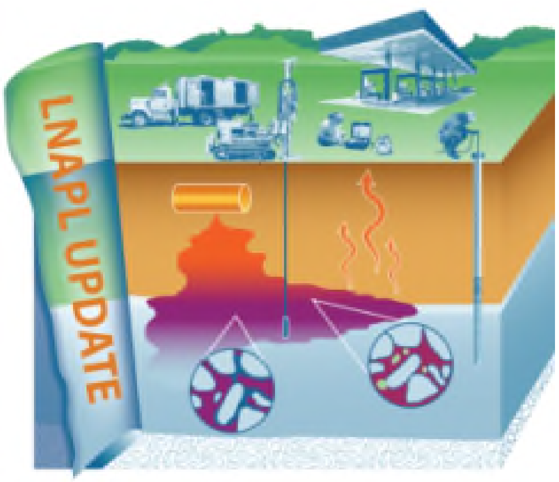
NTC2018 - LNAPL Review
September 10, 2018

Based on ITRC Guidance Document:
Light Non-Aqueous Phase Liquid (LNAPL) Site Management: LCSM Evolution, Decision Process, and Remedial Technologies (LNAPL-3, 2018)

3-Part Training Series: Connecting the Science to Managing Sites



Part 1: Understanding LNAPL Behavior in the Subsurface

Part 2: LNAPL Conceptual Site Models and the LNAPL Decision Process

Part 3: Using LNAPL Science, the LCSM, and LNAPL Goals to Select an LNAPL Remedial Technology

Sponsored by: Interstate Technology and Regulatory Council (www.itrcweb.org)
Presented by: Randy Chapman, Co-Team Lead – LNAPL Update

Interstate Technology & Regulatory Council (ITRC)

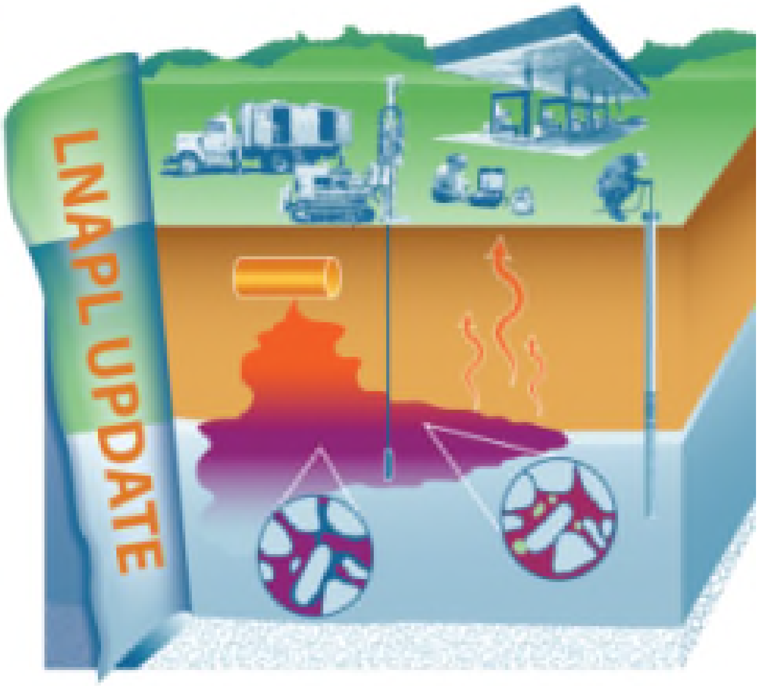
- Host organization
- Network
  - State regulators
    - All 50 states, PR, DC
  - Federal partners

DOE DOD EPA

  - ITRC Industry Affiliates Program
  - Academia
  - Community stakeholders

- ITRC materials available for your use
- Available from www.itrcweb.org
  - Technical and regulatory guidance documents
  - Online and classroom training schedule
  - More…
- Follow ITRC

Our Focus is on LNAPL
(Light Non-Aqueous Phase Liquid)



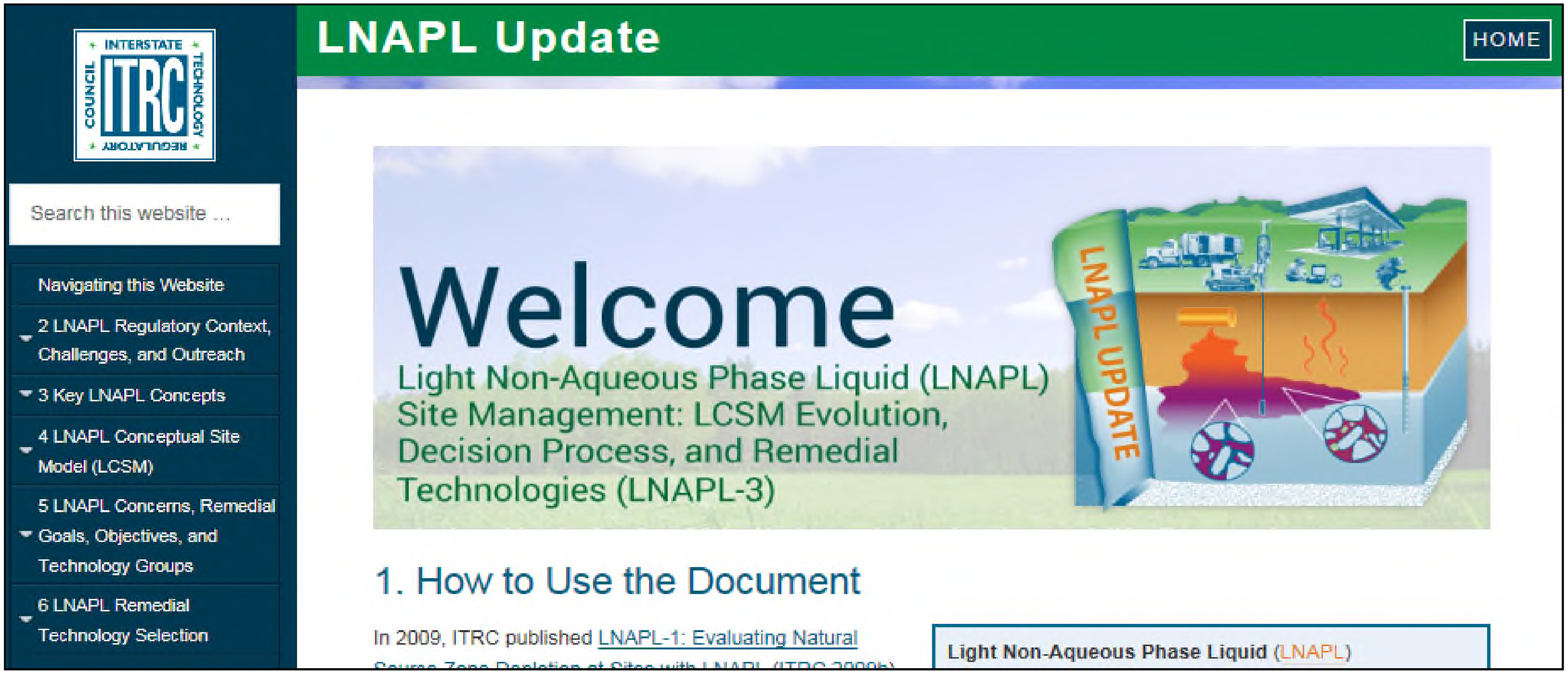
- What is LNAPL?
- Why Do We Care About LNAPL?
  - LNAPL Concerns
  - LNAPL can be difficult to accurately assess or recover
- Use LNAPL science to your advantage and apply at your sites

ITRC's History as LNAPL Solution Provider

- **2009:** *LNAPL-1 (Natural Source Zone Depletion) and LNAPL-2 (Evaluating LNAPL Remedial Technologies)*
- **2010 - 2017:**
  - LNAPL Online Training (3-parts)
  - LNAPL Classroom Training
  - Over 19,000 Trained
- **2016 - 2018:** ITRC LNAPL Update
- **March 2018:** *LNAPL-3 (LNAPL Site Management: LCSM Evolution, Decision Process, and Remedial Technologies)*
- **Spring 2018:** Updated 3-Part LNAPL Online Training

Your Online LNAPL Resource

https://lnapl-3.itrcweb.org/

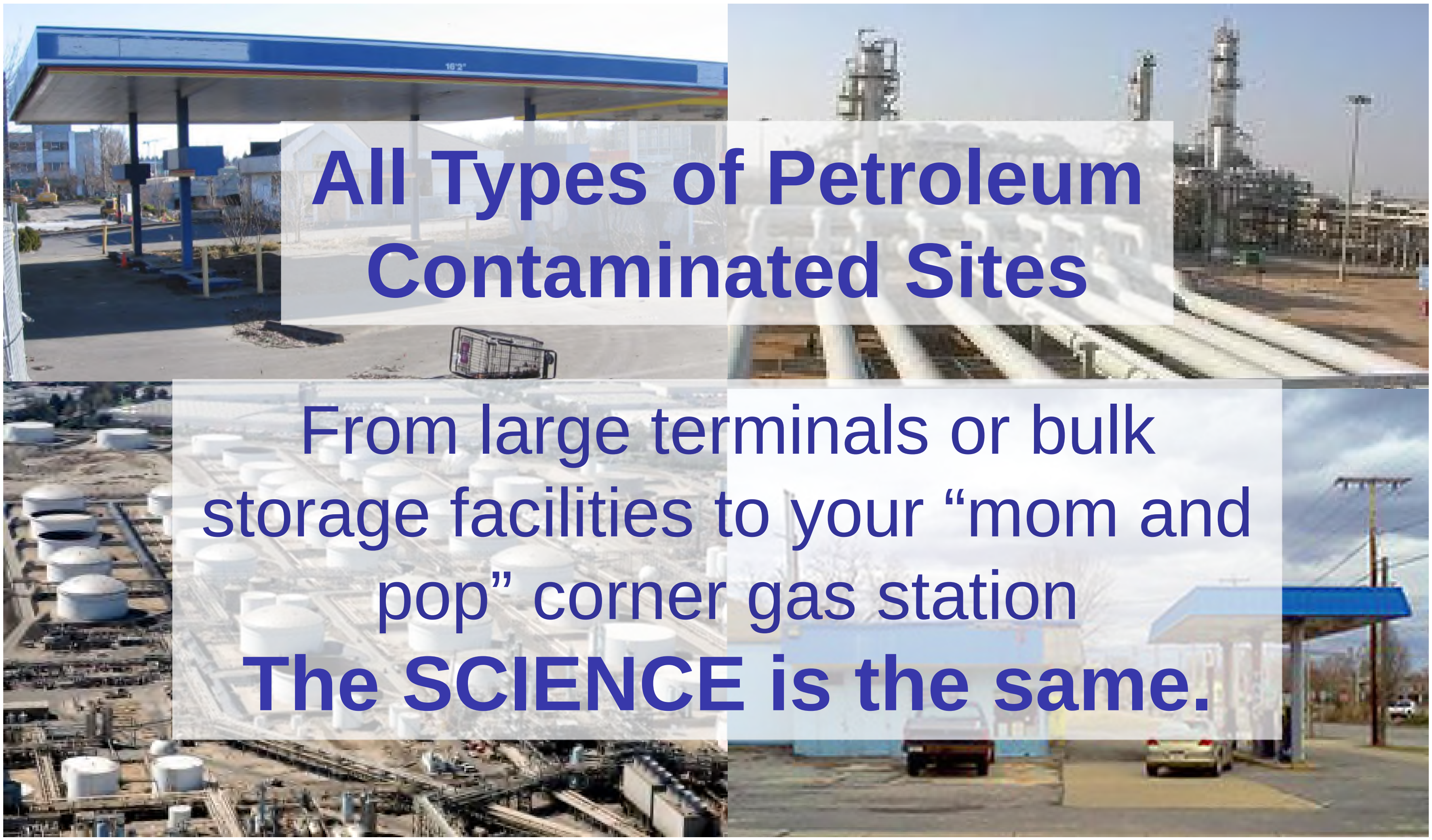


- Expansion of LNAPL Key Concepts
- Development of a LNAPL Conceptual Site Model (LCSM) Section
- Emphasis on identifying SMART objectives
- Expansion of Transmissivity (Tn) and Natural Source Zone Depletion (NSZD) via Appendices

Who Should Use This Document?

- State and federal regulators in CERCLA, RCRA, UST, voluntary programs
- Remediation groups within integrated petroleum and services companies
- Environmental consulting firms, suppliers, and vendors supporting LNAPL site management
- Universities and colleges professors / college students in the environmental field

Where Does This ITRC LNAPL Document Apply?



All Types of Petroleum Contaminated Sites

From large terminals or bulk storage facilities to your “mom and pop” corner gas station

The SCIENCE is the same.

Learning Objectives
3-Part Training Series

Part 1	▶ Use LNAPL science to your advantage and apply at your sites
Part 2	▶ Develop LNAPL Conceptual Site Model (LCSM) for LNAPL concern identification ▶ Inform stakeholders about the decision-making process
Part 3	▶ Select remedial technologies to achieve objectives ▶ Prepare for transition between LNAPL strategies or technologies as the site moves through investigation, cleanup, and beyond ▶ "SMART"-ly measure progress toward an identified technology-specific endpoint

ITRC 3-Part Online Training Leads to YOUR Action

Based on the ITRC LNAPL-3 Document: LNAPL Site Management: LCSM Evolution, Decision Process, and Remedial Technologies

LNAPL Remediation Process and Evolution of the LCSM – Related to the Training Courses

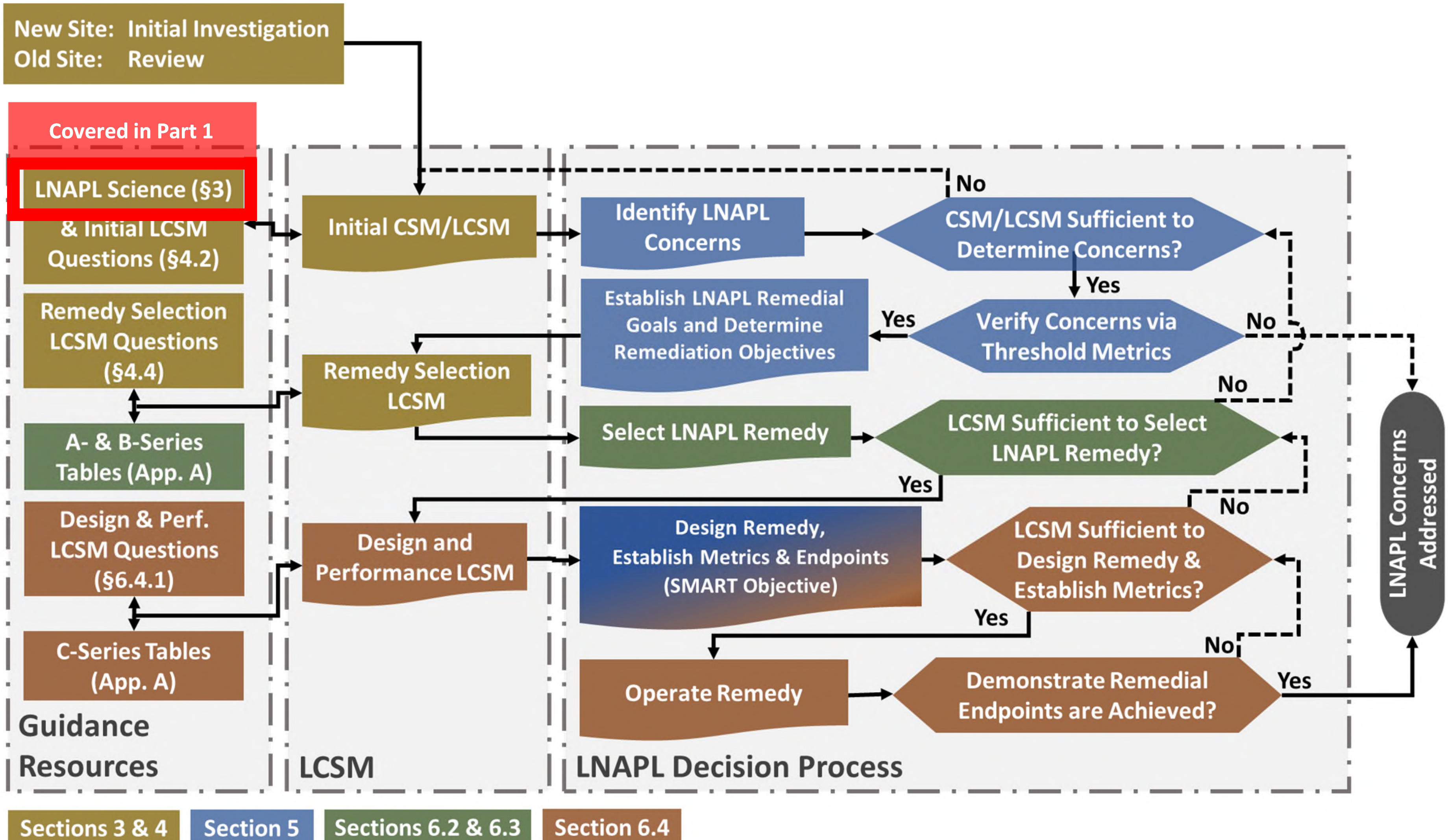


Figure 1-1 – ITRC LNAPL-3

Key Messages

1. LNAPL in wells does not mean 100% LNAPL saturation (dispel "pancake model")
2. LNAPL can be present in subsurface even if not in wells
    - Indicators
3. LNAPL Composition vs. LNAPL Saturation
    - Raoult's Law
4. Apparent LNAPL Thickness Challenges in Unconfined Conditions
    - Amount changes with soil type
    - Thickness changes with water table position

Key Messages

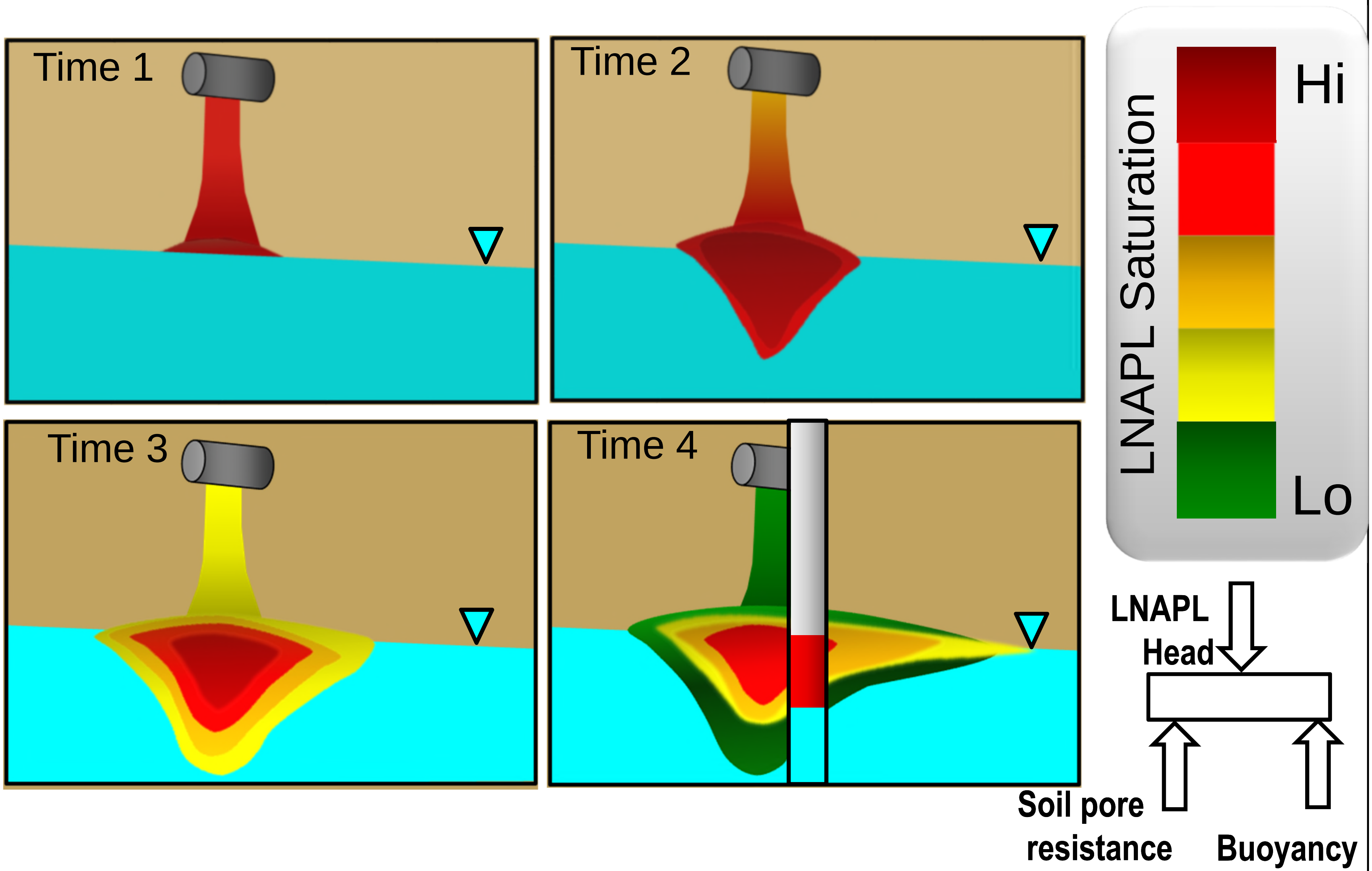
5. Apparent LNAPL Thickness in various hydrogeologic conditions (i.e., perched, confined, etc.)
6. LNAPL in well does not mean it is migrating
   - Darcy's Law
   - Limiting processes
7. Transmissivity is a better indicator of recoverability
8. Stable LNAPL bodies can still result in sheens
   - Mechanisms
9. Biological processes are significant in LNAPL depletion

Key Message 1

Groundwater and LNAPL share pore space

LNAPL in MWs ≠ 100% LNAPL Saturation in Formation

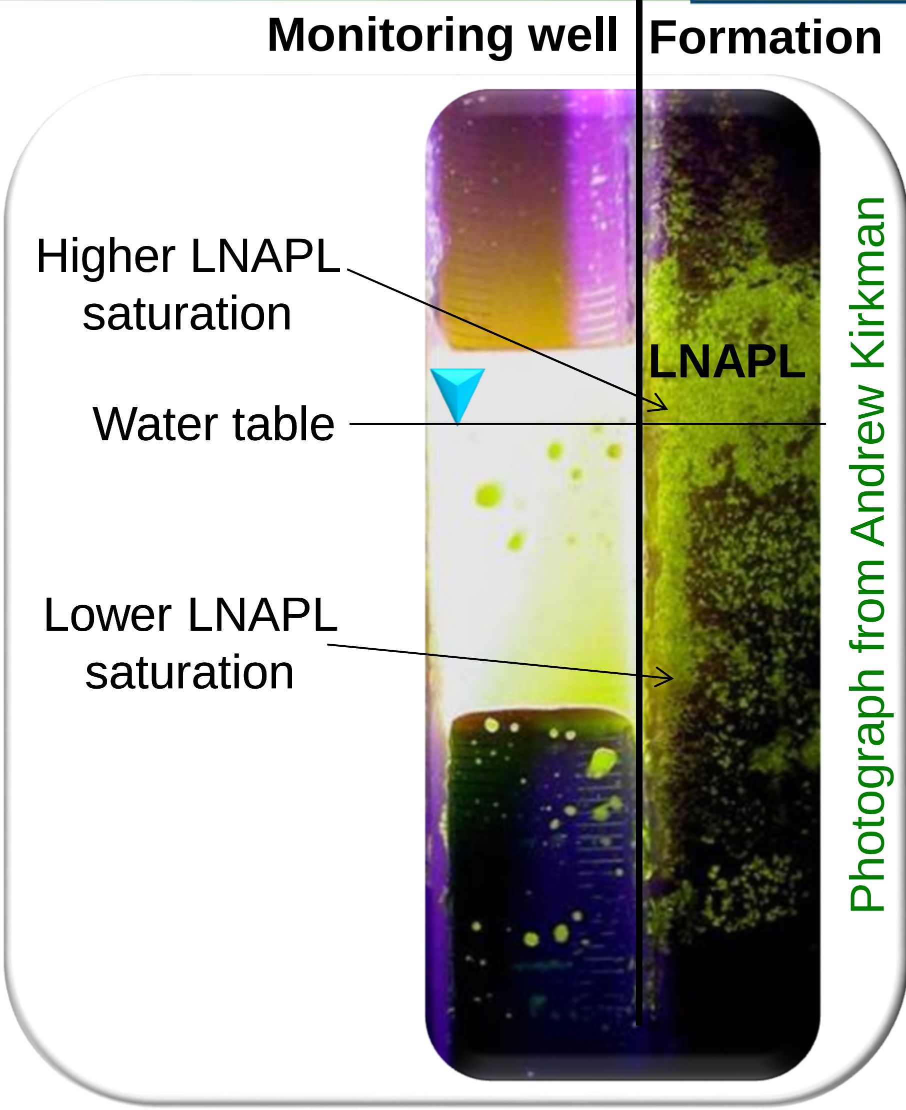
Time Series LNAPL Body Development:
Cross Section View



