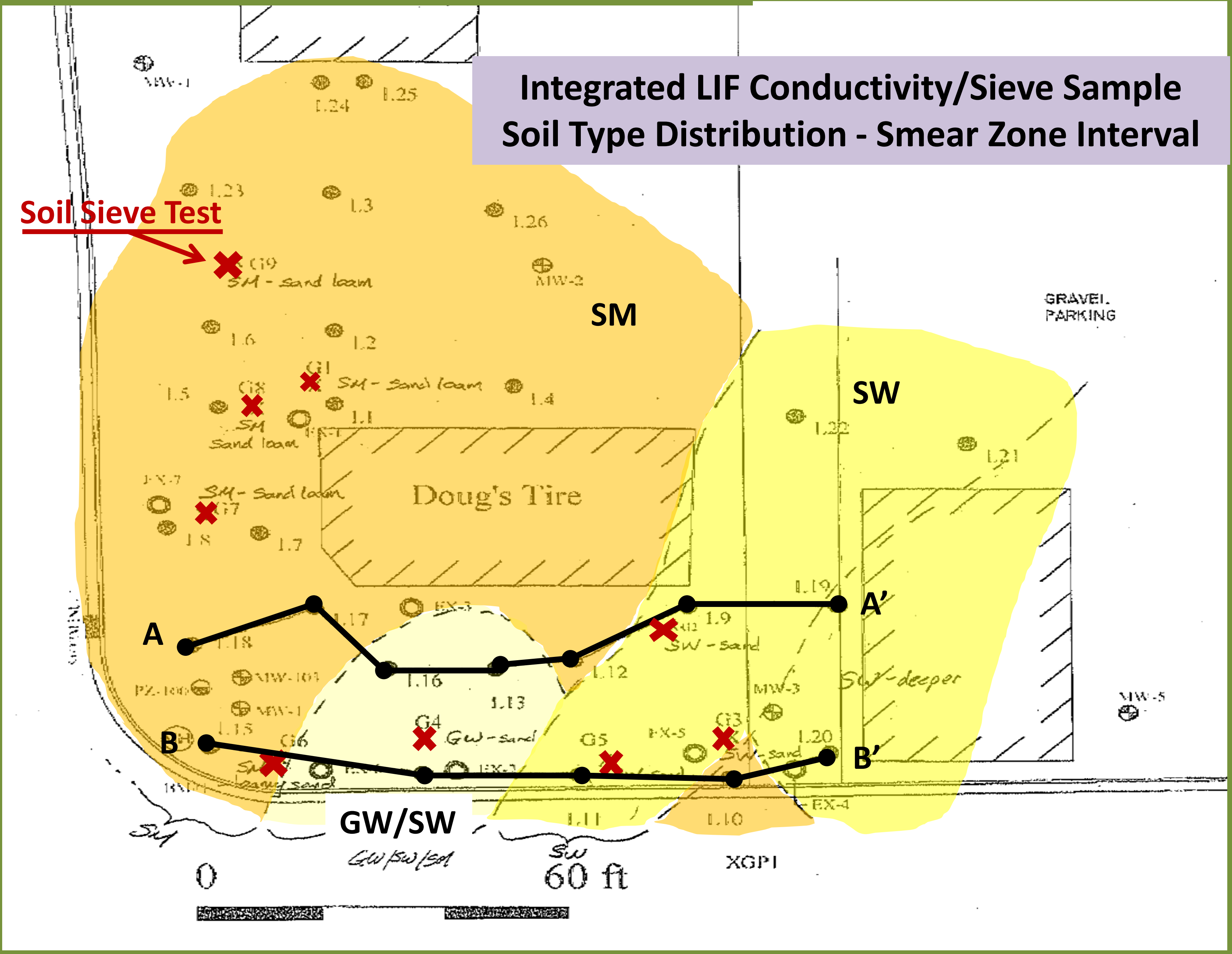


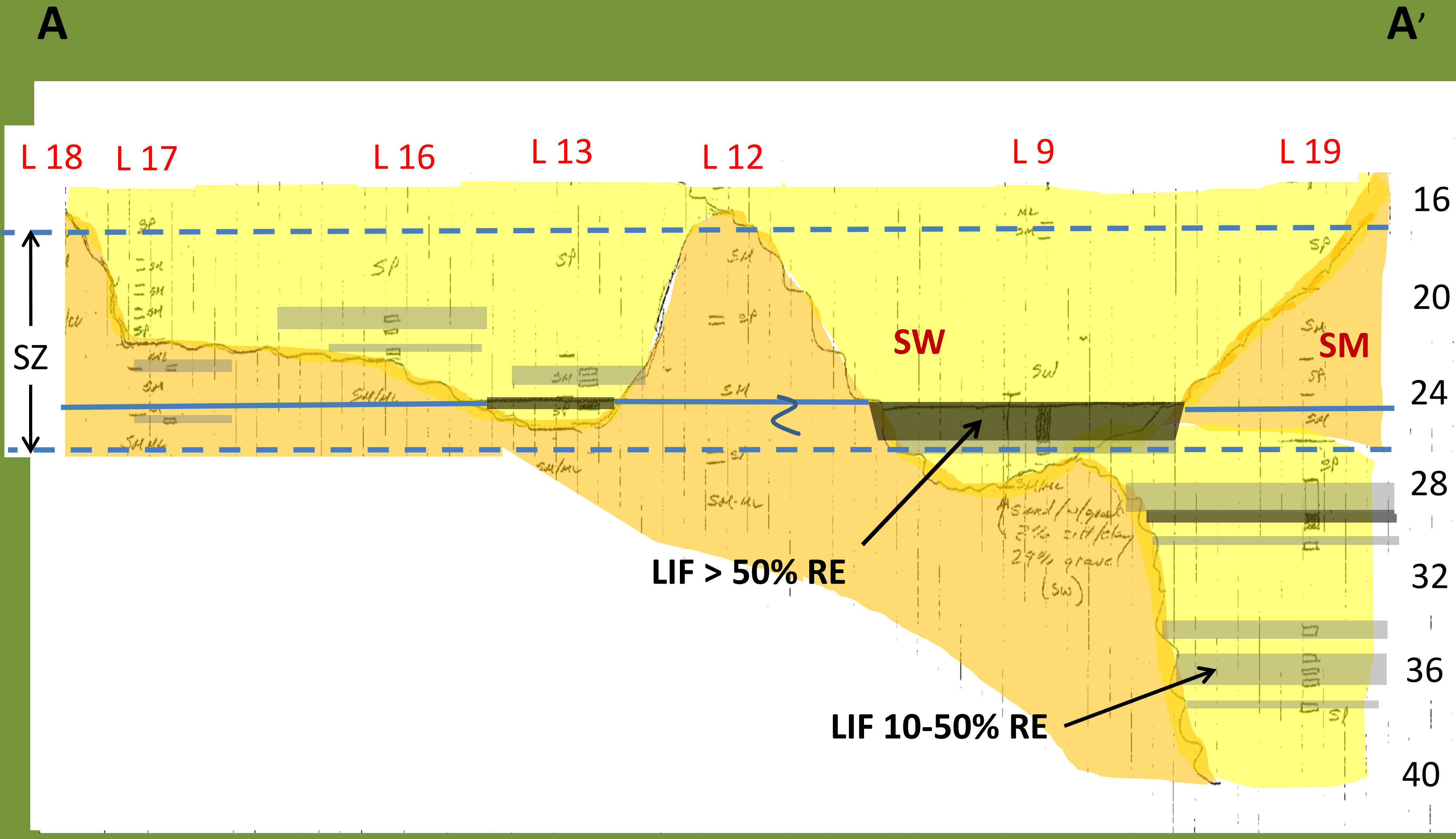
10% RE Signal

(Below Smear Zone: > 26'bgs)