Impacts of LNAPL in the Formation: Key Messages

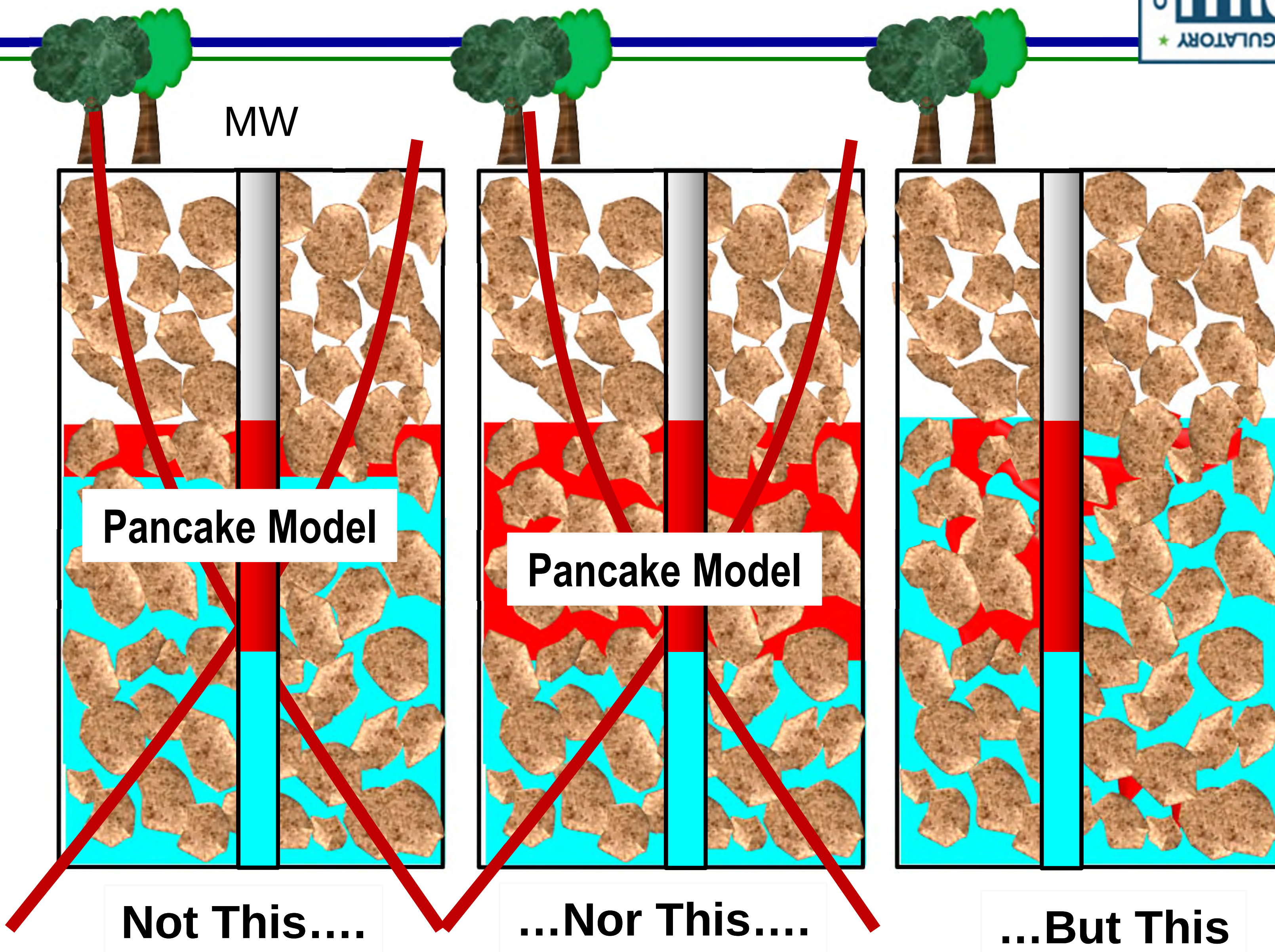
- LNAPL penetrates below the water table
- LNAPL saturation in the formation is not 100% and varies with depth
    - LNAPL shares the pore space with water

Coming Next: How to determine LNAPL is there and how much



LNAPL vertical distribution in a lab tank

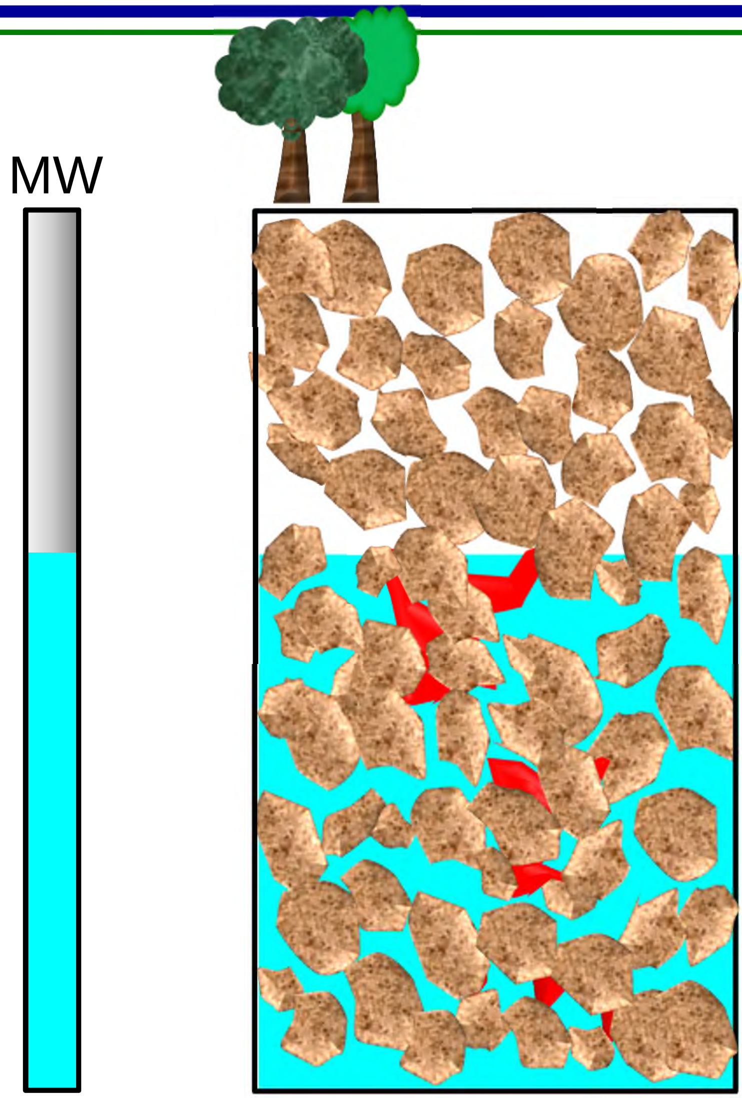
Nature of LNAPL Impacts in the Formation:
Below Water Table And Saturation Varies



Key Message 2

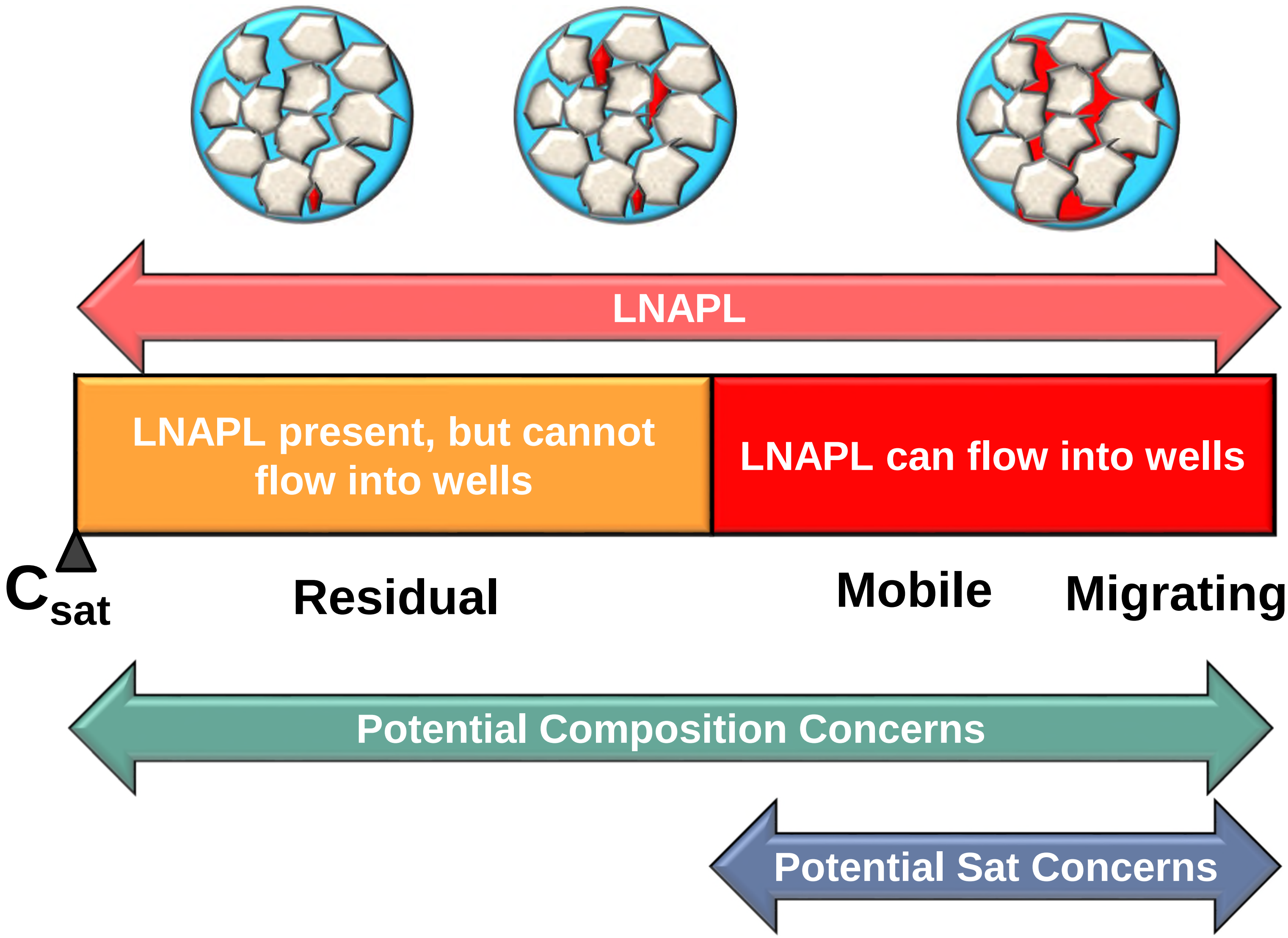
LNAPL can be in the formation even when it is not accumulating in a well

Nature of LNAPL Impacts in the Formation:
LNAPL May Not Even Flow Into A Well



- **How do you know that LNAPL is present?**
- **How do you find out where it is?**

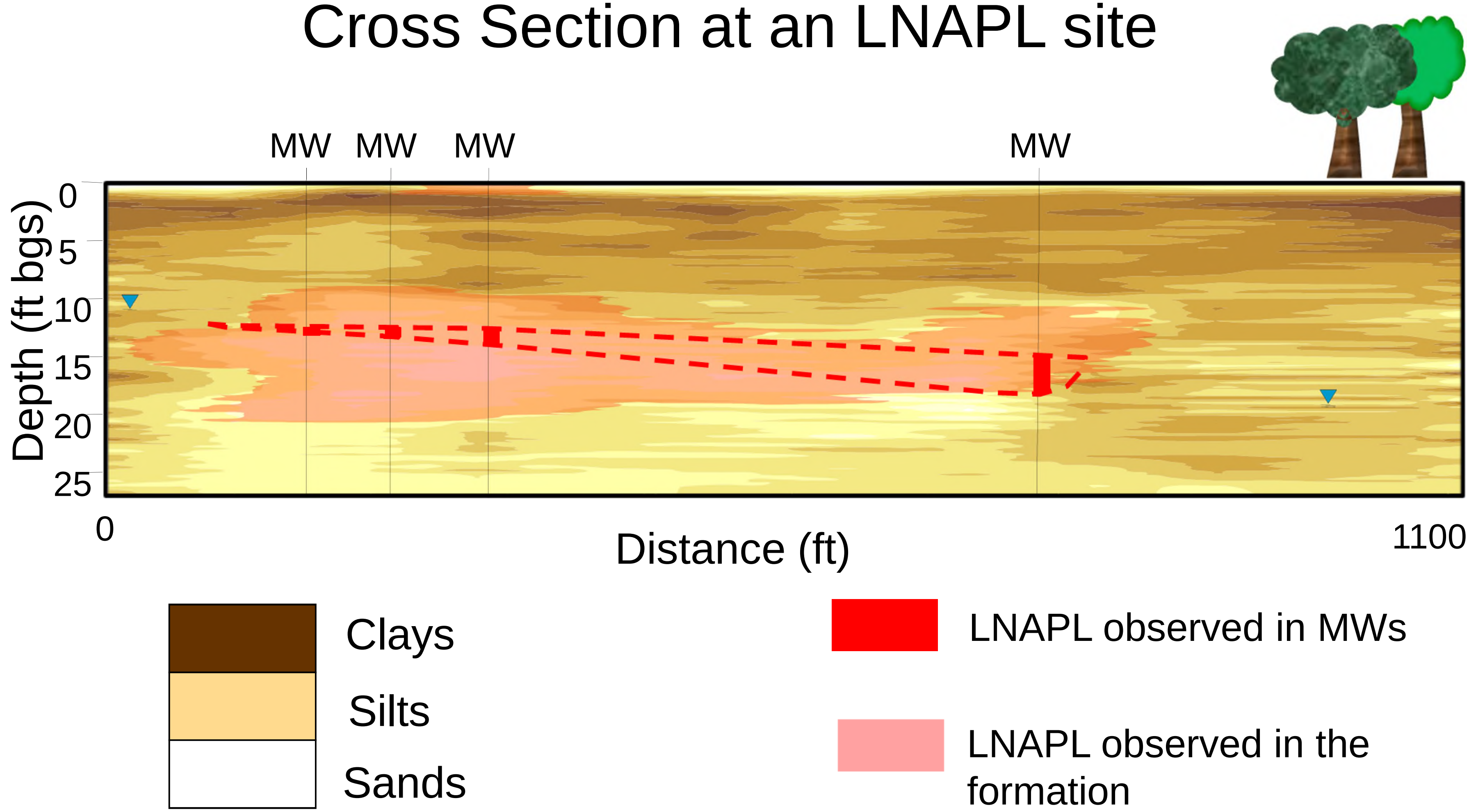
It is All LNAPL!



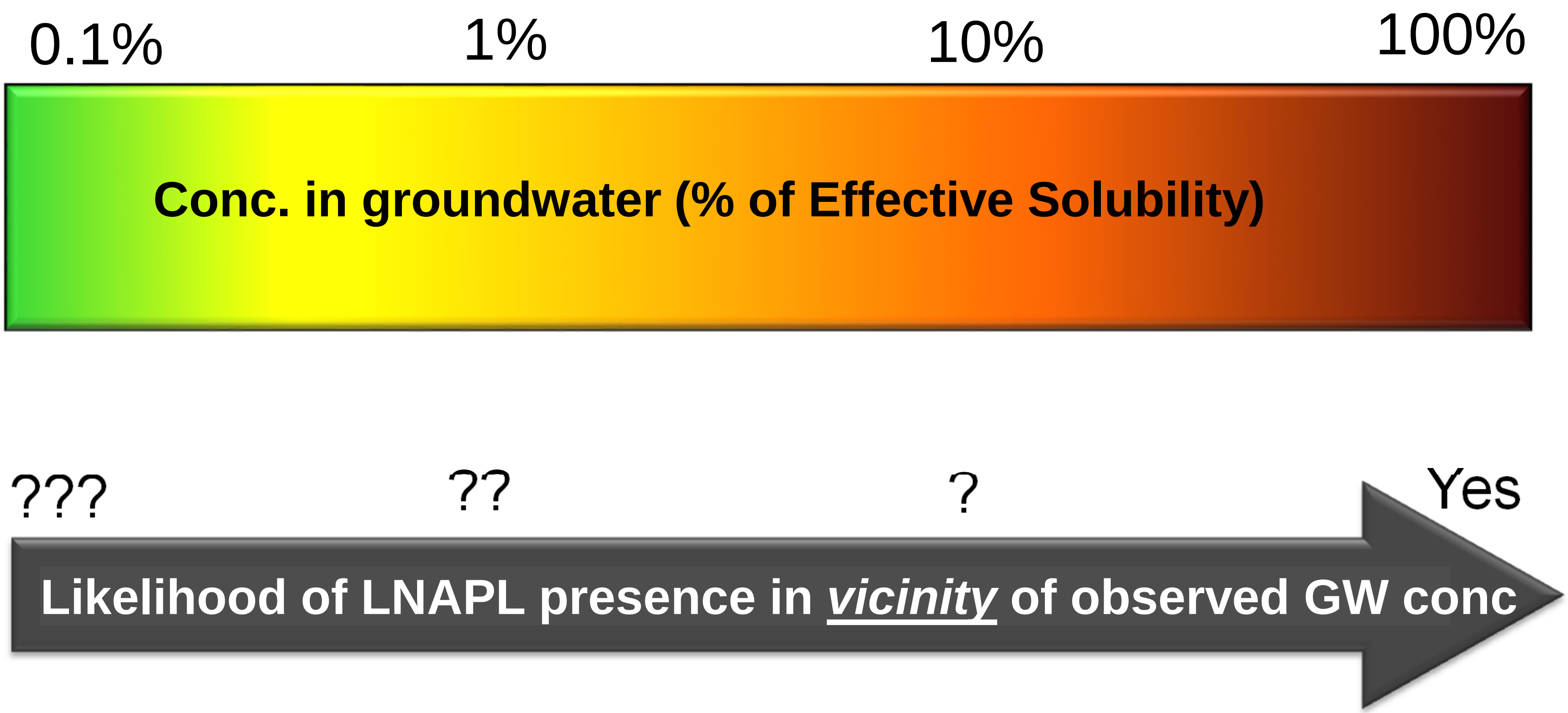
LNAPL *Vertical* Extent Can Be Greater Than In-Well LNAPL Thickness

Indicator: In-well LNAPL Thickness

Cross Section at an LNAPL site



Groundwater Concentrations As An Indicator Of LNAPL

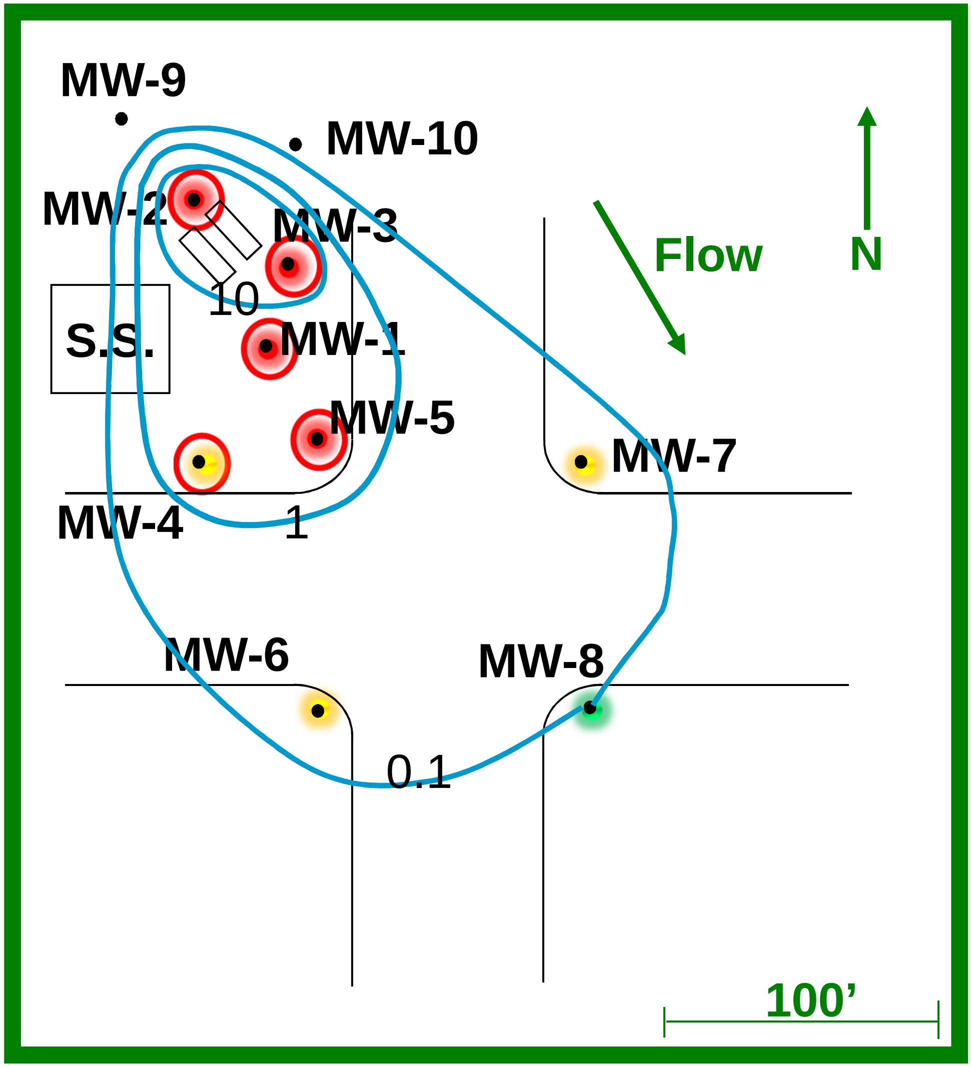


GW – groundwater, conc - concentration

TPH Cautions

- Do not collect soil samples at predetermined intervals (e.g., not each 5 feet)
- Collect soil samples based on field screening
- Ensure that TPH range is representative of the LNAPL type
  - Do not assess a diesel spill using TPH-G
  - If heavy hydrocarbons (e.g., crude, >C35) then use Oil & Grease method
- Do not stop at the water table!

Inferring LNAPL from Soil TPH Concentrations

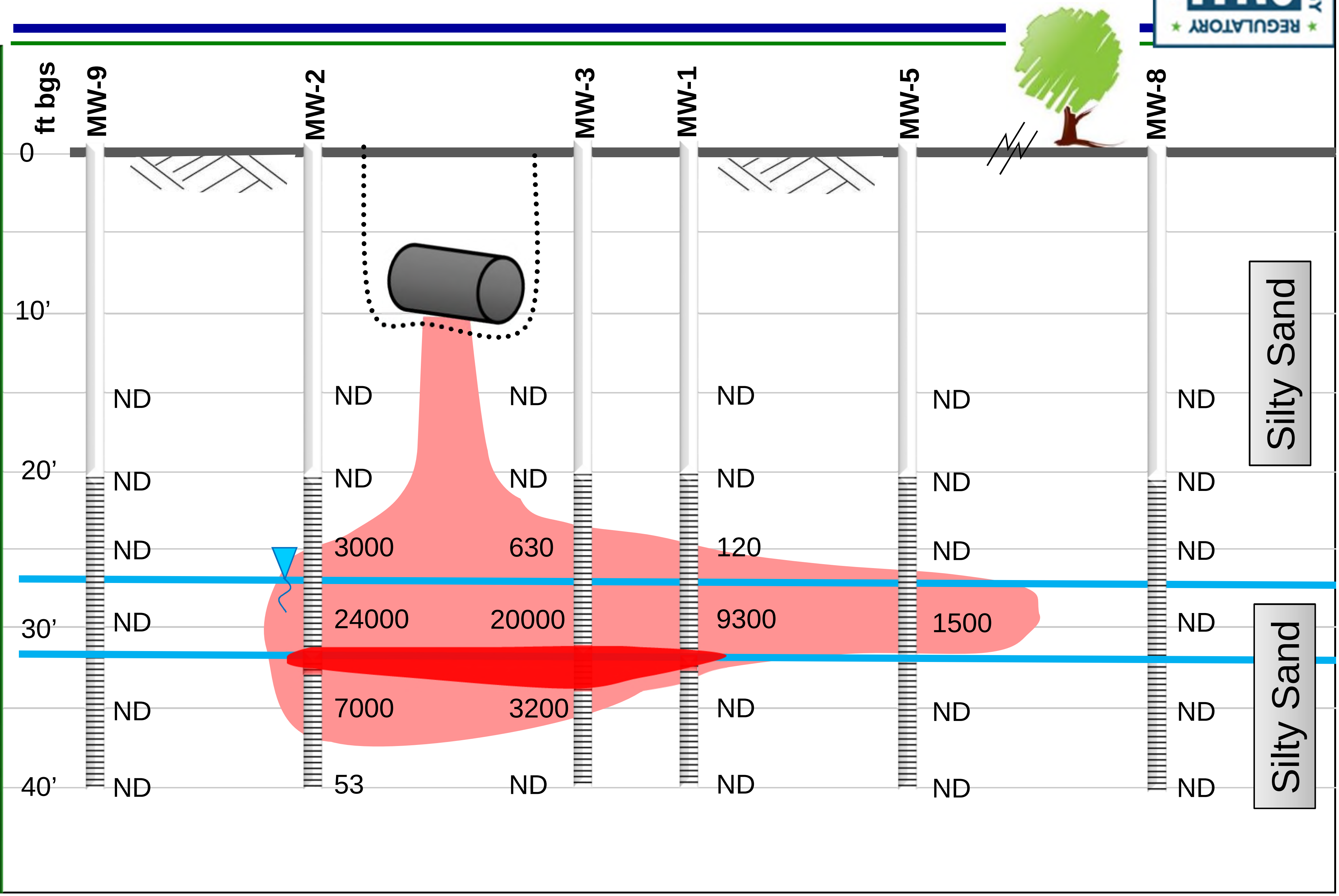


MW	Historical Benzene Concs (mg/L)	*Maximum* Soil TPH Concs (mg/Kg)
1	5	9300
2	13	24000
3	15	20000
4	1.6	1700
5	3.4	1500
6	0.6	12
7	0.35	10
8	0.1	ND<0.005
9	ND<0.001	ND<0.005
10	ND<0.001	ND<0.005

LNAPL present – MW-1, -2, -3, -4, -5

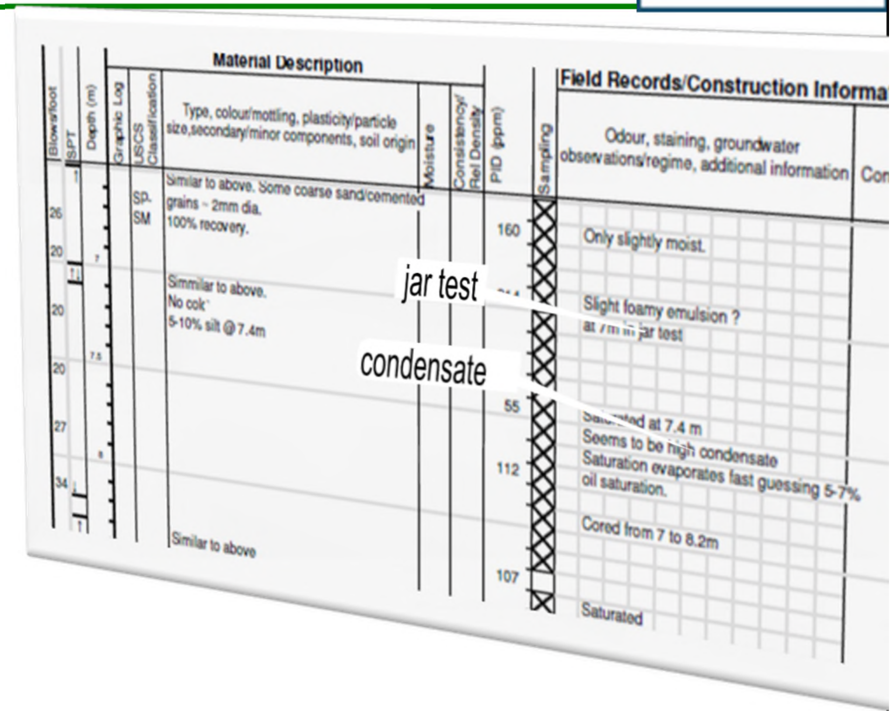
LNAPL Vertical Extent
TPH-G Versus In-Well Thickness

Indicator: Conventional Assessment



OVA and Other Field Observations

- Boring logs to characterize LNAPL source zone geometry
  - Lithology, water content, stain, odor, OVA readings



Picture cheiron-resources.com

- Shake test
- Oleophyllic dyes for presence of LNAPL
  - Detection +/- 1000 ppm TPH

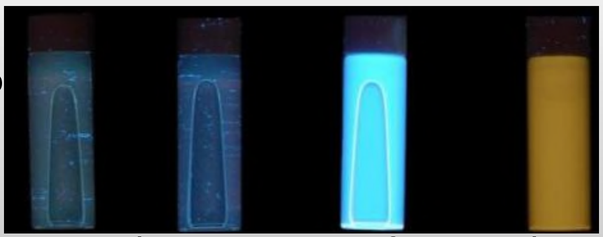
Fluorescence of LNAPL

Indicator: Specialized Assessment

White light

Gasoline Jet A Diesel Bunker C

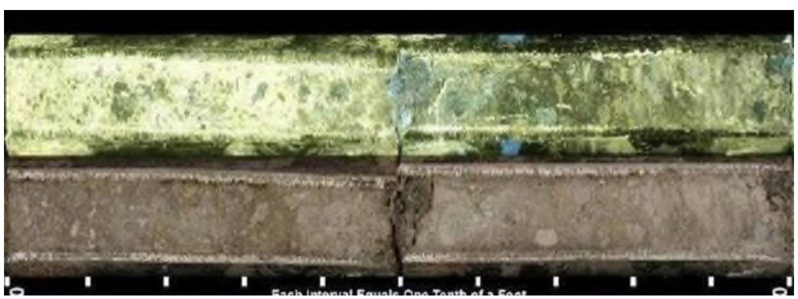
UV light



Photographs: Courtesy of PTS Lab

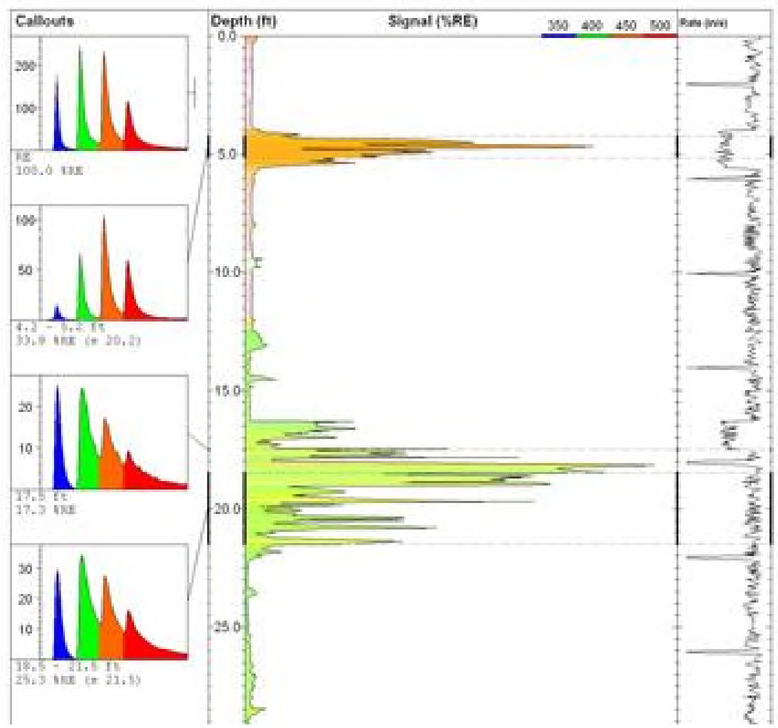
- All that fluoresces may not be LNAPL
  - Minerals, antifreeze, detergents, peat
- All LNAPLs do not fluoresce

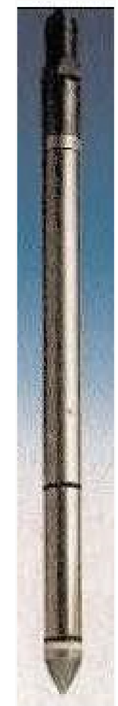
Laboratory Core UV Photograph



10 inches

Laser Induced Fluorescence

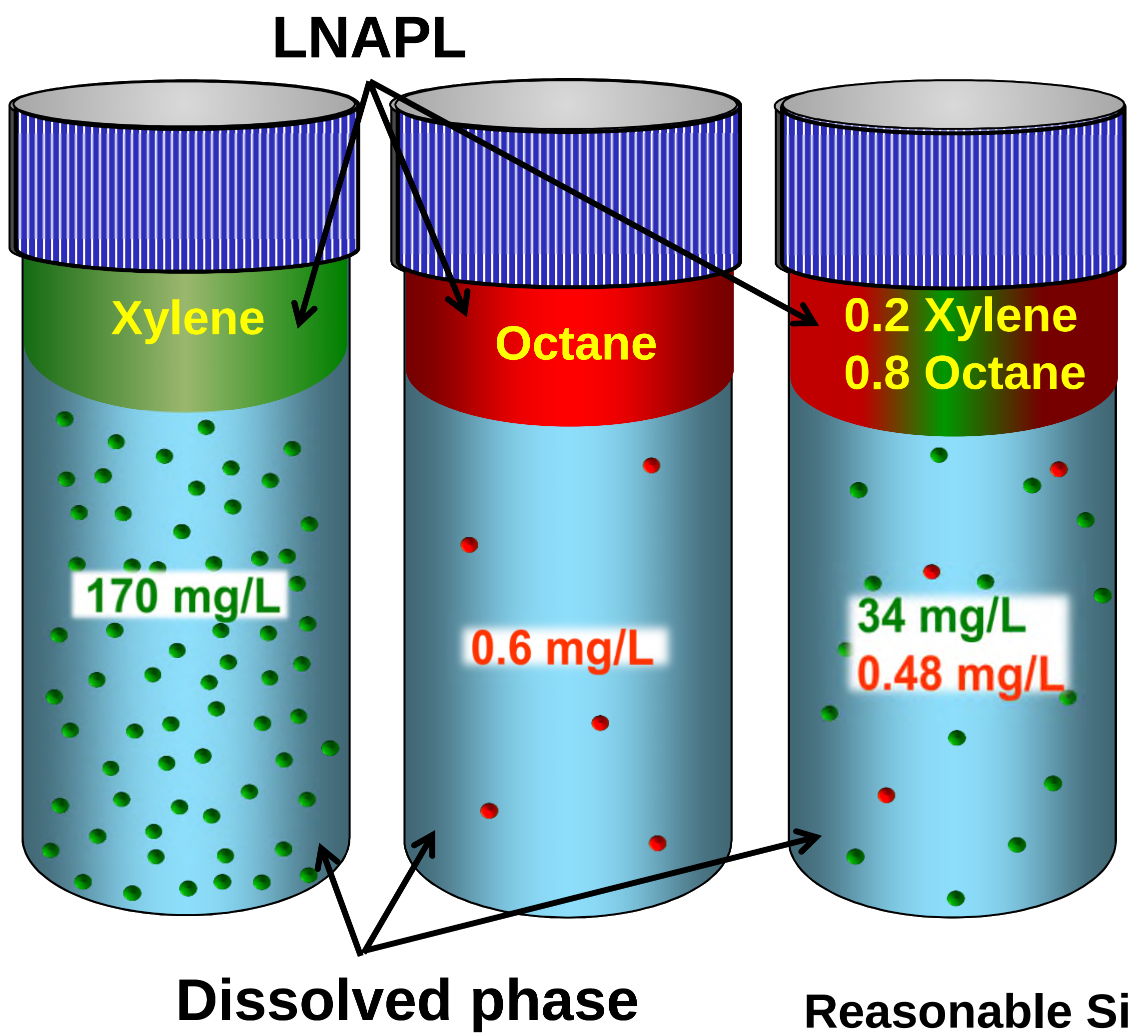




Key Message 3

LNAPL Saturation vs. Composition

Effective Solubility: Raoult's Law



Raoult's Law

$$S_i = x_i S$$

S_i = Effective solubility

S = Sol. of pure chem.

x_i = Mole frxn. of chem.

$$= \text{wt frxn} \times \frac{MW_{NAPL}}{MW_{chem}}$$

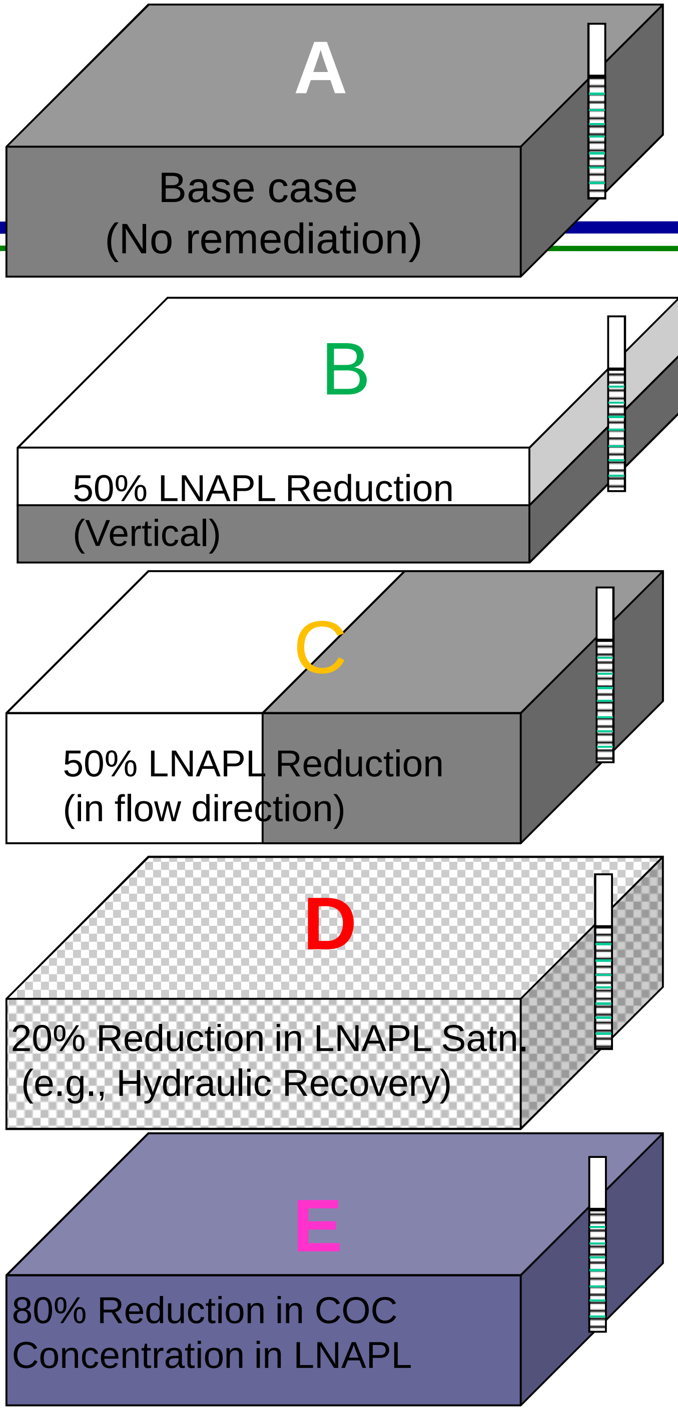
Reasonable Simplification for BTEX:

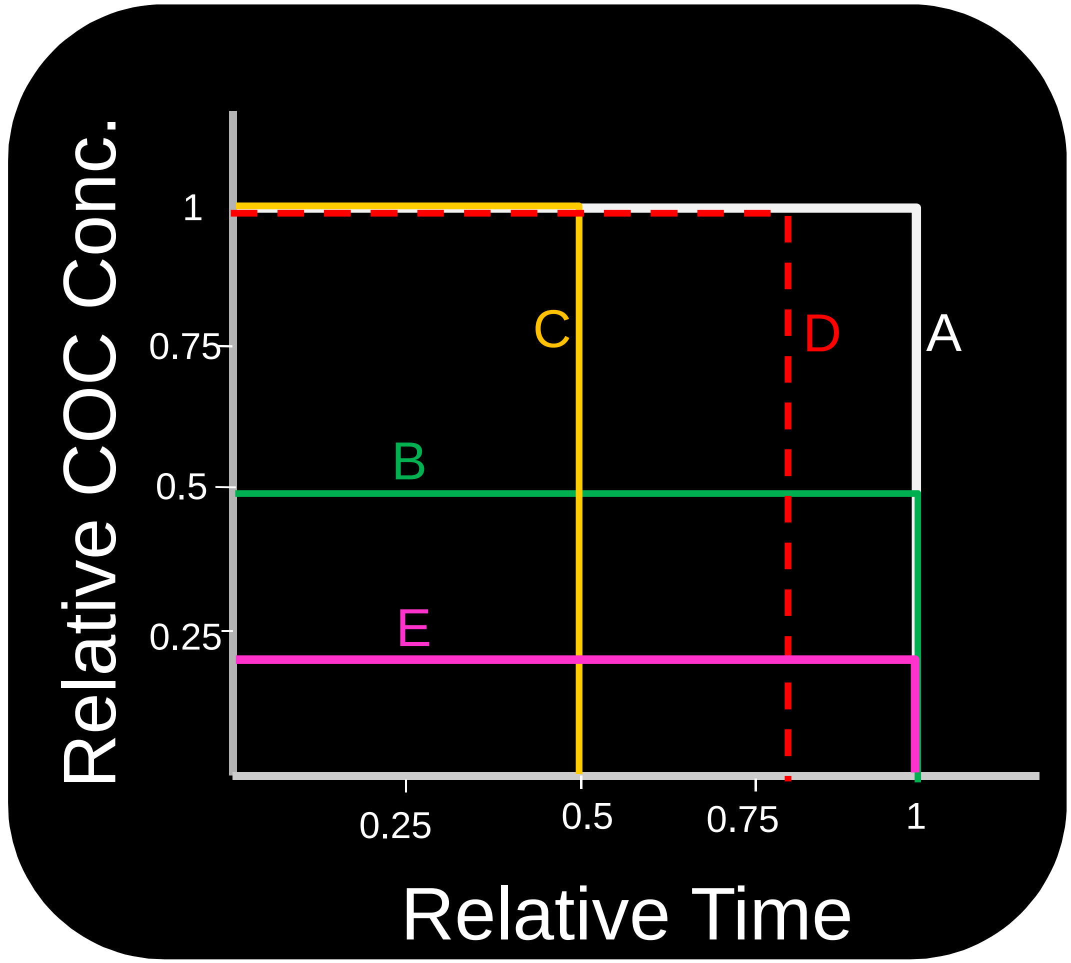
For gasoline: mole frxn. ~ wt. frxn

For diesel: mole frxn ~ 2.5 x wt frxn

Mass Reduction vs. Composition Change

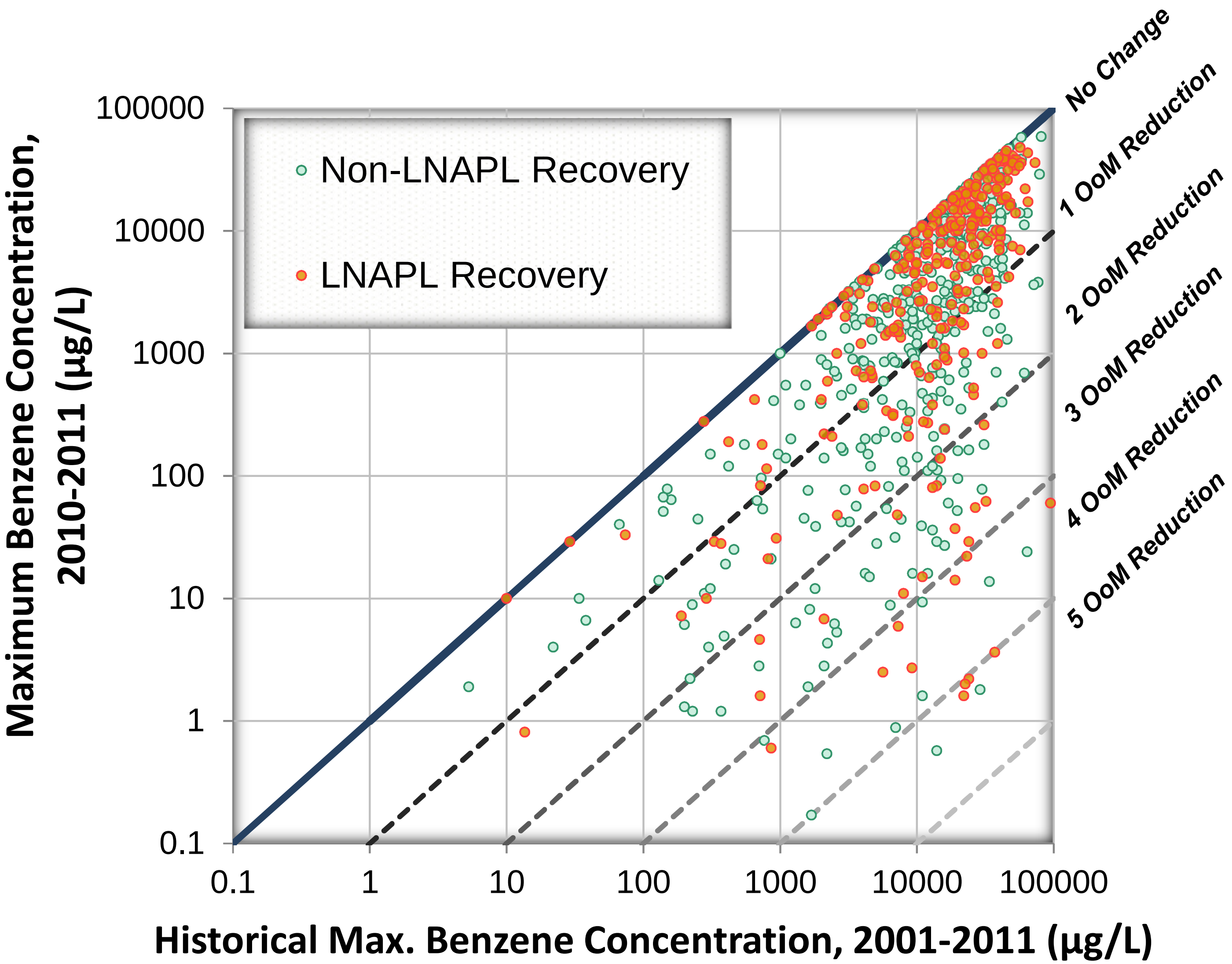
Strategy





Impact of LNAPL Recovery –
Little Benefit In Reducing Dissolved BTEX Concentration