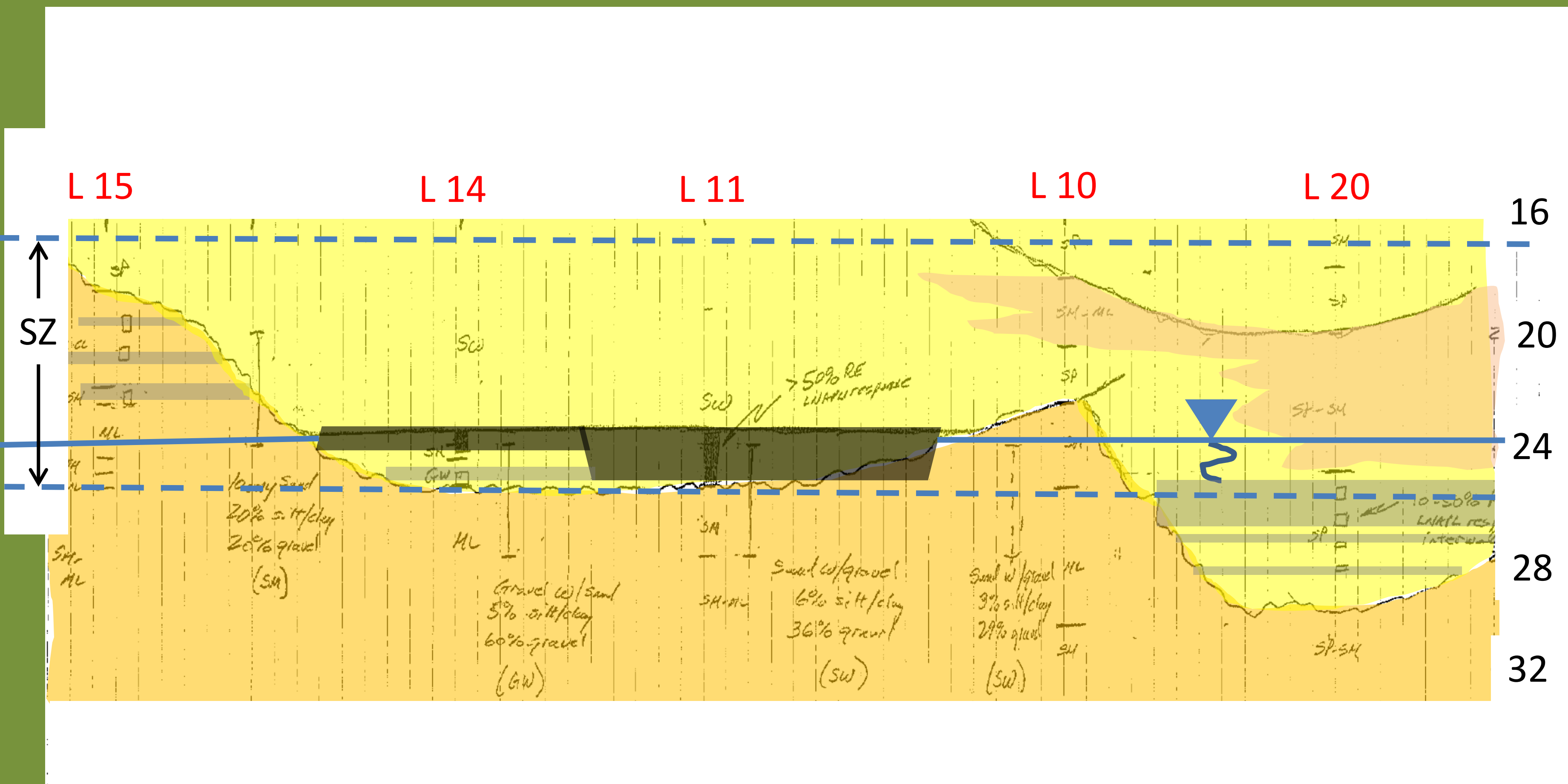
Integrated LIF Conductivity/Sieve Sample Soil Type Distribution - Smear Zone Interval





A
A'
L 18
L 17
L 16
L 13
L 12
L 9
L 19
16
20
24
28
32
36
40
SZ
SW
SM
LIF > 50% RE
LIF 10-50% RE

B **B’**


L 15
L 14
L 11
L 10
L 20
SZ
16
20
24
28
32
Loamy Sand
20% silt/clay
20% gravel
(SM)
Gravel w/Sand
5% silt/clay
60% gravel
(GW)
Sand w/gravel
6% silt/clay
36% gravel
(SW)
Sand w/gravel
3% silt/clay
29% gravel
(SW)
>50% RE
LNAPL response

Lessons Learned

LIF survey-based distribution maps allow:

- Improved means to estimate in-place volumes and mobility estimates (i.e., better LNAPL h).
- Ability to focus LNAPL remedial efforts (location).
- Determine if LNAPL volumes are present below the water table.