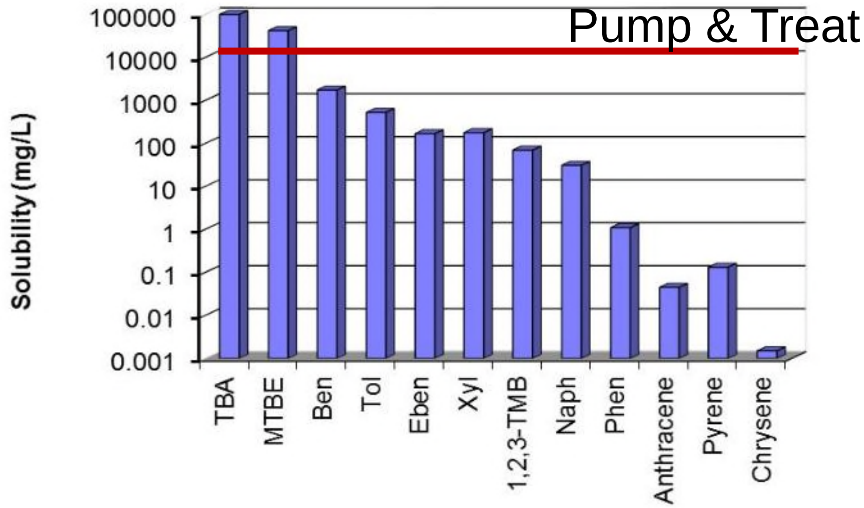
Strategy



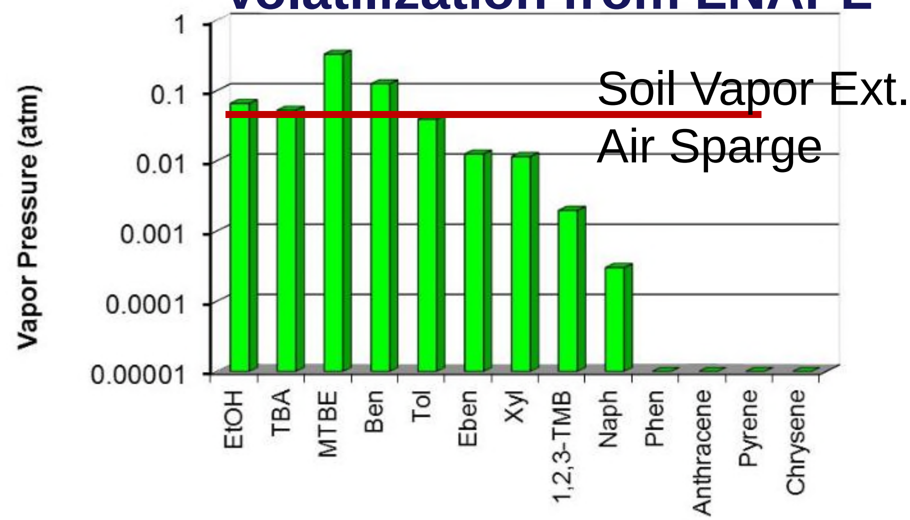
Source: McHugh et al., 2013

How to Change LNAPL Composition

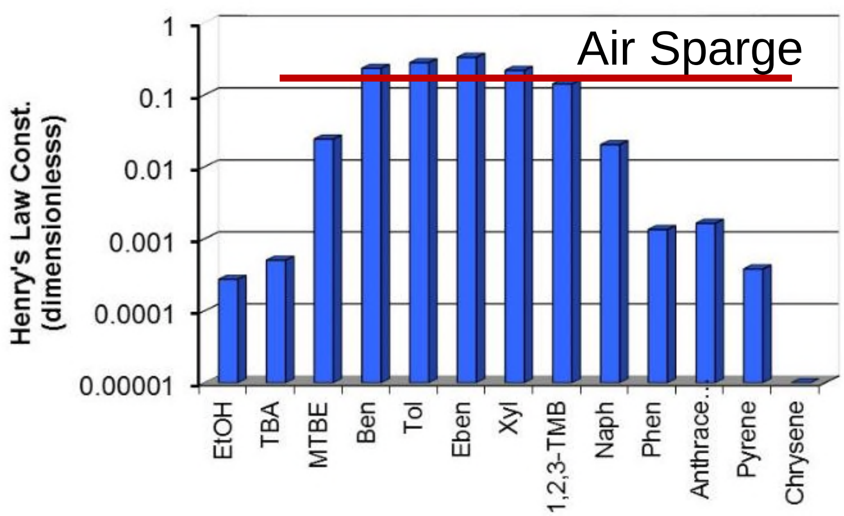
Dissolution



Volatilization from LNAPL



Volatilization from Water



Biodegradation

Compound	Aerobic conditions	Denitrifying conditions	Sulfate-reducing conditions	Iron-reducing conditions
Benzene	++	-	+	-
Toluene	++	++	+	+
m-Xylene	++	++	+	+
p-Xylene	++	+	+	
o-Xylene	++	+/-[1)]	-	-
Ethylbenzene	++	+/-		-
1,2,4-trimethyl-benzene	++			

Knowledge Check

Poll Question

Background: Consider a site with gasoline release:

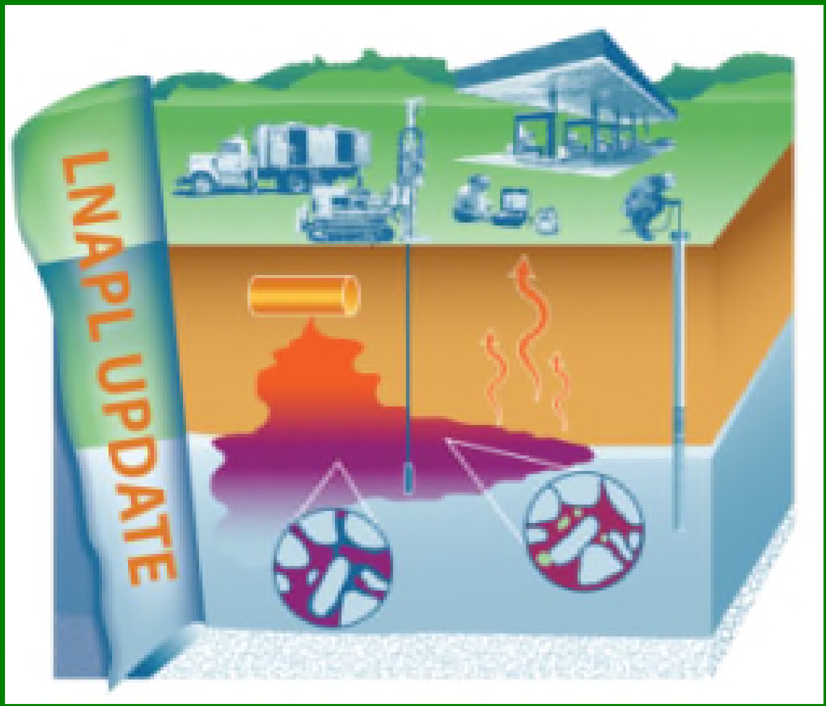
- LNAPL is observed in onsite MWs
- Goal is to reduce concentrations of Benzene in groundwater in ~2 years

Question: What would be the appropriate remediation approach?

A. Start LNAPL removal by pumping
B. Change LNAPL composition
C. Let Monitored Natural Attenuation take its course

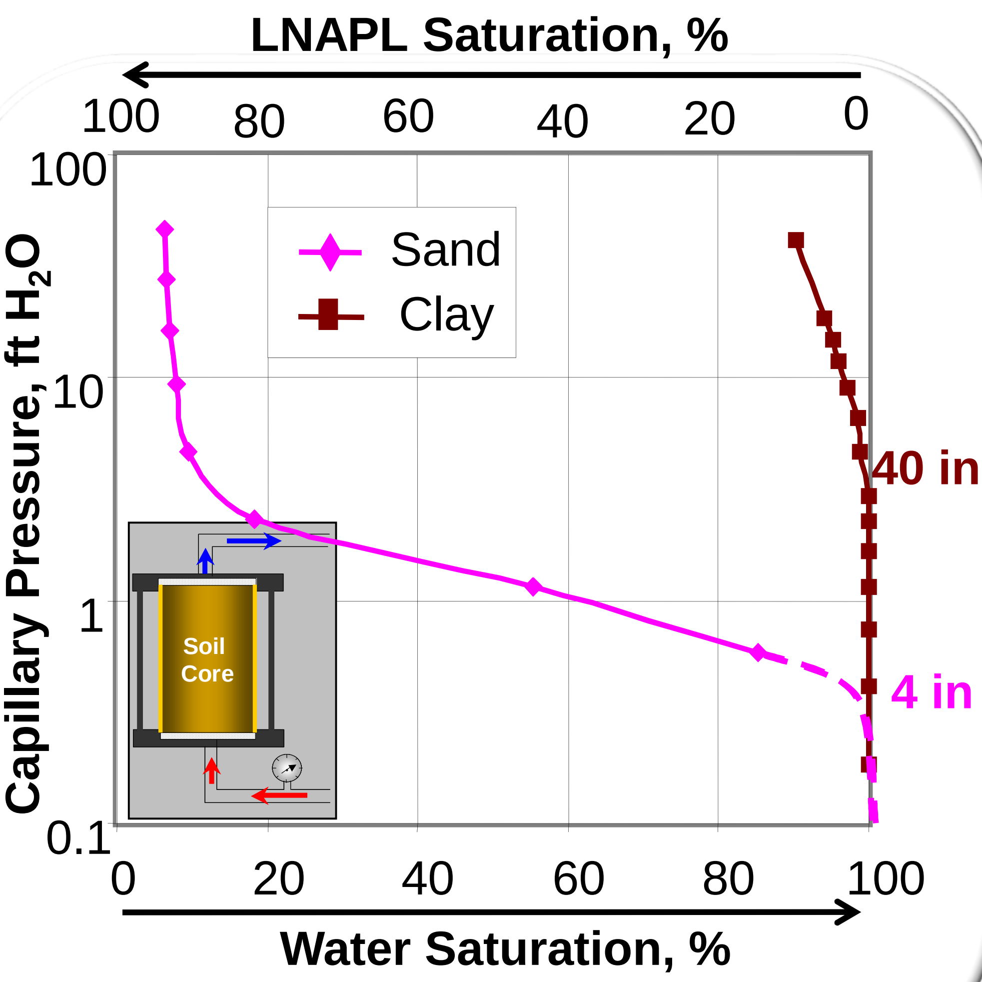
Key Message 4

ALL Apparent LNAPL Thicknesses are not created equal!



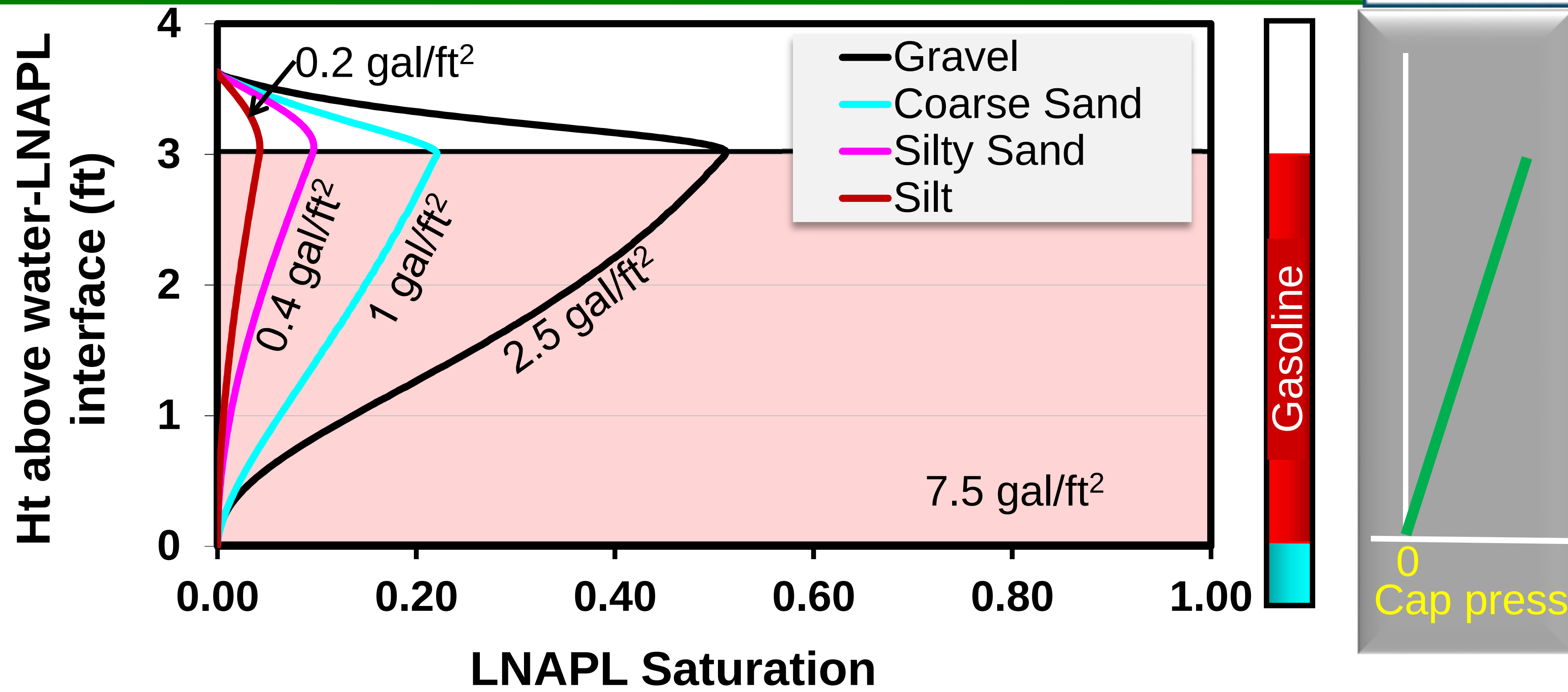
Apparent LNAPL Thicknesses in Unconfined Conditions

Moisture Retention Curves:
Relate Capillary Pressure & Fluid Saturation



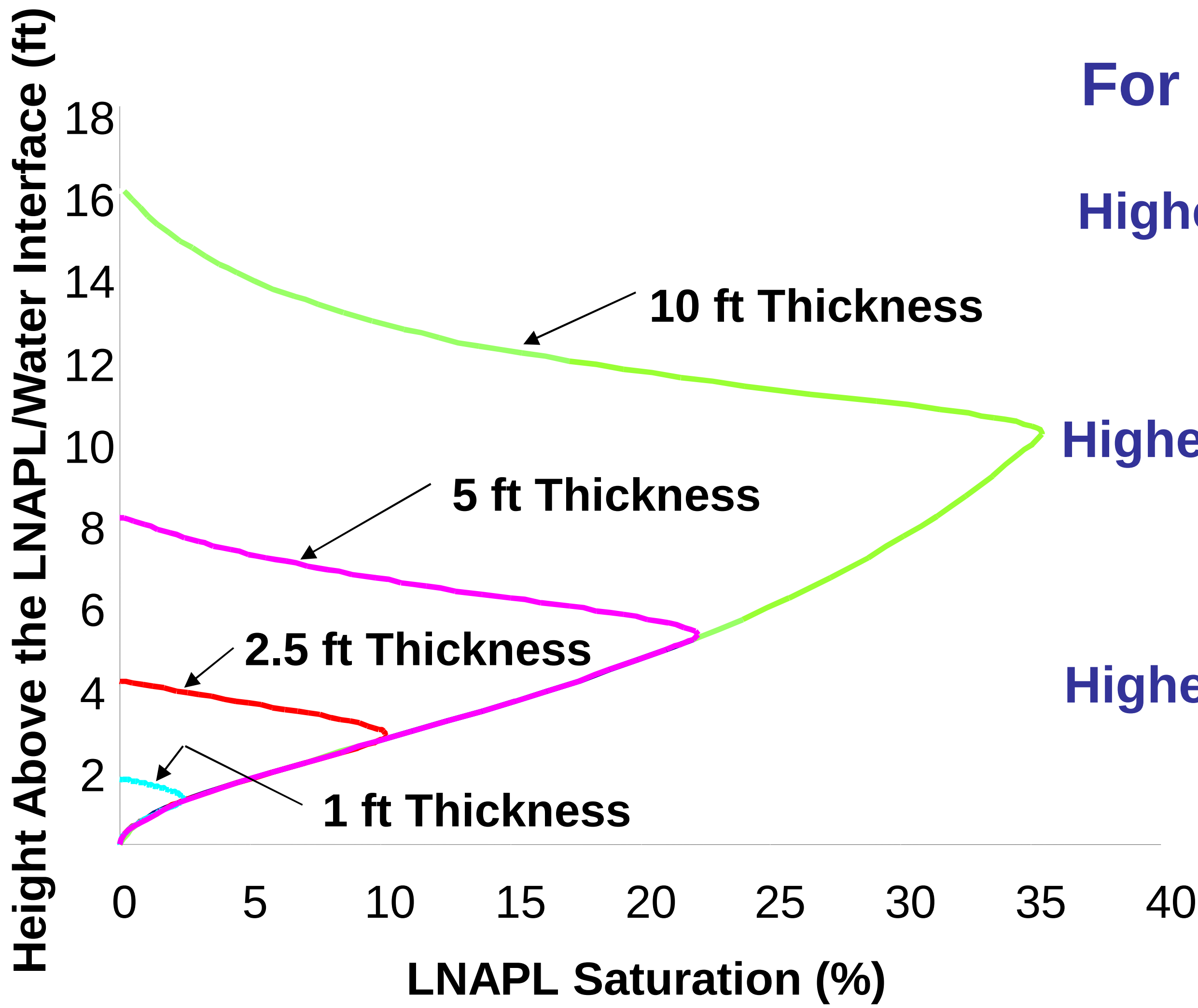
- Relationship between capillary pressure and fluid saturation is established using moisture retention curves
- Unique relationship between capillary pressure and fluid saturations for a given soil type and LNAPL

Grain Size Effects on Vertical LNAPL Distribution (assumed 3 ft of LNAPL in well)



- Volumes based on pancake model (uniform saturations) are over estimated!
- For a given LNAPL thickness, LNAPL saturations and volumes are different for different soil types (greater for coarser-grained soils)

In-Well LNAPL Thickness Inference on Relative Saturation in Silty Sand



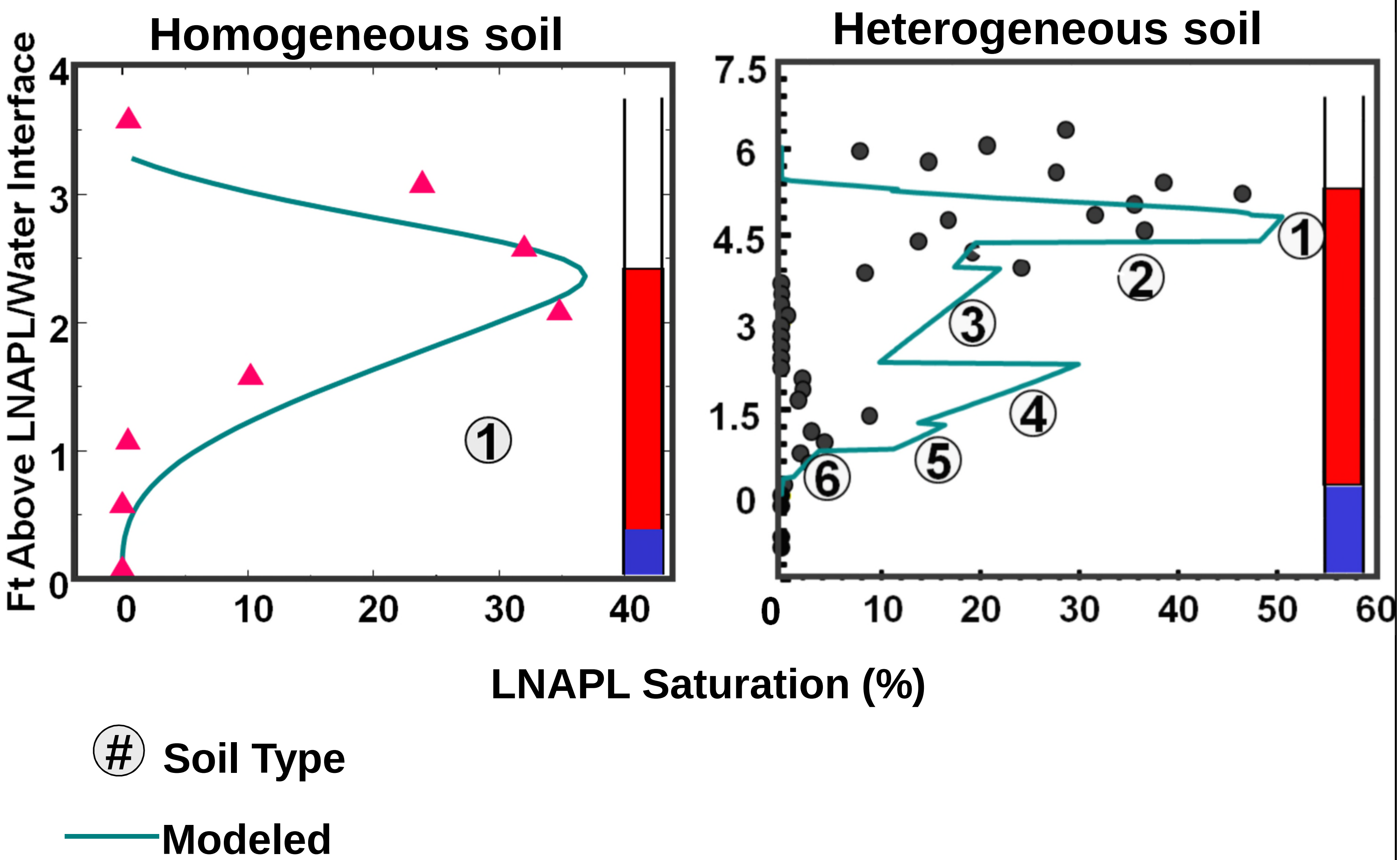
For a *given* soil type

Higher thickness in well

Higher capillary pressure

Higher LNAPL saturation

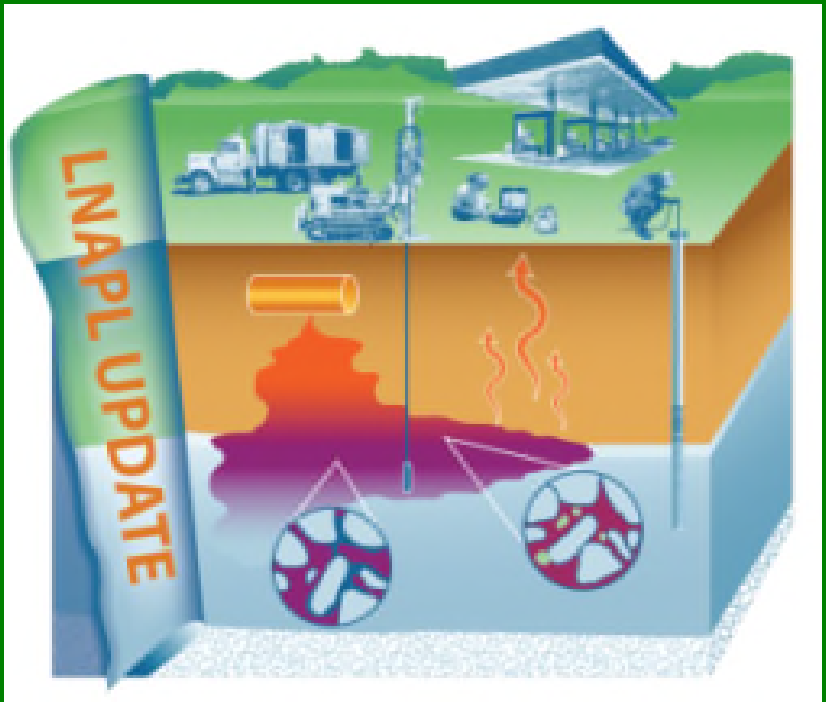
Measured and Modeled Equilibrium LNAPL Saturations



Beckett and Lundegard (1997) , Huntley et al. (1994)

Key Message 5

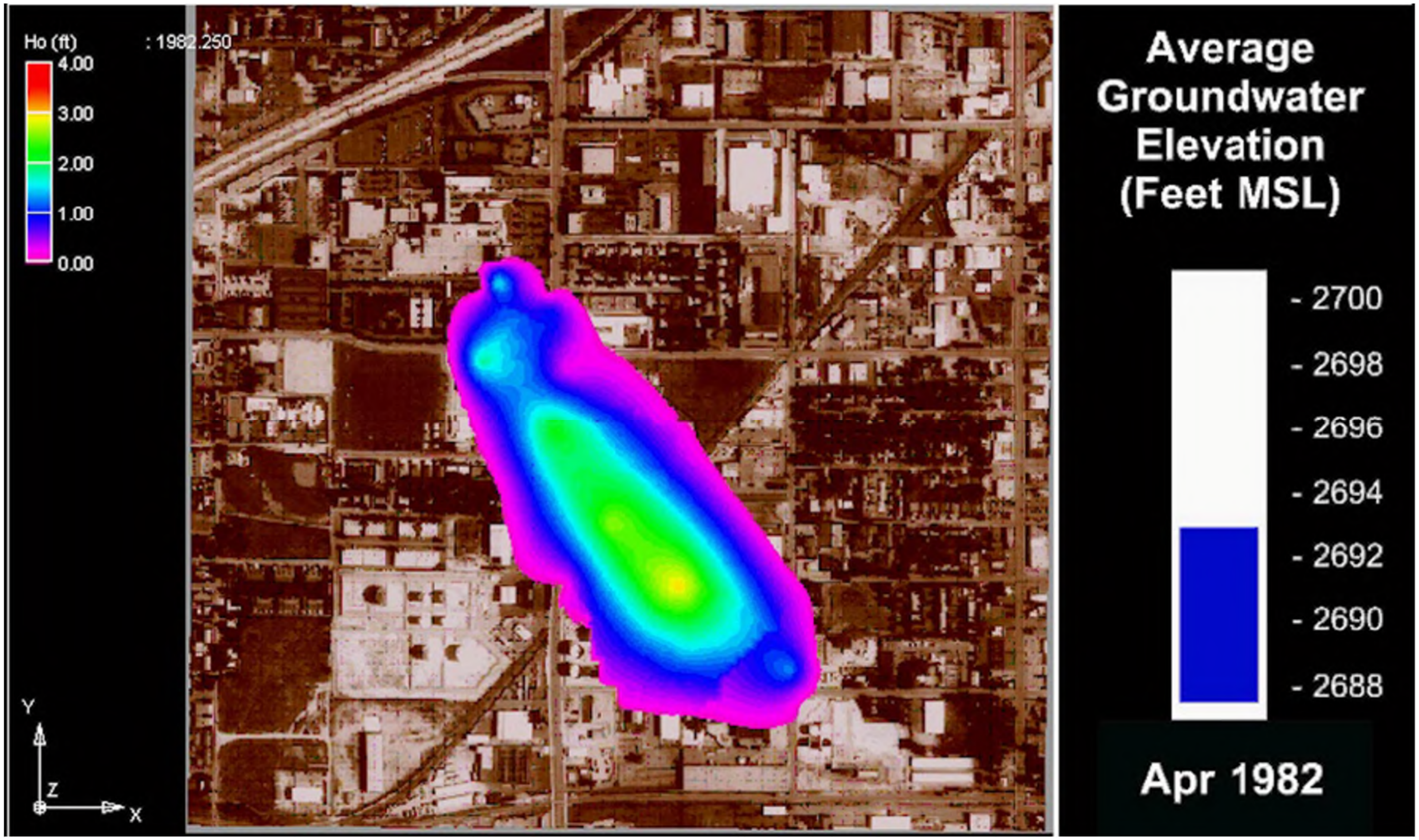
ALL Apparent LNAPL Thicknesses are not created equal!



Apparent LNAPL Thicknesses in Various Hydrogeologic Conditions

Example Seasonal LNAPL Redistribution

LNAPL Monitoring Over Time - Refinery

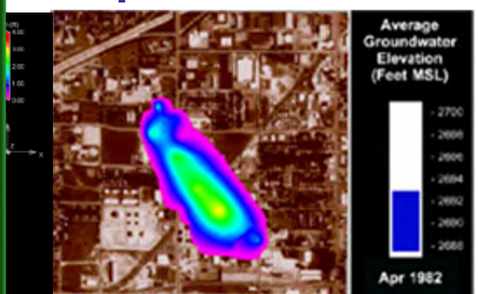


From API Interactive NAPL Guide, 2004

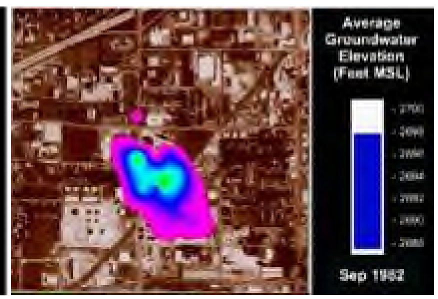
Example Seasonal LNAPL Redistribution

LNAPL Monitoring Over Time - Refinery

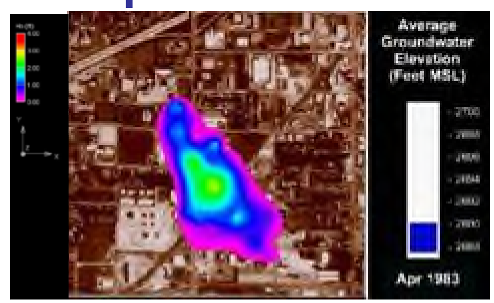
Low Water April 1982



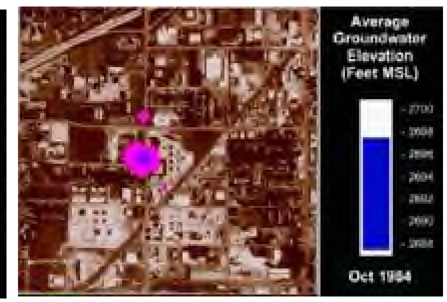
High Water Sept 1982



Low Water April 1983

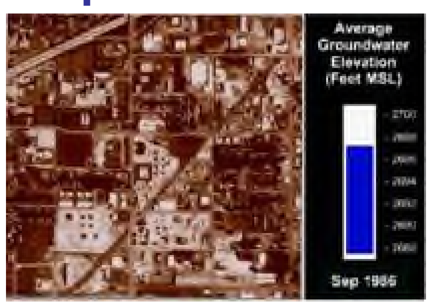


High Water Oct 1984

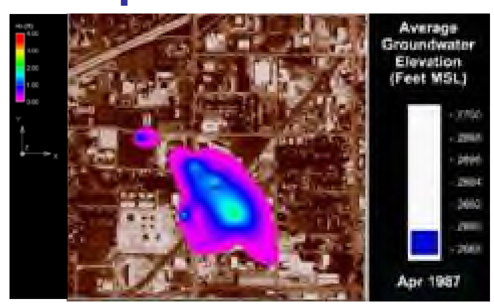


Low Water April 1985

High Water Sept 1986



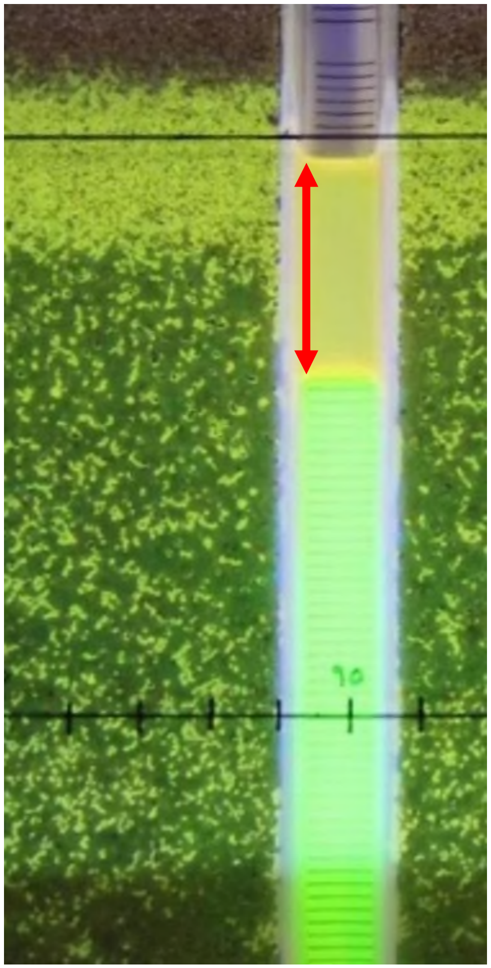
Low Water April 1987



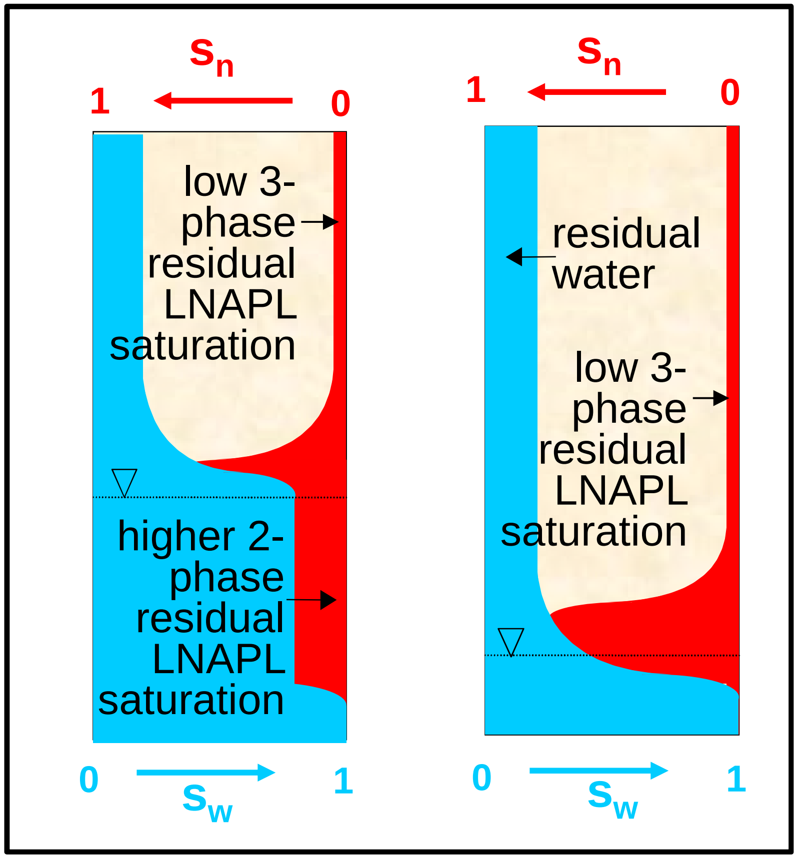
From API Interactive NAPL Guide, 2004

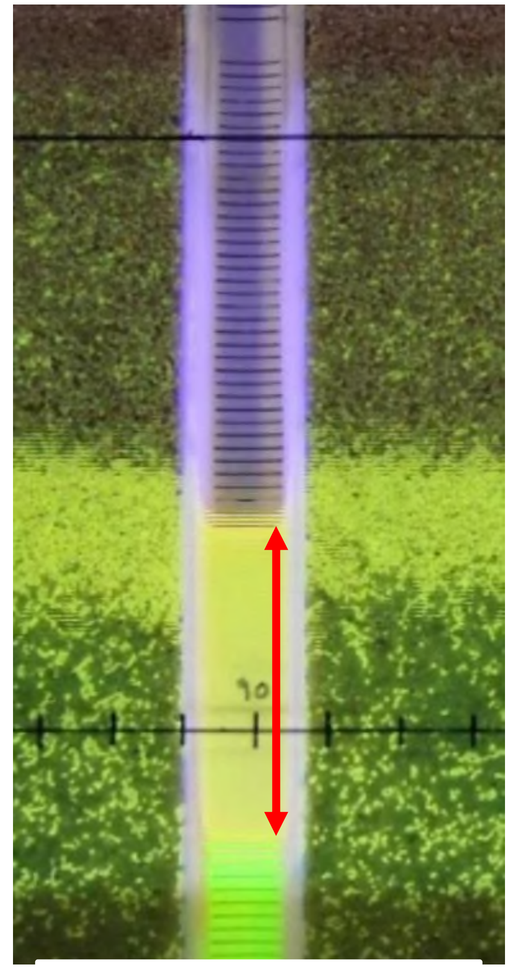
- **Measured LNAPL Depth in Monitoring Wells: 0 to 3 feet**
- **Seasonal Water Table Variation: 8 foot range**

LNAPL Thickness change with water table fluctuation (sand tank study)



High water table



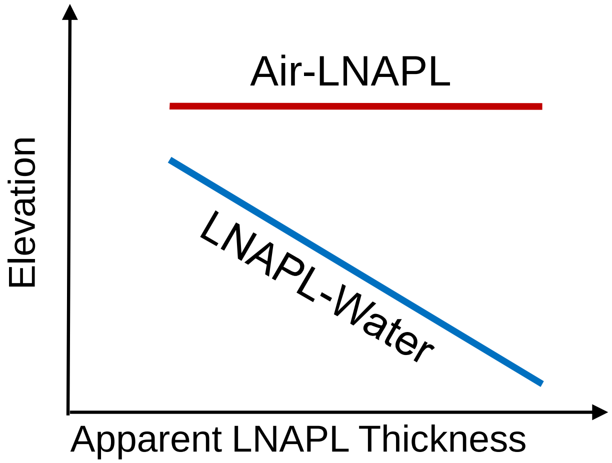


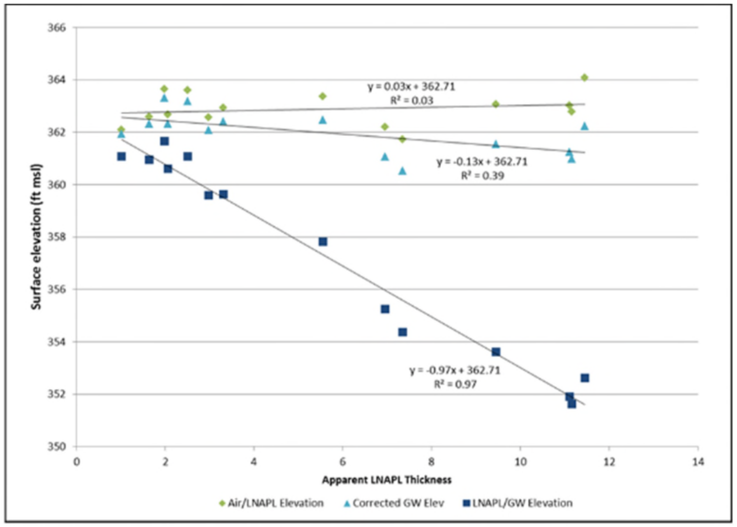
Low water table

Tank Photo From Alison Hawkins (CSU), graduate student of Dr. Tom Sale

Perched LNAPL Conditions
(Exaggerated Well Thickness)

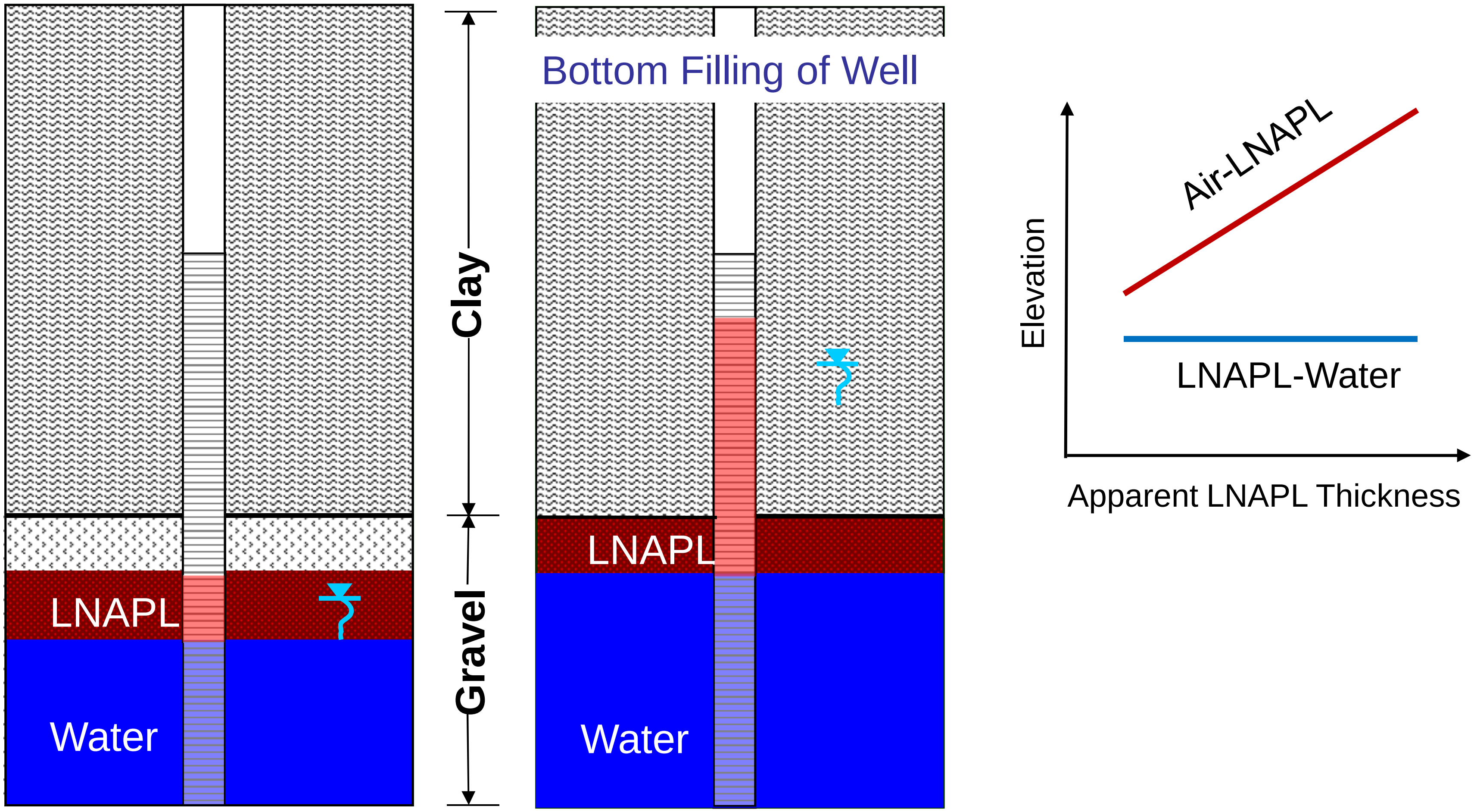
Conceptual Challenges–Perched





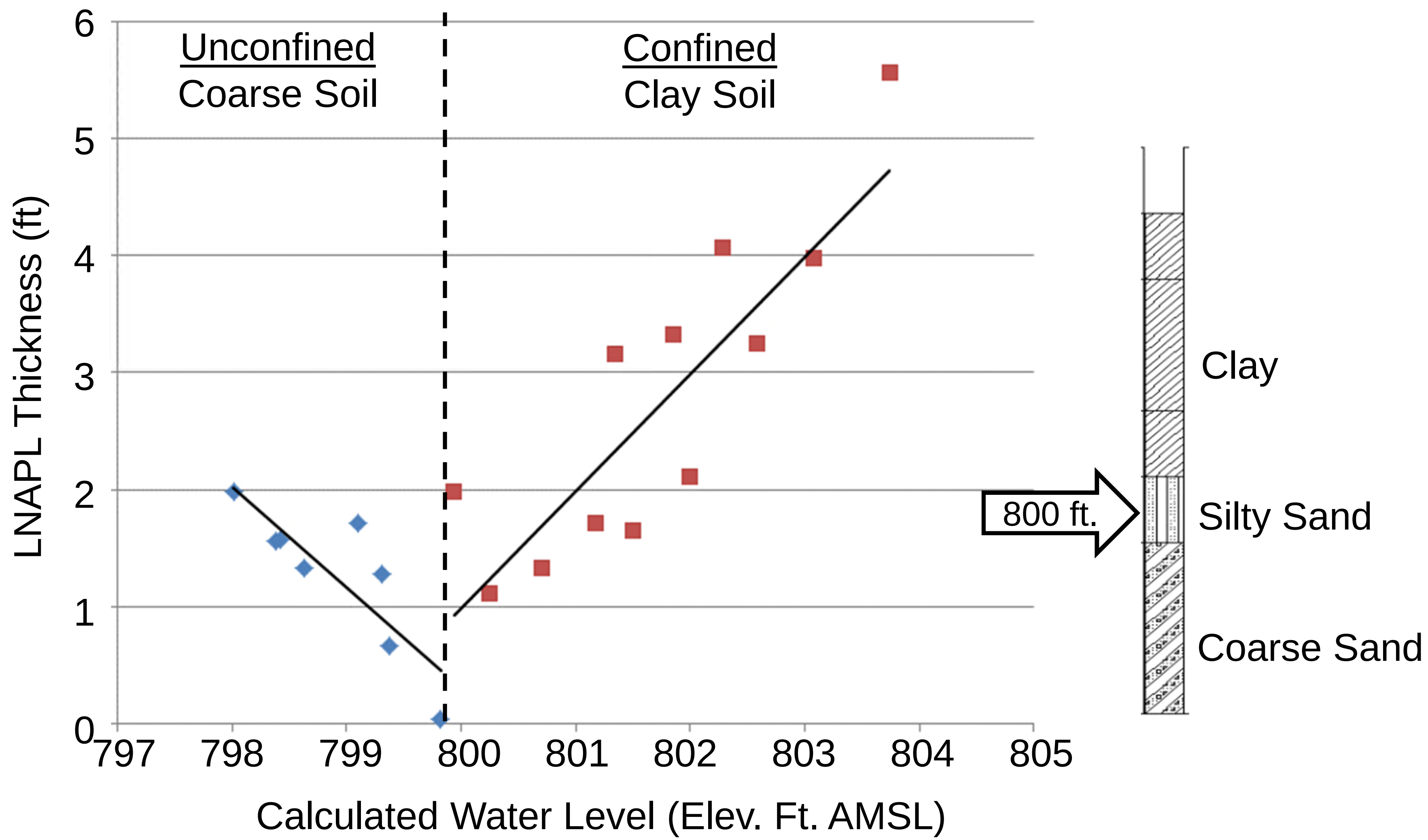
Source: Andrew Kirkman, PE, AECOM

Confined LNAPL Thickness in Well Increases With Water-Level Rise?



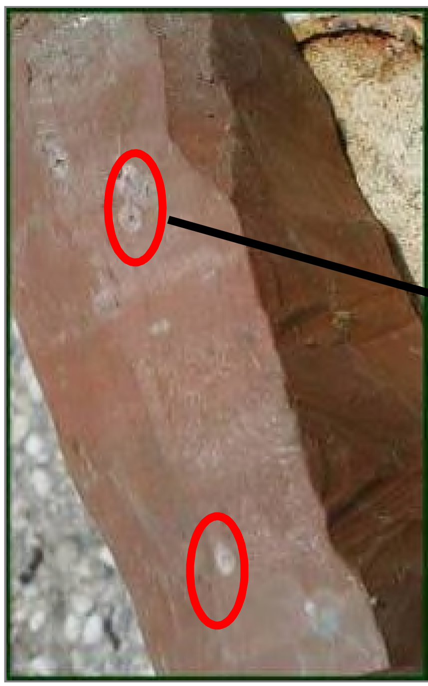
Monitoring well is a giant pore!

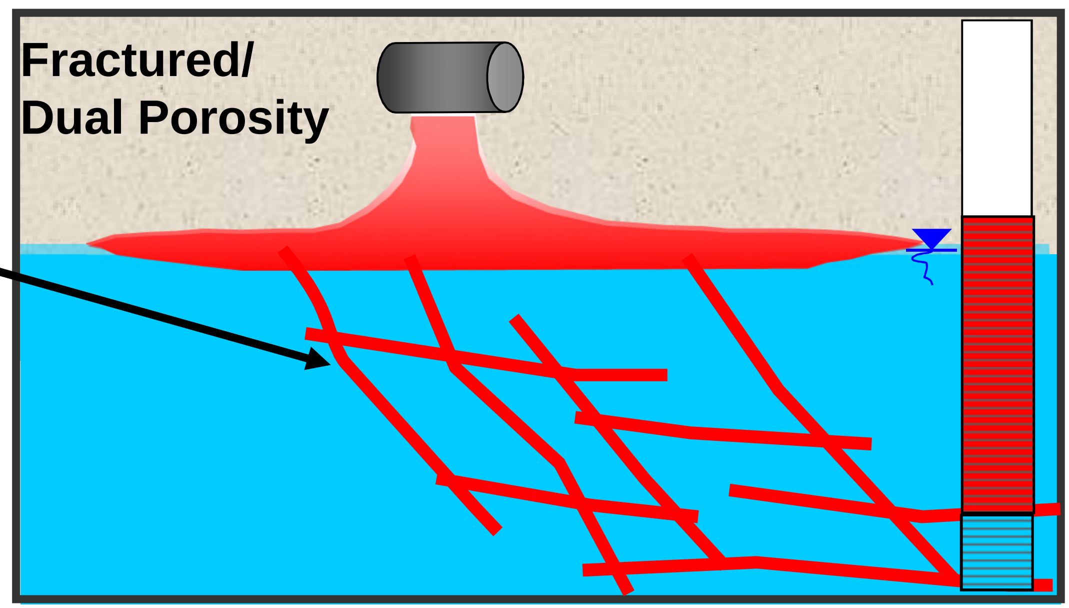
LNAPL Thickness vs. Potentiometric Surface Elevation (Confined)



Fractured and Preferential Pathway Conditions

- LNAPL that is confined in a large pore network that is defined by capillary pressure contrast
  - e.g., open fractures, sand surrounded by clay, macropores





Why Identifying Hydrogeologic Condition of LNAPL Occurrence Important

- Minimizes or exaggerates LNAPL thickness in wells relative to LNAPL thickness in formation
- Volume estimates – modeling and recovery system implications
- Recovery can decrease – while LNAPL thickness is constant
- Understanding LNAPL migration pathways
- Development of effective LNAPL remedial strategy
  - Identify zones to target for LNAPL remediation
  - Critical for identifying appropriate LNAPL remediation technology
- Recovery rate constant for perched – controlled by rate draining off the perching layer (lowering water table won't help)

Knowledge Check

Poll Question

Background: A site has 7 ft. of LNAPL in a well. After a heavy rainfall season, the LNAPL thickness increases to 9 ft.