LNAPL Assessment Reports - Data Integration Is Necessary for Meaningful Assessments

<u>Model Inputs Provided By</u>:

LNAPL Smear Zone Soil Sampling, Cross Sections, HC, and VG

LNAPL Fluid Parameters

LIF Survey

LDRM Modeling

Adjust Model

LNAPL Baildown Results: **Transmissivity (T_n) ft^2/d**

Multiple Wells

ASTM Standard E2856
LNAPL Transmissivity Workbook – Baildown Analysis (API)

<u>Model Output:</u>

Specific Volume Factors (In-place Volume Est.)

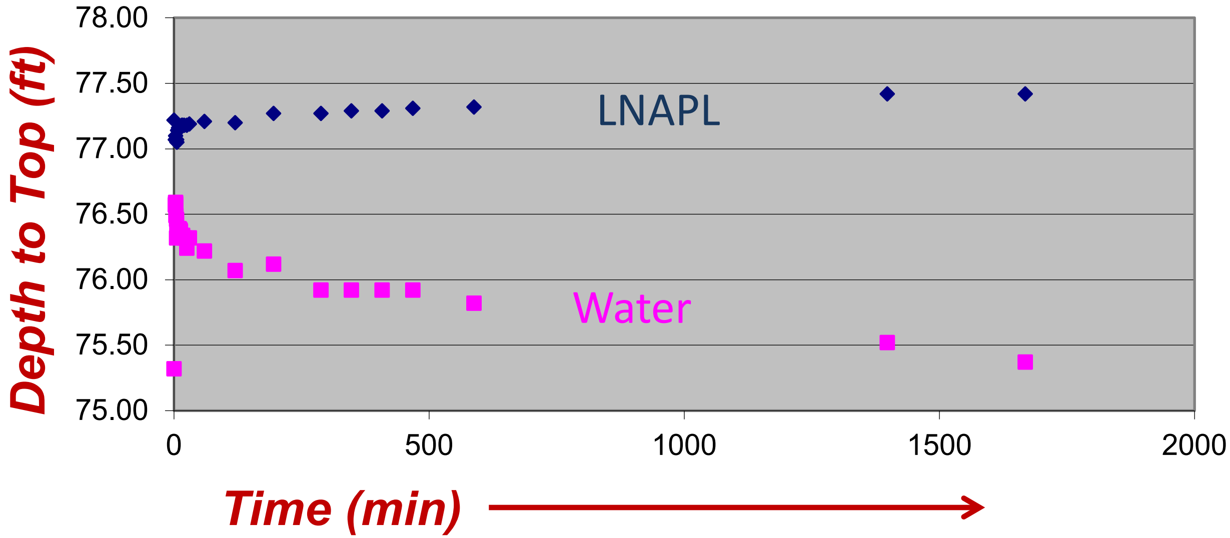
Recovery Efficiencies - Characterize ***<u>Relative</u>*** Mobility – Not Absolute Mobility

High-Grade LNAPL Recovery Areas (Focus Remedy)

LDRM: LNAPL Distribution and Recovery Model (API)
HC: aquifer hydraulic conductivity
VG: vertical gradient