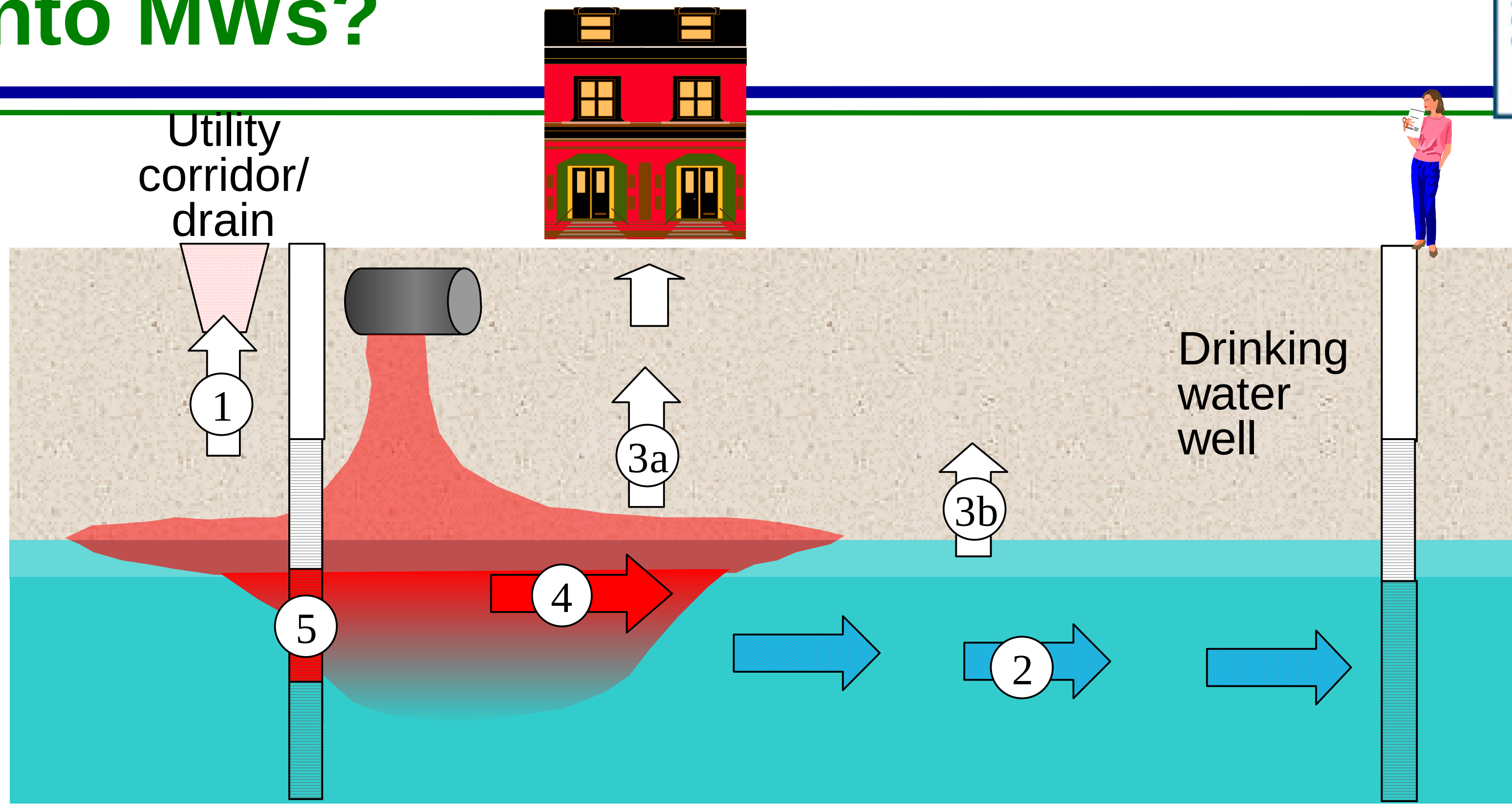
Question: Which of these is likely to be correct?

A. LNAPL is unconfined
B. LNAPL is perched
C. LNAPL is confined
D. LNAPL is moving/migrating

Key Message 6

Mobile LNAPL does not necessarily mean that the LNAPL is migrating

What Changed When LNAPL Flowed Into MWs?



Source: Garg

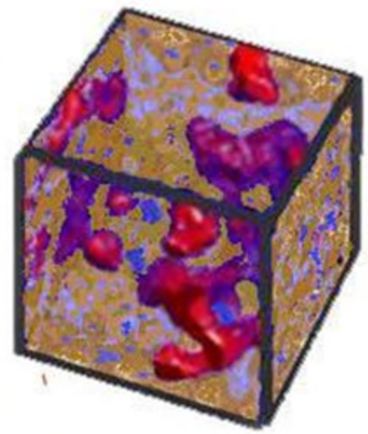
Emergency concerns when LNAPL in the ground	Concerns when LNAPL in the ground (evaluated using standard regulations)	Potential concerns when LNAPL in wells (not evaluated using standard regulations)
(1) Vapor accumulation in confined spaces causing explosive conditions ***Not shown*** - Direct LNAPL migration to surface water ***Not shown*** - Direct LNAPL migration to underground spaces	(2) Groundwater (dissolved phase) (3a) LNAPL to vapor (3b) Groundwater to vapor ***Not shown -*** Direct skin contact	(4) LNAPL potential migration (5) LNAPL in well (aesthetic, reputation, regulatory)

Darcy's Law for LNAPL

- Darcy's Law governs fluid flow in a porous media
  - $q = K\, i$
- In a water / LNAPL system, not just dealing with a single fluid (groundwater or LNAPL)
- Darcy's Law applicable to each fluid (water / LNAPL) independently

Darcy's Law for water flow: $q_w = K_w\, i_w$

Darcy's Law for LNAPL flow: $q_n = K_n\, i_n$



q = Darcy flux (L/T)

K = fluid conductivity (L/T)

i = gradient

$_w$ = water

$_n$ = LNAPL

Will next look at LNAPL conductivity (K_n) and LNAPL gradient (i_n)

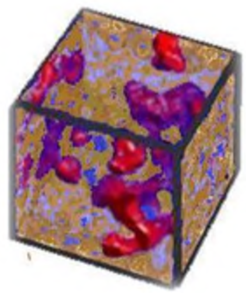
LNAPL Conductivity

Darcy's Law: Applicable to LNAPL

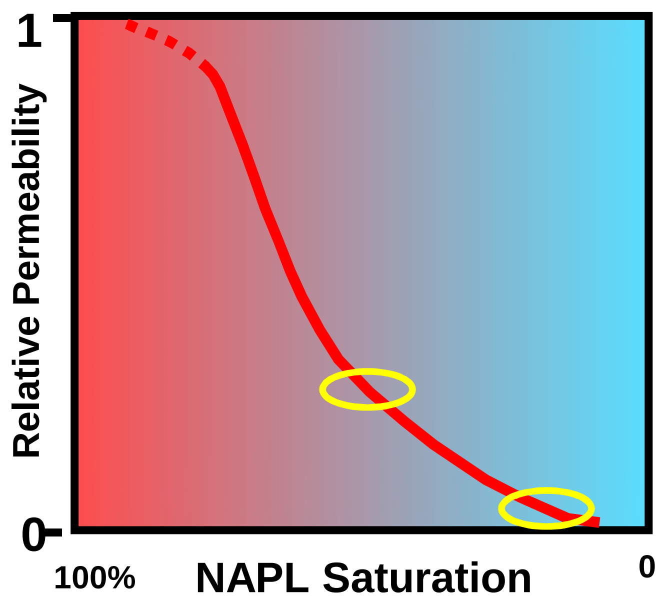
LNAPL conductivity:

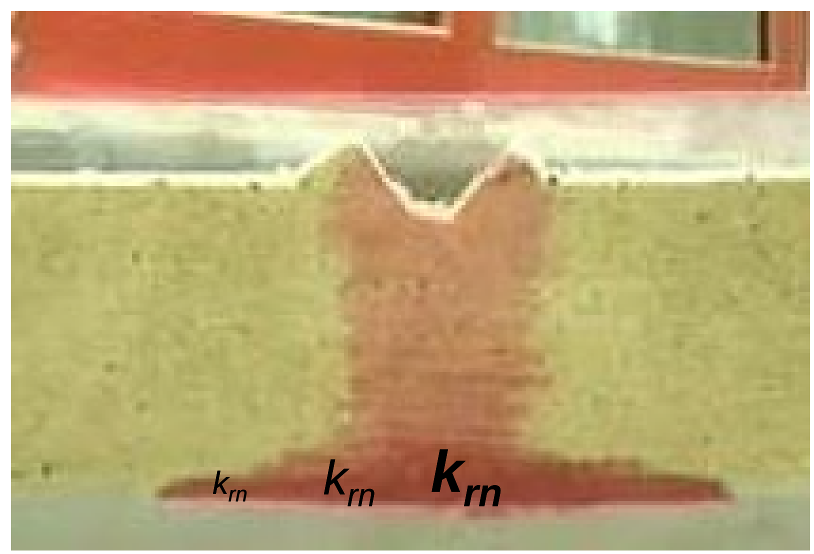
$$K_n = \frac{\rho_n \cdot g \cdot k}{\mu_n} k_{rn}$$

$$K_n = K_{w,sat} \frac{\rho_n}{\rho_w} \frac{\mu_w}{\mu_n} k_{rn}$$



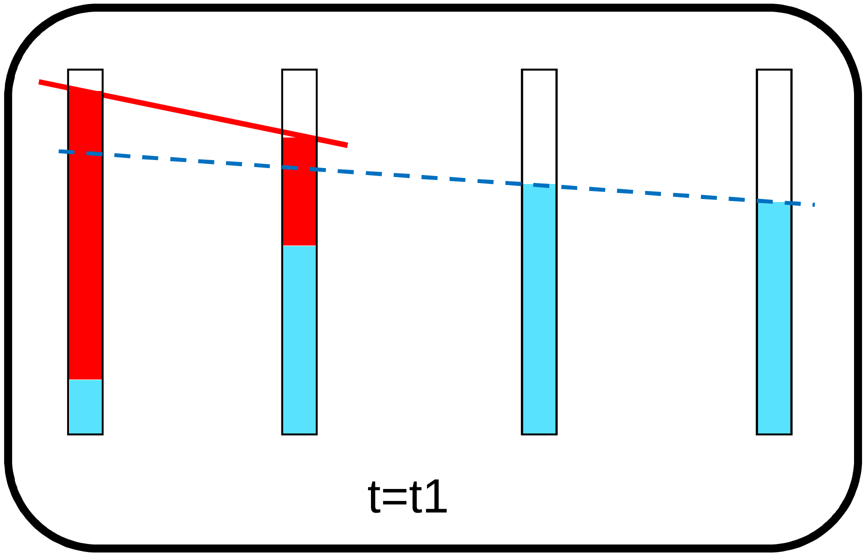
K = conductivity
k = intrinsic permeability
k_r = relative permeability
ρ = density μ = viscosity
$_n$ = LNAPL $_w$ = water
g = acceleration due to gravity

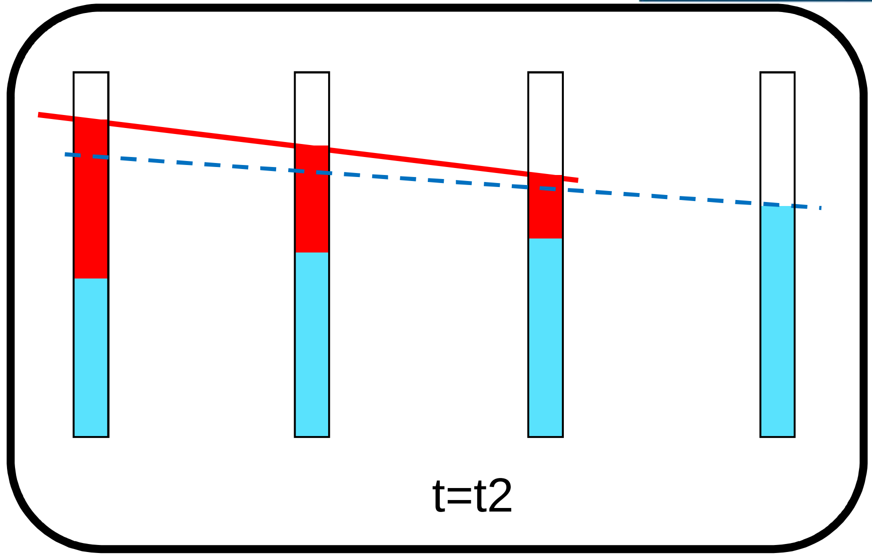


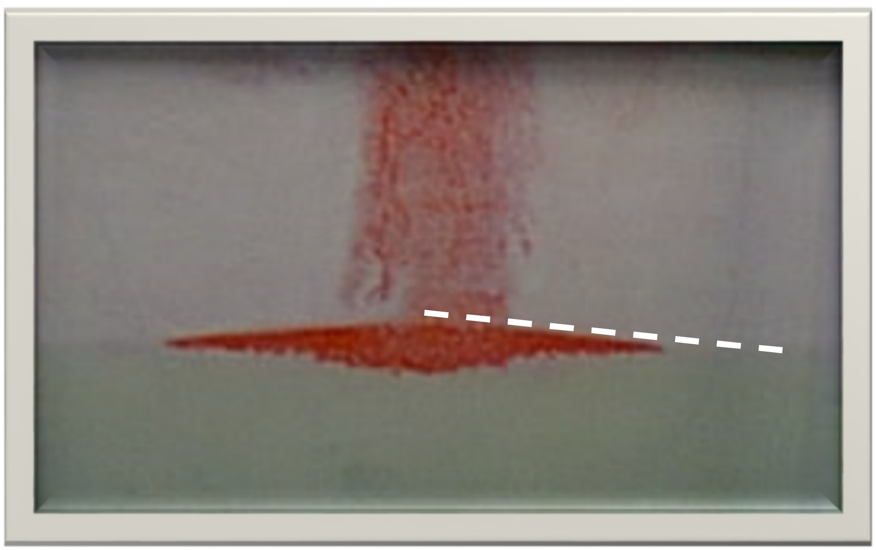


LNAPL Gradient:
For a Finite Release Flattens over Time

Darcy's Law: Applicable to LNAPL



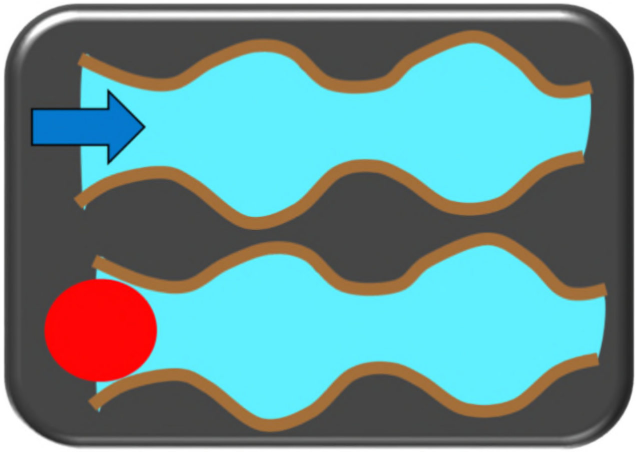




Pore Entry Pressure: LNAPL Behavior

- Similar behavior when LNAPL tries to enter pores with pre-existing fluids
  - Fluid does not encounter resistance when flowing into like (e.g., groundwater flow)
  - Soil pores less wetting to LNAPL than water: LNAPL encounters resistance
  - Soil pores more wetting to LNAPL than air: LNAPL displaces air easily
- LNAPL only moves into water-wet pores when entry pressure (resistance) is overcome
  - To distribute vertically and to migrate laterally

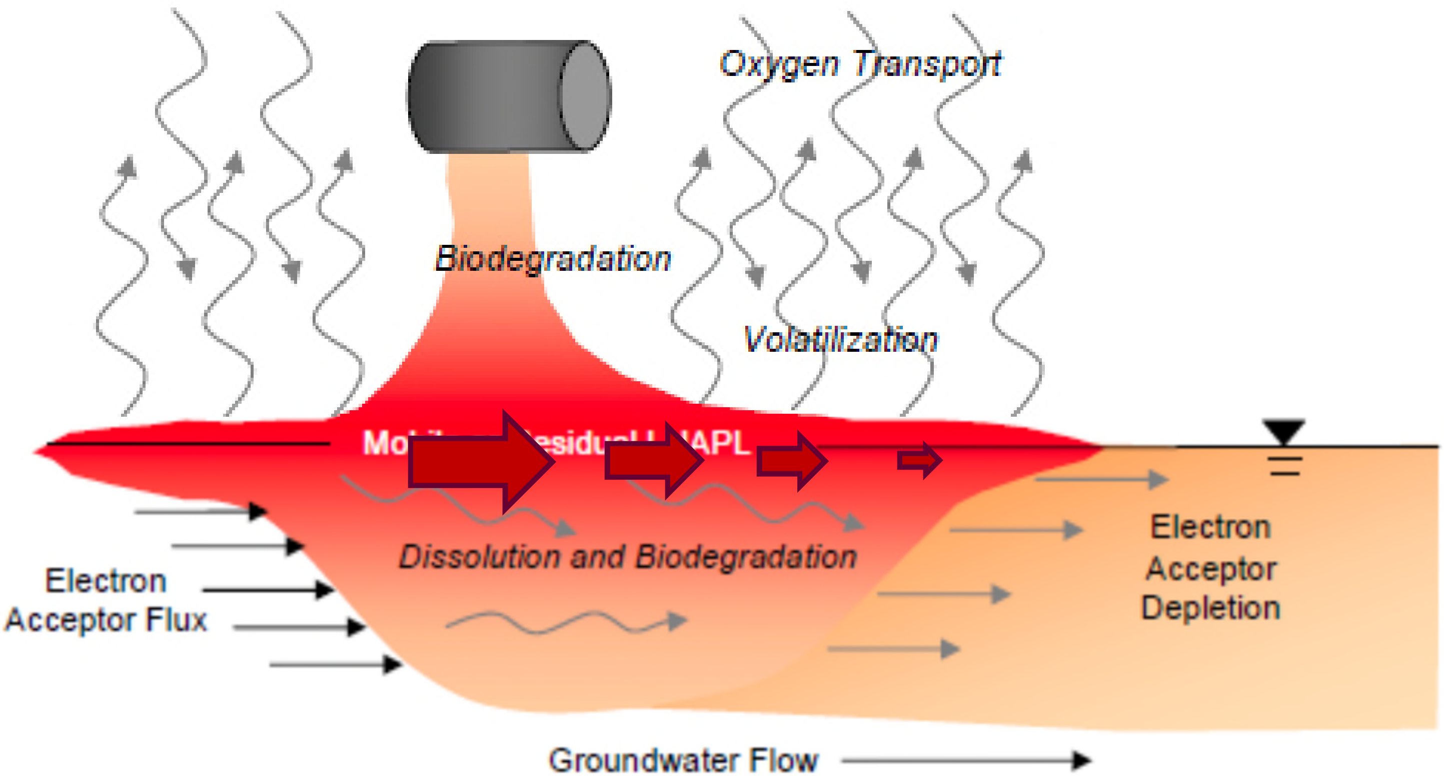
For water-wet media



Key Point: Pore Entry Pressure is the resistance that LNAPL encounters when flowing into a pore with preexisting groundwater

NSZD (Natural Source Zone Depletion) Contributes to LNAPL Stability

- Rates have been measured at about 100 to 1000 gallons per year per acre *(Lundegard & Johnson 2006; ITRC 2009; Sale 2011)*

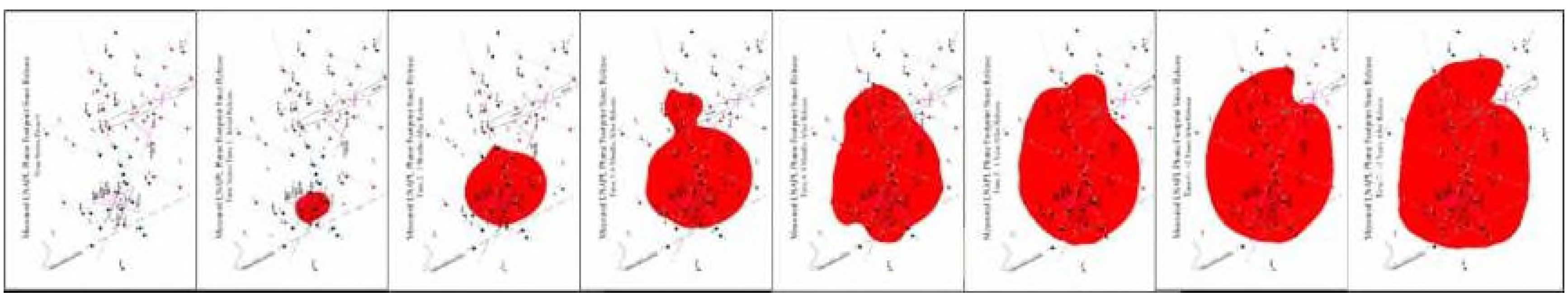


Lines of Evidence:
1. Gauging Data

- Monitoring results (assumes adequate well network)
  - Stable or decreasing thickness of LNAPL in monitoring wells
  - Sentinel wells outside of LNAPL zone remain free of LNAPL

Caution: Need to account for water-table fluctuations when evaluating thicknesses

time = 0 - **0+** **3 months** **6 months** **9 months** **1 year** **2 year** **3 year**



LNAPL Footprint Stability LOE

Lines of Evidence: 2. Groundwater Data

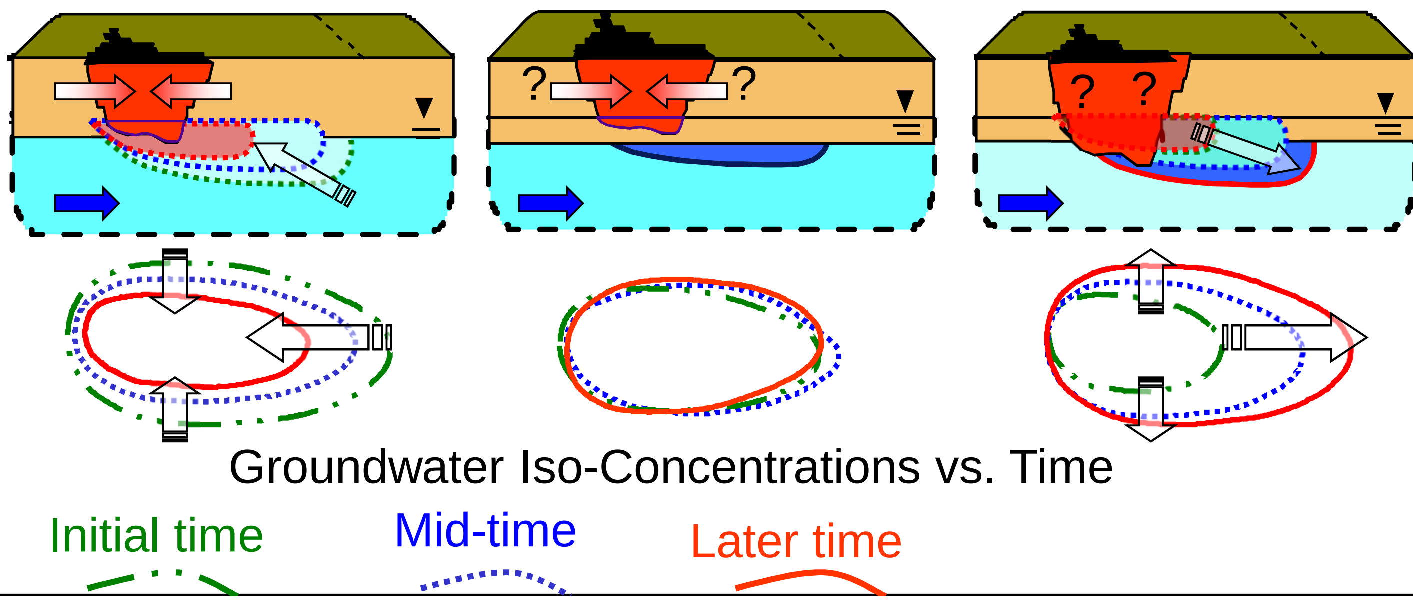
LNAPL Footprint Stability LOE

- Dissolved-phase plume maps
  - Characterize source area shape, size and depth
  - Assess if natural attenuation on-going
  - Shrinking/stable GW plume = shrinking/stable LNAPL body

Shrinking GW = Shrinking LNAPL

Stable GW = Stable/Shrinking LNAPL

Expanding GW= Shrinking/Stable/Expanding LNAPL

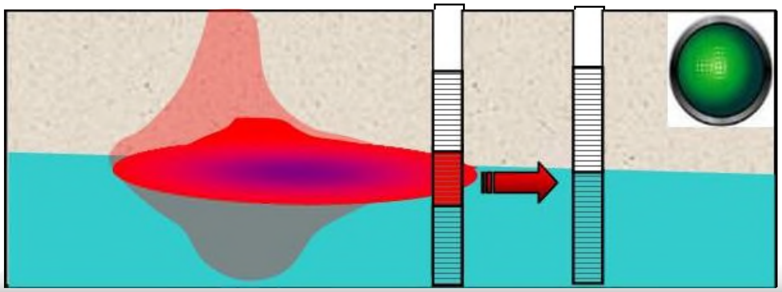


Groundwater Iso-Concentrations vs. Time

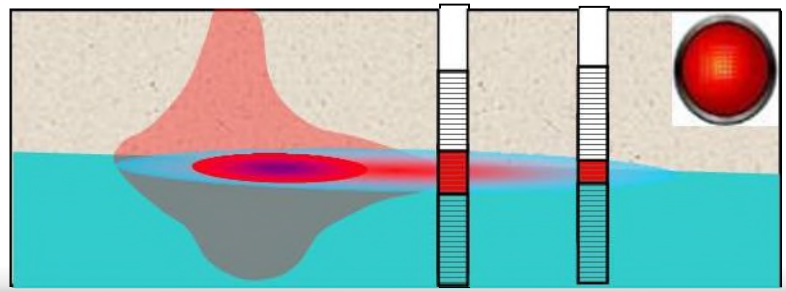
Lines of Evidence: 3. Measured LNAPL Thickness < Critical Thickness