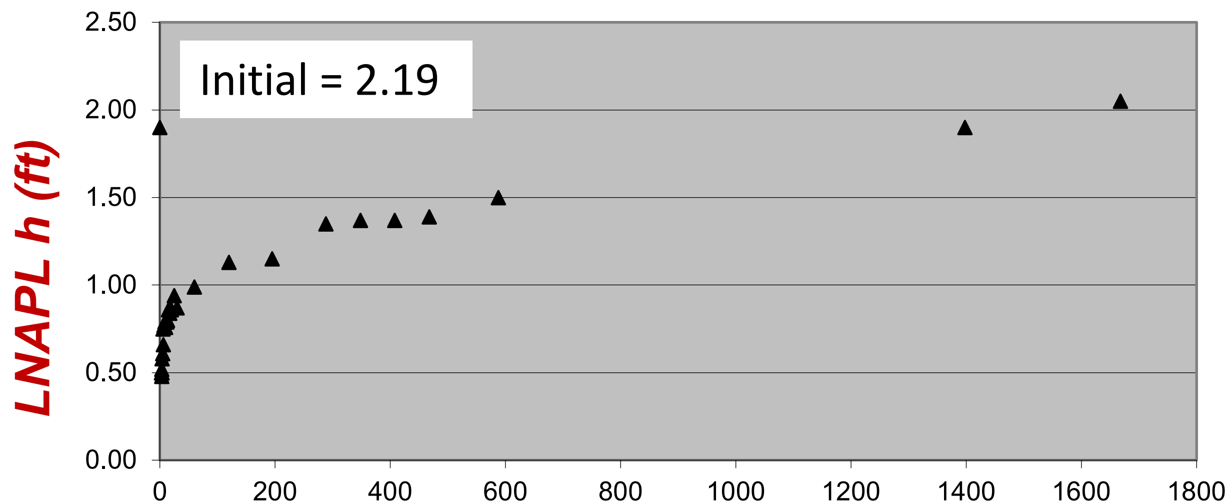
Baildown Results MW3

Raw Data



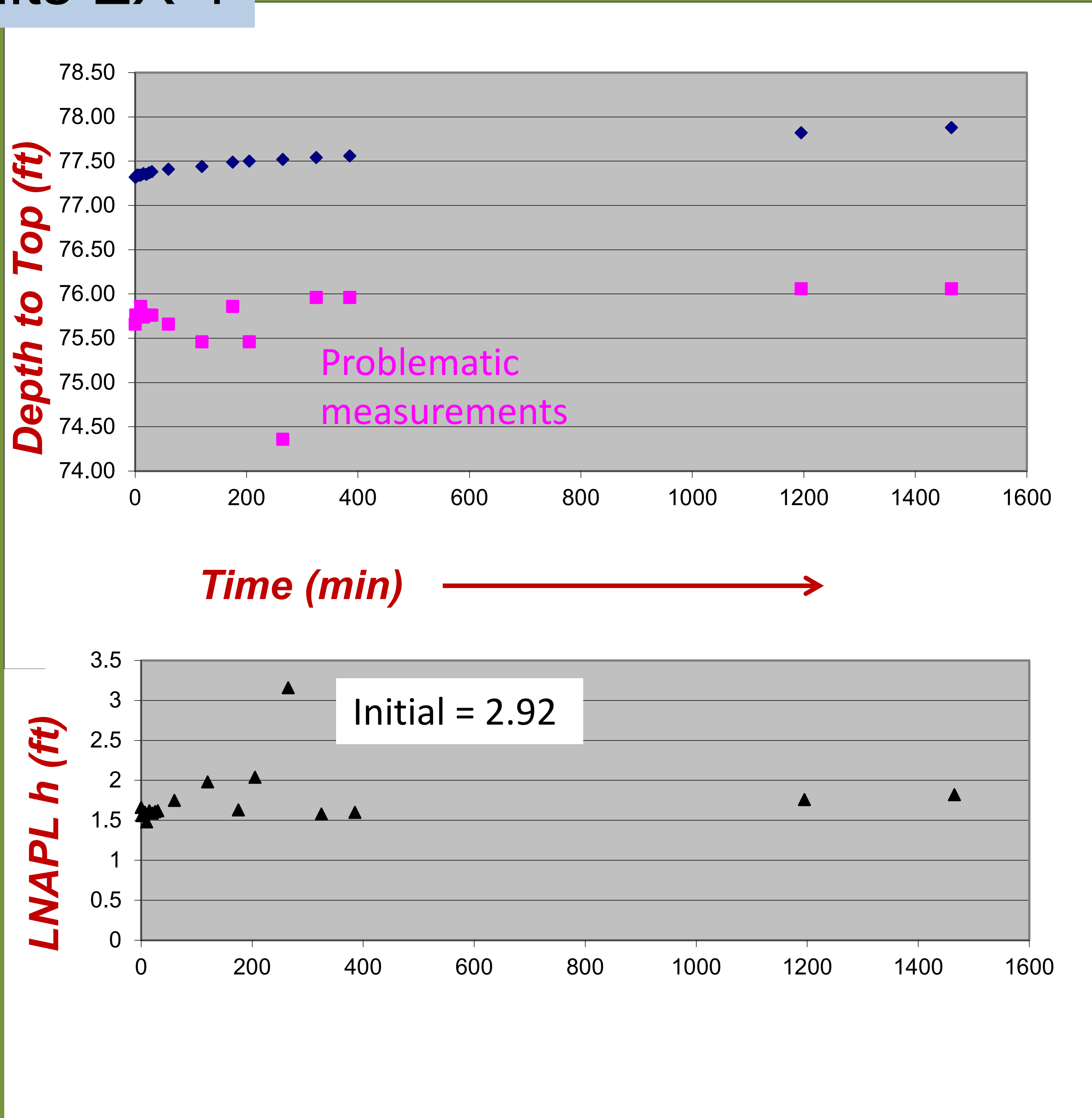
LNAPL Recovery

Analysis Result:
$T_n = 0.3\ ft^2/d$



Baildown Results EX-1

Raw Data



LNAPL Recovery

Analysis Result:

T_n = 0.02 ft²/d

Lessons Learned

LNAPL Baildown Tests:

- As conducted, difficult to obtain accurate raw data - five of six were problematic, based on inspection alone (i.e., inaccurate LNAPL/water interface measurements).
- Analyses provided relative mobility ($\mathbf{T_n}$) results. Allowed comparisons between wells, but data accuracy severely limited use as a LDRM model calibration tool.
- Sufficient LNAPL must be present (> 1 foot) – analysis assumes only LNAPL removed.
- Baildown analysis tool provides three $\mathbf{T_n}$ estimates and their associated statistical qualifications.
- Consideration needed for field techniques to improve data quality.
- Consideration needed for temporal effects on $\mathbf{T_n}$.

Summary Table of LDRM Model Results

LNAPL Model Results - Dougs Tire, Ladysmith (54848-1215-11)

API van Genuchten-Burdine Model of LNAPL Distribution and Realtive Permeability (Single Layer)[1]

API van Genuchten-Mualem Model of LNAPL Distribution and Realtive Permeability (Single Layer)[1]

Aquifer Hydraulics

	t (yr)	Rc (ft)	Ri (ft)
Skimmer well: $Q_w = 0$	2	20	20
Vertical Gradient (site)	-0.05		
HC groundwater (ft/d) (site)	1.42		

LNAPL Fluid Properties

Fluid Parametes		hered gas	site gas	site diesel
LNAPL density (gm/cc)	ρ_o	0.73	0.754	0.79
LNAPL viscosity at 60^{0}F (cP	μ_0	0.62	0.6	1.1
air-water tension (dynes/cm	σ_{aw}	65	57.8	59.3
air-oil tension (dynes/cm)	σ_{aw}	21	21.3	24.3
oil-water tension (dynes/cm)	σ	50	15.1	15

Individual, Site-Specific Model Run (Inputs)

Geologic Subareas

Dual Phase Soil and Saturation Parameters

Inputs

						Site - Smear Zone (gasoline)				BWT (gasoline)		Site - Smear & BWT (diesel)		
model		Burdine[1]						Mualem		Burdine		Mualem		
soil types		Ideal Sand w/uw fluids	Ideal Sand w/site fluids,grad,h	>50% RE SW/GW	>50% RE SW/GW	10-50% SW/GW	10-50% SW/GW/SM	10-50% SM	10-50% SM	10-50% SW/GW - BWT	10-50% SW/GW - BWT	SM	SM	SM
LNAPL h		3	1.5	1.25	0.5	0.5	0.5	1	0.5	2	0.75	4	2	1
vertical gradient		0	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05	-0.05
porosity	n	0.43	0.43	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
aquifer conductivity (ft/d)	K_w	23	23	23	23	23	11	1.4	1.4	23	23	1.4	1.4	1.4
van Genuchten "N"	N	2.68	2.68	2.68	2.68	2.68	2.28	1.5	1.5	2.68	2.68	1.5	1.5	1.5
van Genuchten "α"	α	4.4	4.4	4.4	4.4	4.4	3.8	1.4	1.4	4.4	4.4	1.4	1.4	1.4
irreducible water saturation	S_{wr}	0.1	0.1	0.1	0.1	0.15	0.25	0.3	0.3	0.15	0.15	0.3	0.3	0.3
LNAPL Residual Saturation (f-Factor) [1]		0.18	0.18	0.20	0.20	0.50	0.55	0.6	0.6	0.5	0.5	0.6	0.6	0.6
Recovery Model Results:														
in-place specific volume (ft)		0.55	0.33	0.24	0.07	0.06	0.03	0.09	0.03	0.52	0.13	0.67	0.24	0.07
recovery efficiency		78%	71%	67%	34%	35%	11%	20%	11%	49%	44%	31%	21%	12%
relative mobility[3] (reduction from ideal sd.)		-	-9%	-14%	-56%	-55%	-86%	-74%	-86%	-37%	-44%	-60%	-73%	-85%
Initial T(ft^2/d)		15.5	9.2	6.5	5.8	0.9	0.8	0.33		18.5	2.7	1.7	0.55	0.14
T(ft^2/d) - 1yr		3.5	2.5	1.3	0.5	0.18	0.18	0.08		7.0	0.7	0.7	0.18	0.04
Initial Sn		0.65	0.65	0.6	0.35	0.42	0.2	0.25	0.15	0.7	0.55	0.5	0.35	0.25