LNAPL Footprint Stability LOE

LNAPL thickness > Critical thickness



LNAPL thickness < Critical thickness



Soil Type	Capillary Fringe Height (ft)	Critical LNAPL Thickness for Gasoline (ft.)	Critical LNAPL Thickness for Diesel (ft.)
Sand	0.23	0.7	1
Sandy Loam	0.43	1.4	2.1
Loam	0.92	2.8	3.6
Silt	2.03	4.8	5.9
Sandy Clay	1.21	3.9	4.9
Clay	4.10	6.6	9.5
Silty Clay	6.56	8.7	13.8

Ref: Charbeneau et al. (1999)
API Publication No. 4682

Other Lines Of Evidence Of LNAPL Footprint Stability

4. Low LNAPL Transmissivity
   - Low Kn
   - Site measurements yield average values – can have higher Kn lenses
5. Age of the release
   - Abated release
   - Timing of release (if known)
   - Weathering indicators
6. Recovery rates
   - Decreasing LNAPL recovery rates
7. Laboratory tests
   - Saturation and residual saturation values
8. Tracer test
   - Measures rate of dilution of hydrophobic tracer

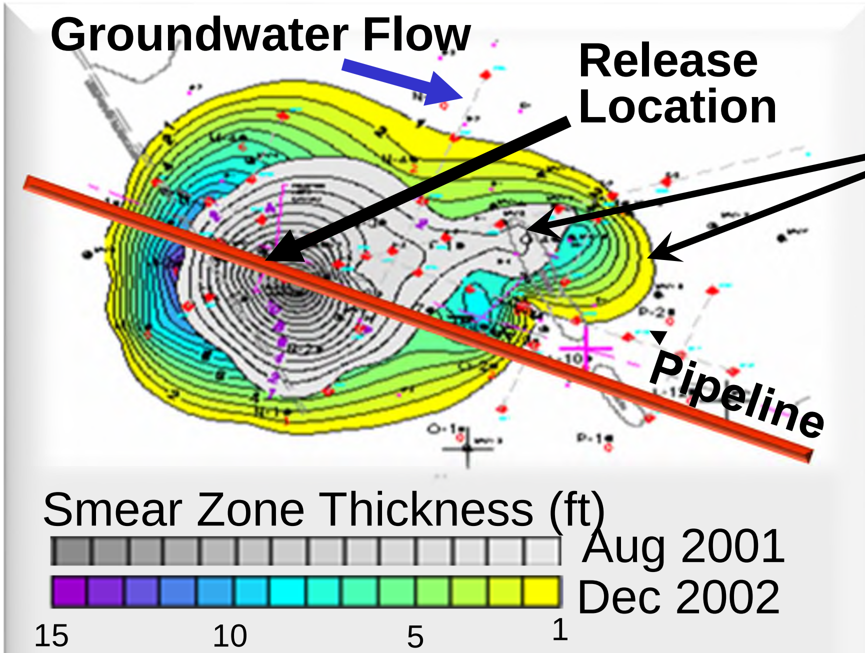
LNAPL Migration:
Case Examples

What we have observed at sites:

- LNAPL can initially spread at rates higher than the groundwater flow rate due to large LNAPL hydraulic heads at time of release
- LNAPL can spread opposite to the direction of the groundwater gradient (radial spreading)
- After LNAPL release is abated, LNAPL bodies come to be stable configuration generally within a short period of time

Case Example 1:
LNAPL Release and Spreading

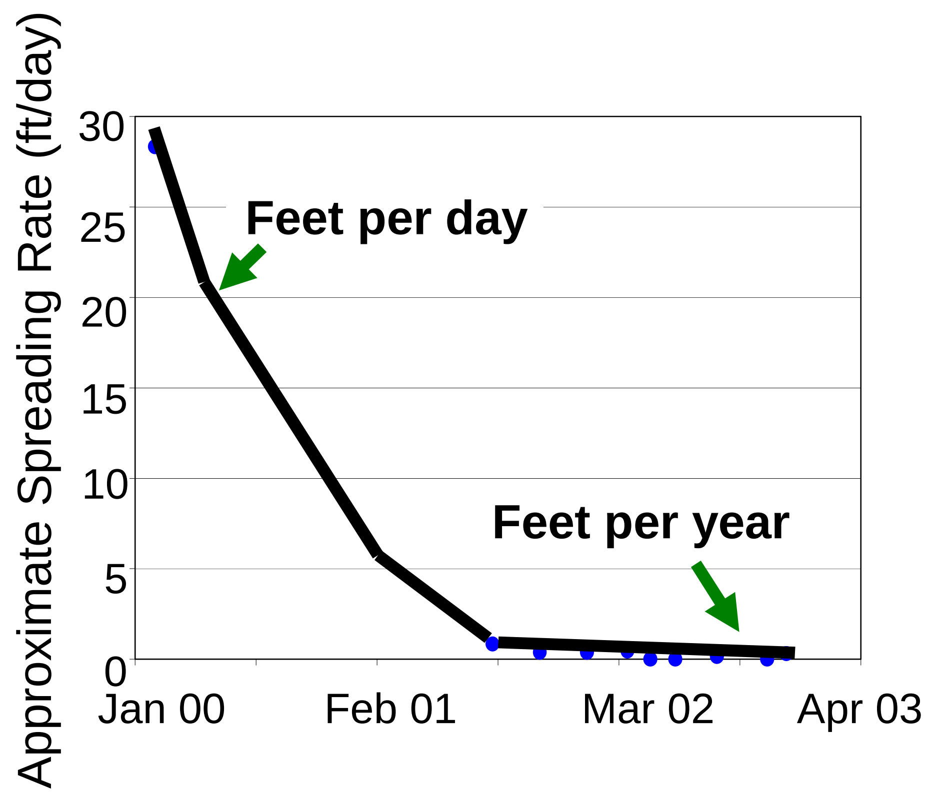
LNAPL Migration: Case Examples



Change in LNAPL footprint from Aug '01 to Dec '02

Pipeline release in Feb 2000

- Sweet Texas crude
- Unknown release volume



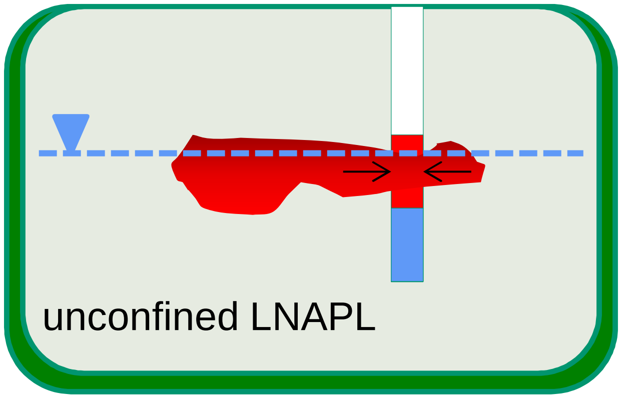
LNAPL Migration Potential / Stability Summary

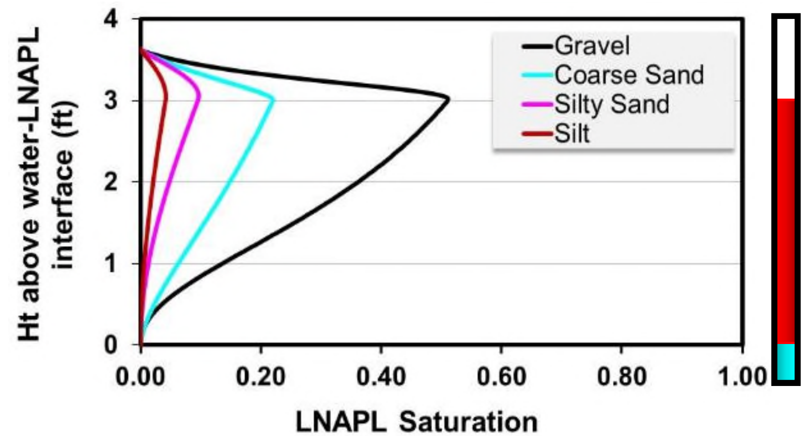
- Mobile LNAPL is not necessarily migrating LNAPL
  - In-well LNAPL does not mean it is moving
- Principles of Darcy's Law apply
  - LNAPL can spread upgradient and migrate rapidly in the early phases following a release
  - Self-limiting process, once the release is abated
- LNAPL needs to overcome pore-entry pressure to move into a water-saturated pore
- NSZD (Natural Source Zone Depletion) contributes to LNAPL stability
- Use multiple lines of evidence to assess LNAPL stability

Key Message 7

LNAPL Transmissivity is a better indicator of recoverability

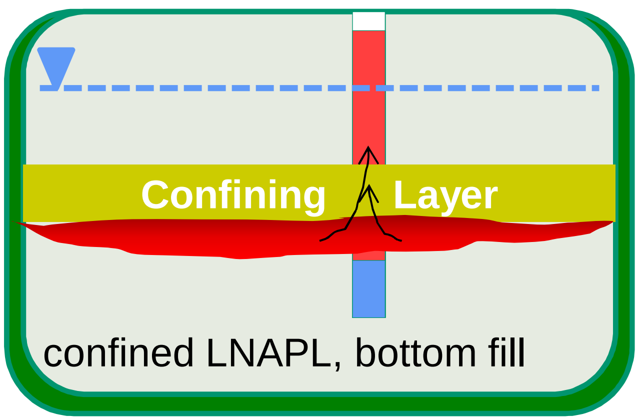
Apparent LNAPL Thickness Not a Good Indicator of Recoverability

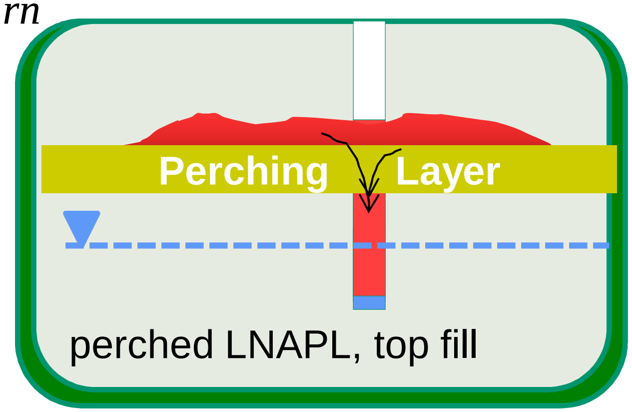




LNAPL conductivity:

$$K_n = \frac{\rho_n \cdot g \cdot k}{\mu_n} k_{rn}$$



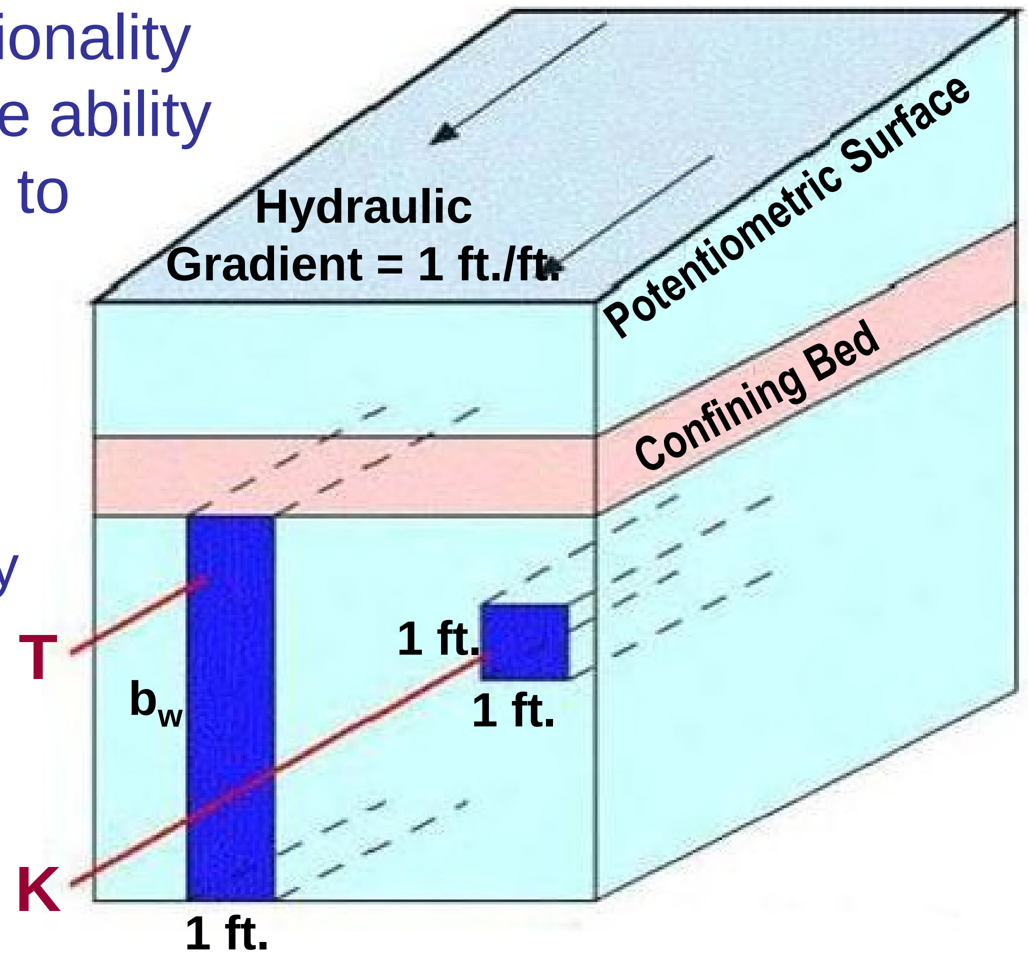


Need a metric that is indicative of LNAPL recoverability!

Groundwater Transmissivity – The Standard for Groundwater Producibility

- **Transmissivity** - proportionality coefficient describing the ability of a permeable medium to transmit water

$T_w = K_w \cdot b_w$
K_w = hydraulic conductivity
b_w = aquifer thickness



Modified from Driscoll (1989)

LNAPL Transmissivity – The New Standard for LNAPL Recoverability

LNAPL Transmissivity (T_n) is a proportionality coefficient that represents the ability of a permeable medium to transmit LNAPL

$$q_n = K_n i_n$$

$$q_n b_n = K_n b_n i_n$$

$$Q_n = T_n i_n$$

T_n represents *averaged* aquifer & fluid properties (soil permeability, density, viscosity, saturation) AND thickness of mobile LNAPL interval

$$T_n = K_n b_n$$

$$K_n = \frac{\rho_n \cdot g \cdot k}{\mu_n} k_{rn}$$

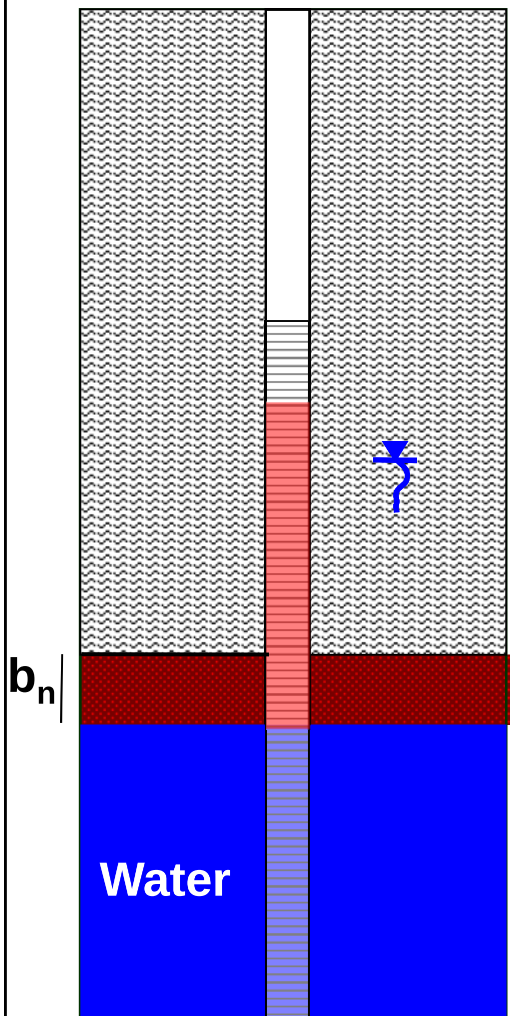
T_n is an averaged indicator of recoverability

- K_n varies with saturation

From Andrew Kirkman

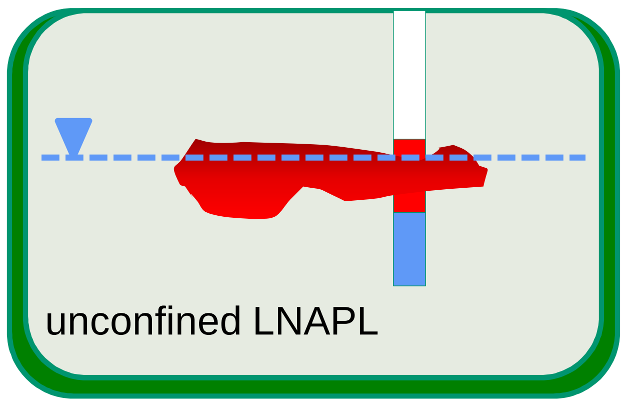
Formation Thicknesses for Confined/Perched Conditions

Confined LNAPL



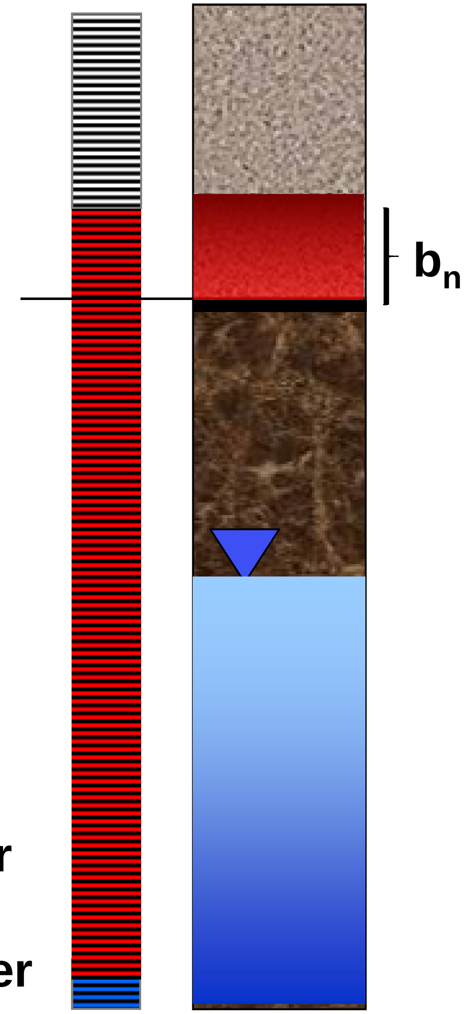
Unconfined LNAPL

b_n = LNAPL thickness in MW



b_n = lower elevation of confining layer – elevation of LNAPL water interface

Perched LNAPL



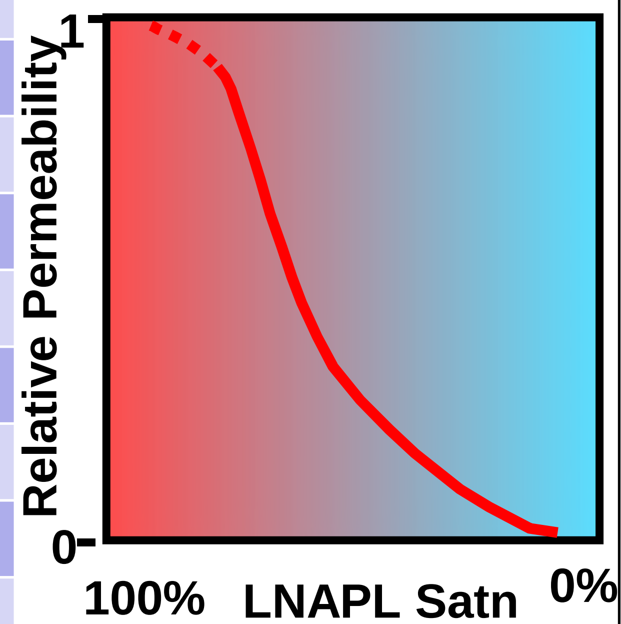
b_n = elevation of LNAPL-air interface – upper elevation of low permeability layer

T_n Values for Gasoline/Diesel

USDA Soil Type	Saturated Hydraulic Conductivity (ft./day)	LNAPL Thickness (ft.)	T_n gasoline (ft^2/day)	T_n diesel (ft^2/day)
Medium Sand	100	1	8.5	0.2
		2	58	2.4
		5*	335	38
Fine Sand	21	1	1.6	0.03
		2	11	0.4
		5*	67	7.4
Sandy Loam	1.25	1	0.3	0.03
		2	1.0	0.1
		5	4.4	0.6
Silt Loam	0.6	1	0.006	0.0
		2	0.05	0.005
		5	0.5	0.05

LNAPL-2 = 0.1 - 0.8 ft^2/day

T_n modeled assuming homogenous soils

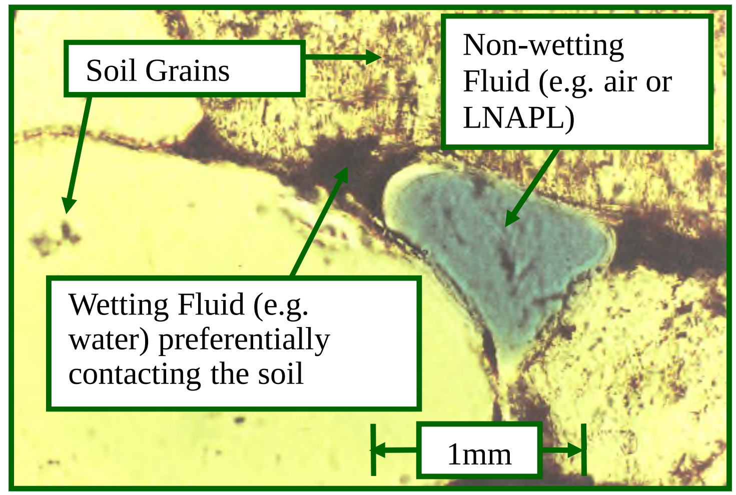


***5 ft formation thickness unlikely at old sites**

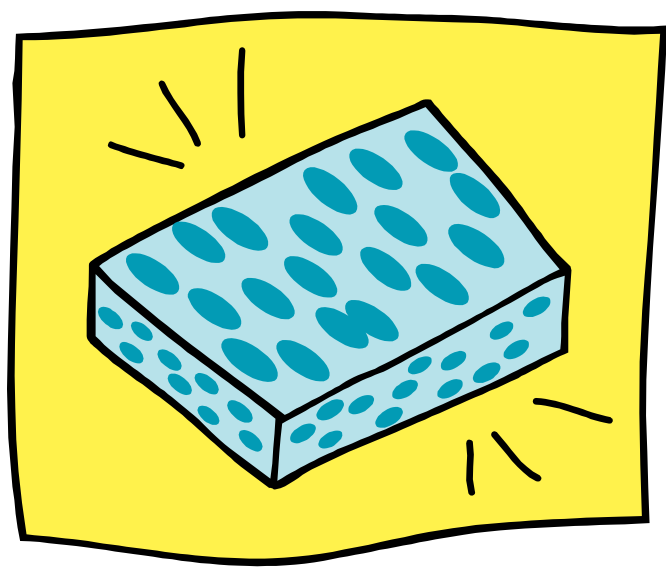
Residual Saturation and Transmissivity

Transmissivity – Indicator of recovery

- **"the oil that remains in an oil reservoir at depletion"**
  Pet. Eng. Handbook, 1987
- **"oil that remains after a water flood has reached an economic limit"**
  Morrow, 1987
- **"saturation at which the NAPL becomes discontinuous and is immobilized by capillary forces"**
  Schwille, 1984; Domenico and Schwartz, 1990; and Mercer and Cohen, 1990



From Wilson et al., (1990)



When LNAPL saturation approaches Residual Saturation, LNAPL Transmissivity approaches Zero

Knowledge Check

Poll Question

Background: A site has 7 ft. of LNAPL in a well. After a heavy rainfall season the LNAPL thickness increased to 9 ft.