Model Outputs (next slide)

Notes: Site HC groundwater were measured from MW2, MW4, and MW5. In the case of -2 and -4, soils appear to be SM

LDRM Model Outputs for Gasoline Smear Zone – Various Sub-Areas

			Site - Smear Zone (gasoline)				
Model Type	Burdine						Mualem
Geologic Subarea	Ideal Sand w/uw fluids	Ideal w/site fluids,grad,h	>50% RE SW/GW	>50% RE SW/GW	10-50% SW/GW	10-50% SW/GW/SM	10-50% SM
LNAPL h	3	1.5	1.25	0.5	0.5	0.5	1
Recovery Model Results:							
in-place specific volume (ft)	**0.55**	**0.33**	**0.24**	**0.07**	**0.06**	**0.03**	**0.09**
recovery efficiency	78%	71%	67%	34%	35%	11%	20%
relative mobility (reduced f/ideal)	**-**	**-9%**	**-14%**	**-56%**	**-55%**	**-86%**	**-74%**
Trans./LNAPL Sat. Results:							
Initial **Tn** (ft^2/d)	**15.5**	**9.2**	**6.5**	**5.8**	**0.9**	**0.8**	**0.33**
Tn (ft^2/d) - 1yr	3.5	2.5	1.3	0.5	0.18	0.18	0.08
Initial S_n	0.65	0.65	0.6	0.35	0.42	0.2	0.25

Recovery Efficiency can not be used in an absolute sense!

- No real world effects: radial drainage, anisotropy, relative permeability, vertical equilibrium, BWT access, etc.
- At a ***minimum*** needs pilot testing calibration, but still not real in terms of time (medium and long-term recovery)

Recovery Efficiency	78%	71%	67%	34%	35%	11%	20%
Relative mobility (reduced f/ideal)	**-**	**-9%**	**-14%**	**-56%**	**-55%**	**-86%**	**-74%**

Hence, relative mobility measure - a comparison metric.

In-Place LNAPL Volume Summary

Total Estimated On-Site, In-Place LNAPL:
28,000 gallons

	Relative Mobility	LNAPL (gal.)
LNAPL In-Place Volume – Gasoline Related		
Vadose	NA	300
Smear Zone >50% RE	-14% to -56%	1,600
Smear Zone 10-50% RE	-55% to -86%	1,400
Below Water Table (BWT)	-37% to -44%*	3,200
LNAPL In-Place Volume – Diesel Related		
Vadose	NA	2,500
Smear Zone	-60% to -85%	10,200
BWT	-60 to -85%*	9,100

* BWT relative mobility values only applicable at exceedingly low water levels (i.e., smear zone much deeper than 26' bgs.)

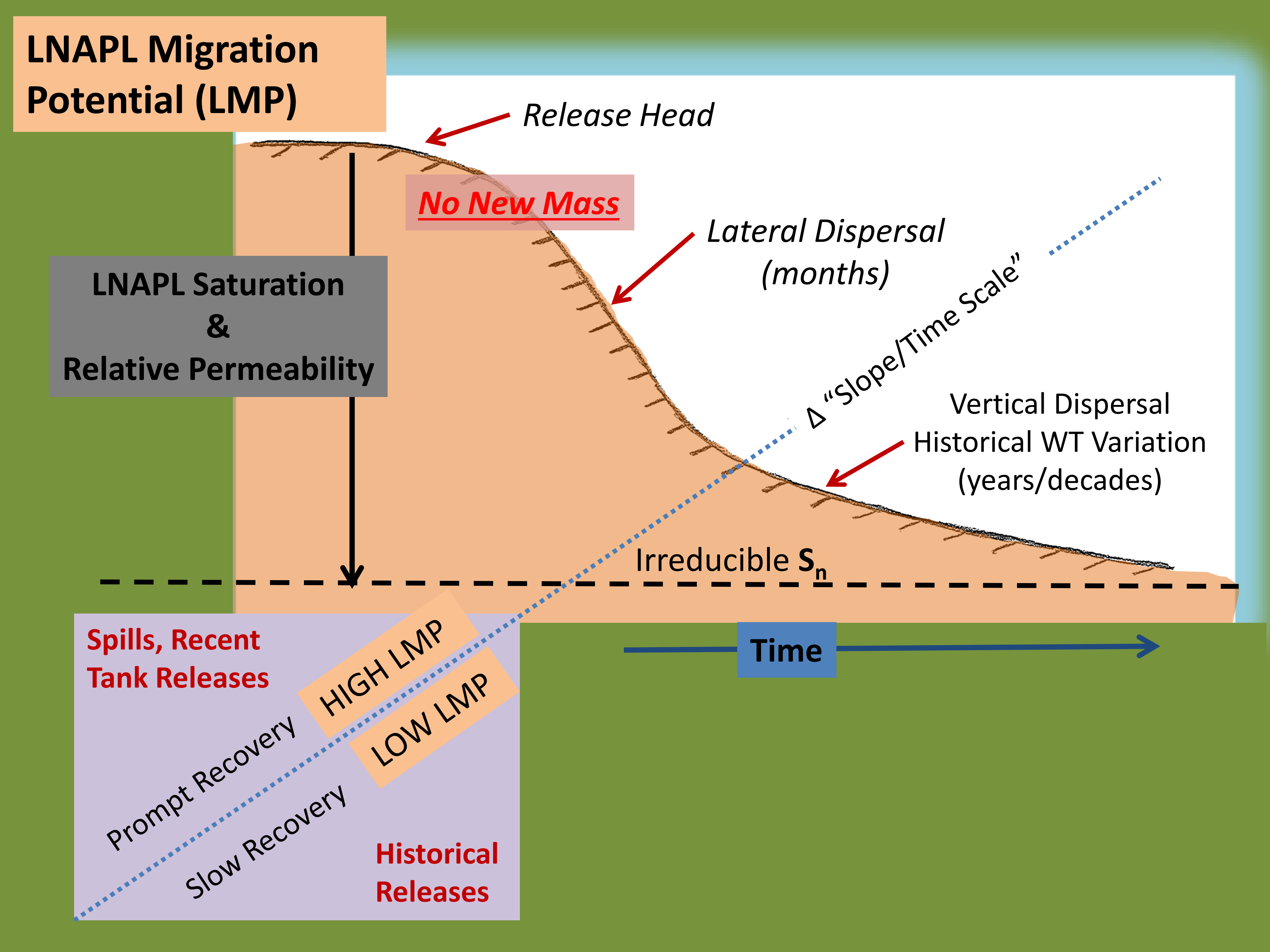
Gasoline Related Smear Zone extents beneath ROW and likely reflects 2-5X or more volume in-place (i.e., 6-15K additional gallons in place)

Lessons Learned

We can integrate a wide range of site-specific, LNAPL-related data to provide estimates of in-place LNAPL volumes (i.e., modeled specific volume factors).

We can use relative mobility results (from above integration/modeling) together with the in-place estimates to drive LNAPL remedial strategies.

Consideration is needed regarding dual phase flow parameters for gravel dominated soils (heterogeneous and homogeneous).


LNAPL Migration Potential (LMP)
Release Head
No New Mass
Lateral Dispersal (months)
Δ "Slope/Time Scale"
LNAPL Saturation & Relative Permeability
Vertical Dispersal
Historical WT Variation
(years/decades)
Irreducible S_n
Time
Spills, Recent Tank Releases
HIGH LMP
LOW LMP
Prompt Recovery
Slow Recovery
Historical Releases