Question: How would one make decision regarding recoverability?

A. There is a lot of LNAPL at the site, and should be readily recoverable
B. LNAPL is confined and does not need to be recovered
C. Bail the LNAPL out and see how fast it recovers

Key Message 8

Causes for Sheens
Not Necessarily LNAPL Migration

Petroleum Sheens

Originating from LNAPL in sediments at the groundwater surface water interface

Key Message: transport of LNAPL to surface water is not necessarily gradient-driven

- 1. Seep: Groundwater discharge carries LNAPL sheen
- 2. Ebullition: Gas generated from degradation carries LNAPL sheen
- 3. Erosion: Erosion of sediments with LNAPL into water column

Image: CH2M (2016)

Key Message 9

Biological processes are important

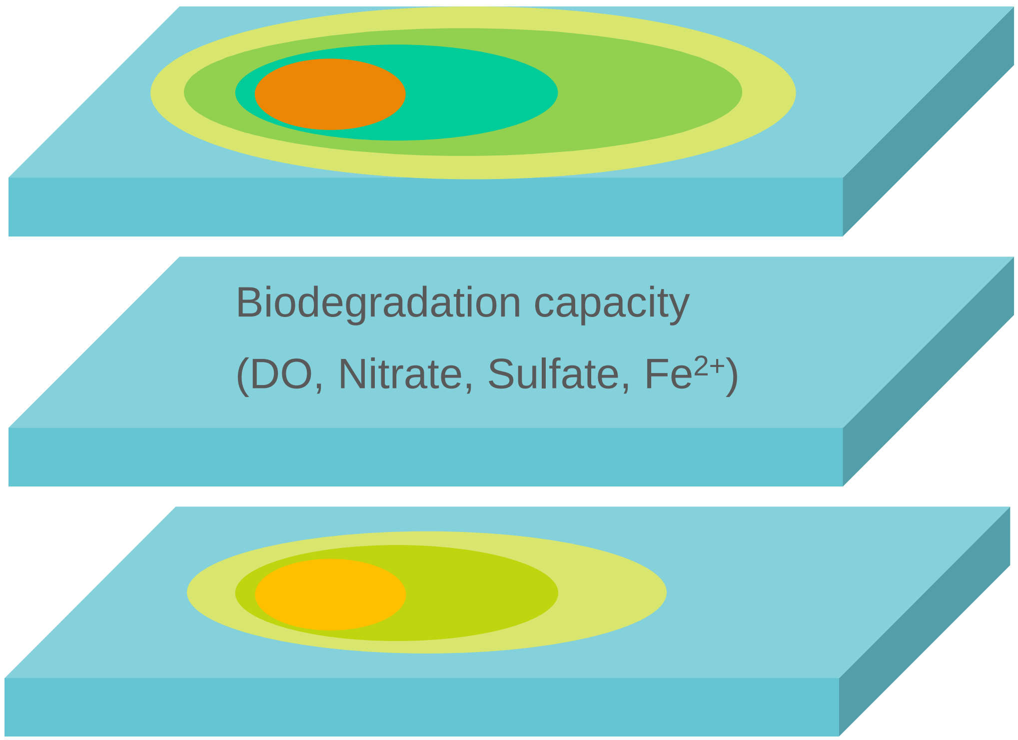
Biodegradation Capacity of Saturated-Zone Electron Acceptors

Biological Processes

MNA focused on groundwater plume: how far and at what concentration

Typical Biodeg Capacity
<~50 gal/ac/yr

Garg et al., 2017



Source: Bioscreen documentation

KEY POINT Electron acceptor mass-balance significantly underestimated LNAPL source zone biodegradation

NSZD Rates Being Observed

NSZD Study	Site-wide NSZD Rate (gallons/ acre /year)
Six refinery & terminal sites (McCoy et al., 2015)	2,100 – 7,700
1979 Crude Oil Spill (Bemidji) (Sihota et al., 2011)	1,600
Two Refinery/Terminal Sites (LA LNAPL Wkgrp, 2015)	1,100 – 1,700
Five Fuel/Diesel/Gasoline Sites (Piontek, 2014)	300 - 3,100
Eleven Sites, 550 measurements (Palaia, 2016)	300 – 5,600

KEY POINT

NSZD rates are in the range of 100s to 1000s of gallons/acre/year

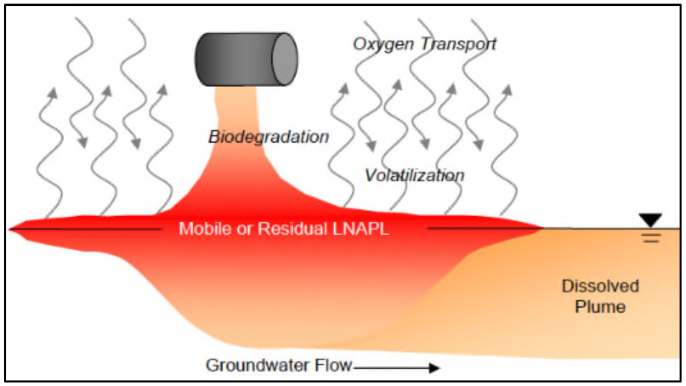
Need Vapor Flux Also

Baedecker et al., 1993

Mass transfer calculations indicated that the primary reactions in the anoxic zone are…and outgassing of CH_4 and CO_2

Molins et al., 2010

"…the main degradation pathway can be attributed to methanogenic degradation of organic compounds …"



ITRC, 2009

Amos & Mayer, 2006

transfer of biogenically generated gases from the smear zone provides a major control on carbon balance

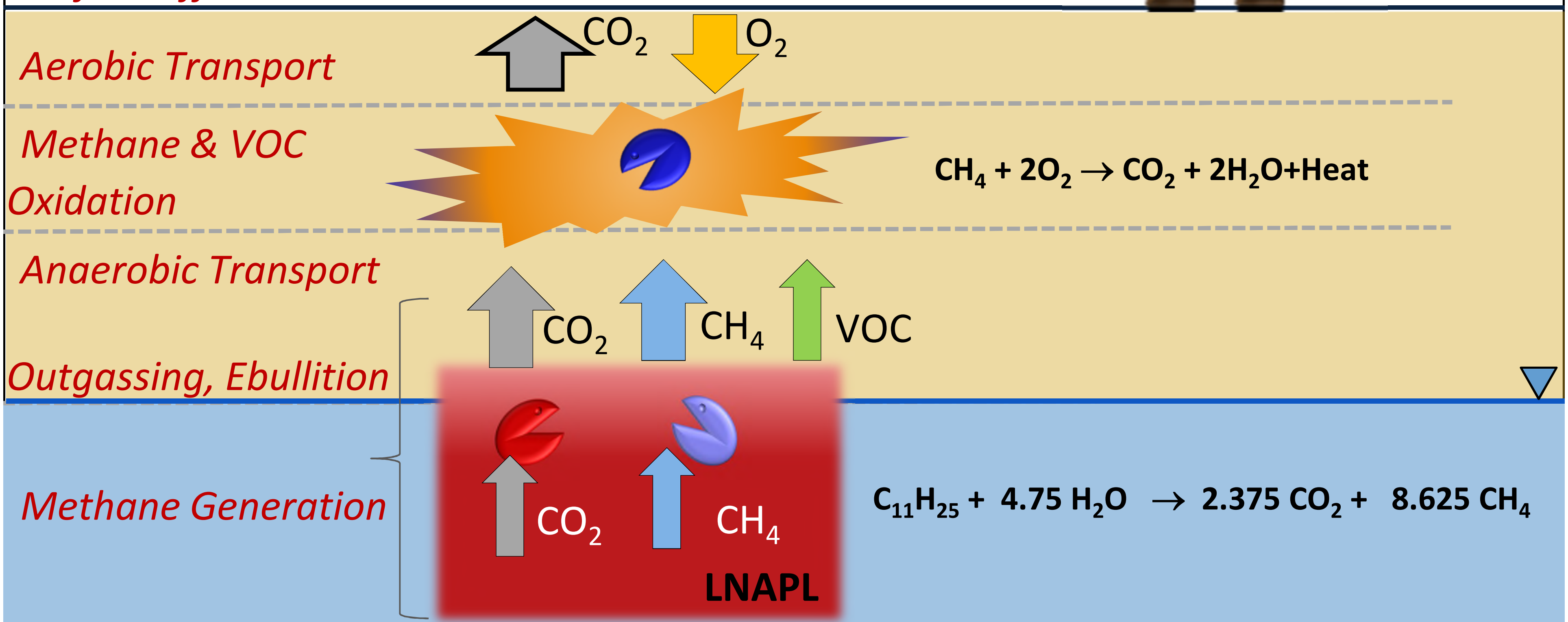
Lundegard & Johnson 2006

Mass loss associated with oxygen diffusion through the vadose zone is more significant (2 OOMs) than dissolution and biodegradation in the saturated zone

NSZD Conceptual Model

KEY PROCESSES

Surface Efflux



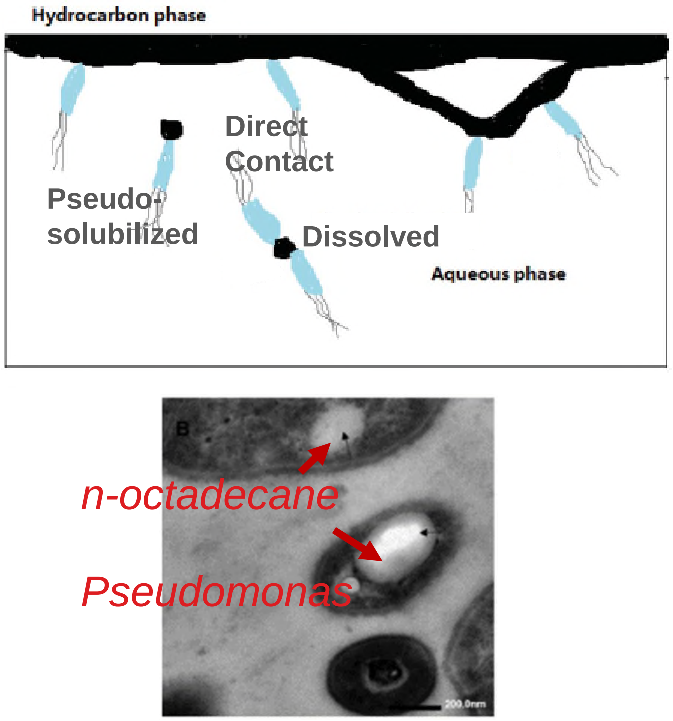
*Note: size of arrows indicates magnitude of flux

Garg et al., 2017

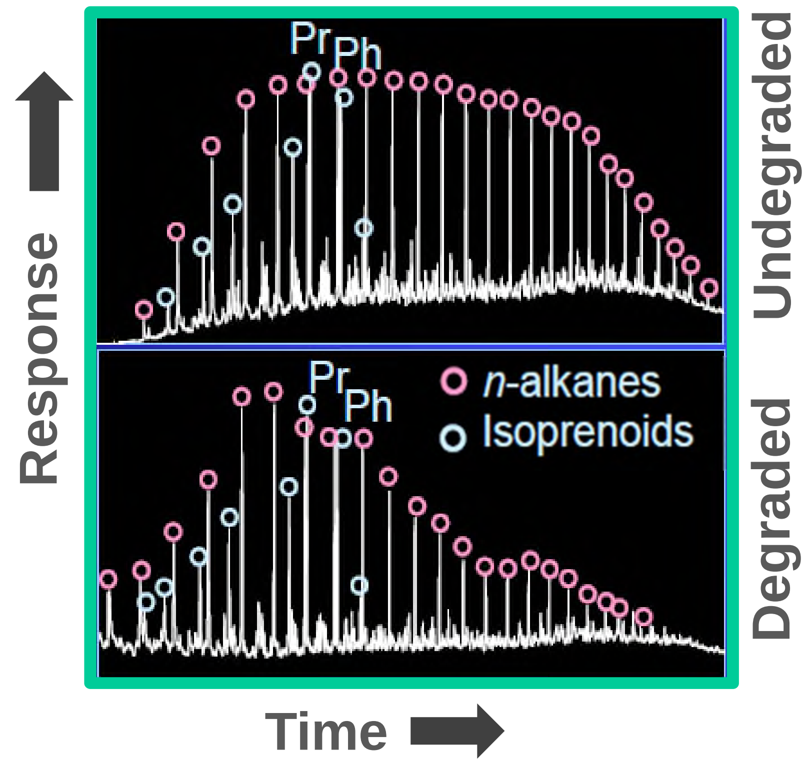
KEY POINT

- **Methanogenesis is a dominant process**
- **NSZD focuses on source depletion: how long**

Direct Outgassing



Hua et al., 2014

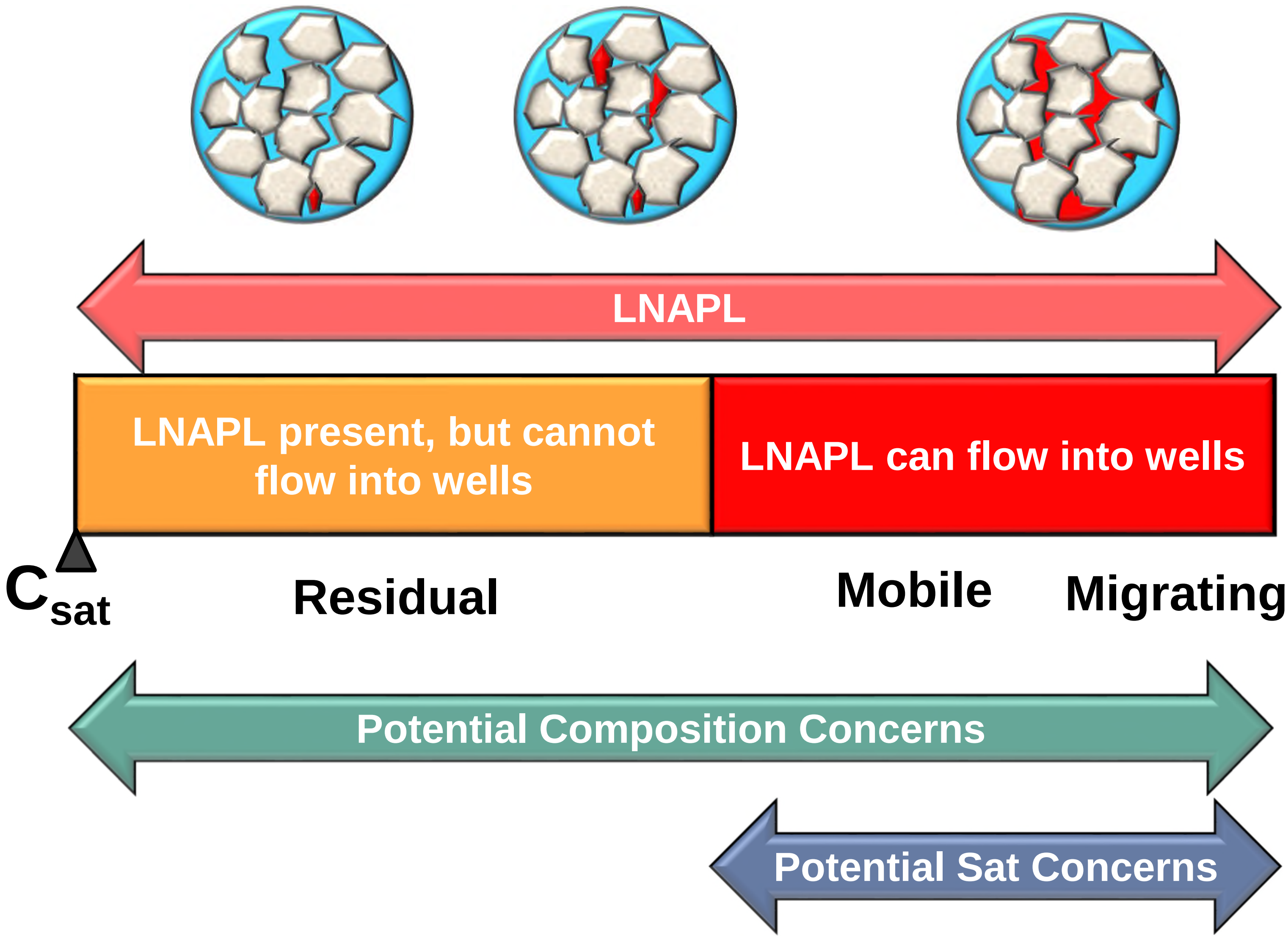


Bekins et al, 2005

KEY POINT

- **Dissolution is not necessary for LNAPL biodegradation**
- **Biodegradation occurs in pore space near LNAPL**

It is All LNAPL!



Biological Processes

Learning Objectives
3-Part Training Series

Part 1	▶ Use LNAPL science to your advantage and apply at your sites
Part 2	▶ Develop LNAPL Conceptual Site Model (LCSM) for LNAPL concern identification ▶ Inform stakeholders about the decision-making process
Part 3	▶ Select remedial technologies to achieve objectives ▶ Prepare for transition between LNAPL strategies or technologies as the site moves through investigation, cleanup, and beyond ▶ "SMART"-ly measure progress toward an identified technology-specific endpoint

ITRC 3-Part Online Training Leads to YOUR Action

Part 1:
Connect Science to LNAPL Site Management
(Section 3)

Part 2:
Build Your LNAPL Conceptual Site Model
(Sections 4 and 5)

Part 3:
Select / Implement LNAPL Remedies
(Section 6)

YOU
Apply at LNAPL Sites and/or Modify Agency Guidance

Based on the ITRC LNAPL-3 Document: LNAPL Site Management: LCSM Evolution, Decision Process, and Remedial Technologies

LNAPL Part 2 Agenda

- Discuss the evolution of the LCSM
  - Concerns
  - Remedy Selection
  - Remedy Performance (Covered in IBT 3)

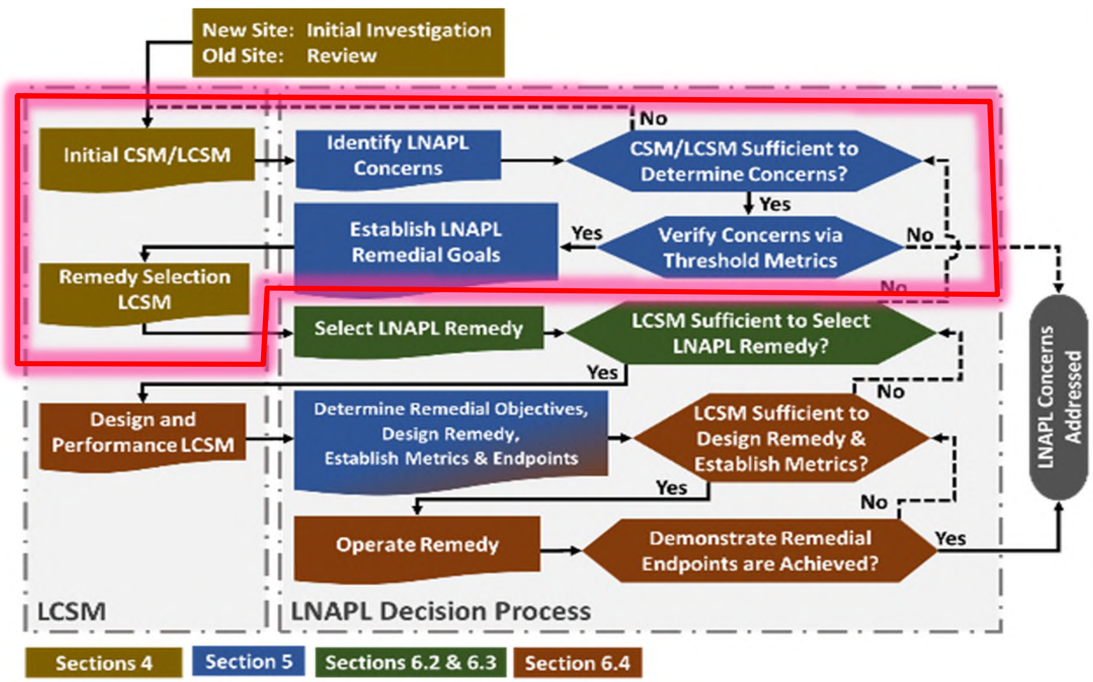


Figure 4-1, LNAPL-3

- Relate the LCSM to Site Strategy
  - Identification and Classification of Concerns
  - Establishing Remedial Goals to Address Concerns
  - Development of Remediation Objectives

Knowledge Check
Choose the Best Answer

Poll Question

- The concept of continually updating the LCSM throughout the remedial process means:
  - A. The LCSM should become increasingly complex throughout the remedial process
  - B. Even if performance monitoring indicates progress toward endpoints, better check between borings to ensure uniform treatment
  - C. Reinvestigate with the latest tools as new characterization technologies evolve
  - D. The LCSM is updated to inform decisions throughout the project. Each decision point may require different data.

Welcome to Progression Beyond Infinity

LCSM Evolution

- The LCSM is continually updated, but each update represents a focus specific to that project phase

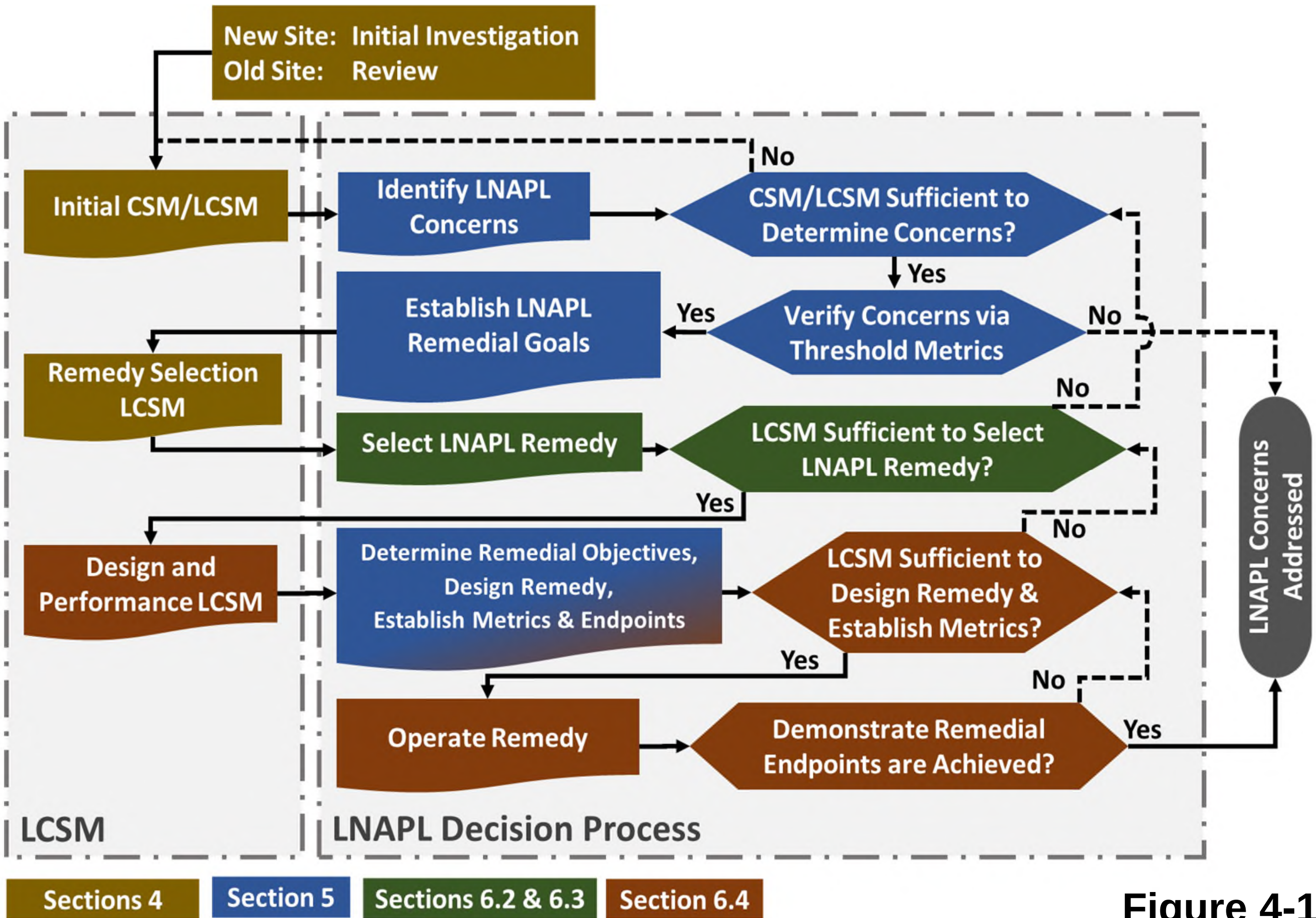
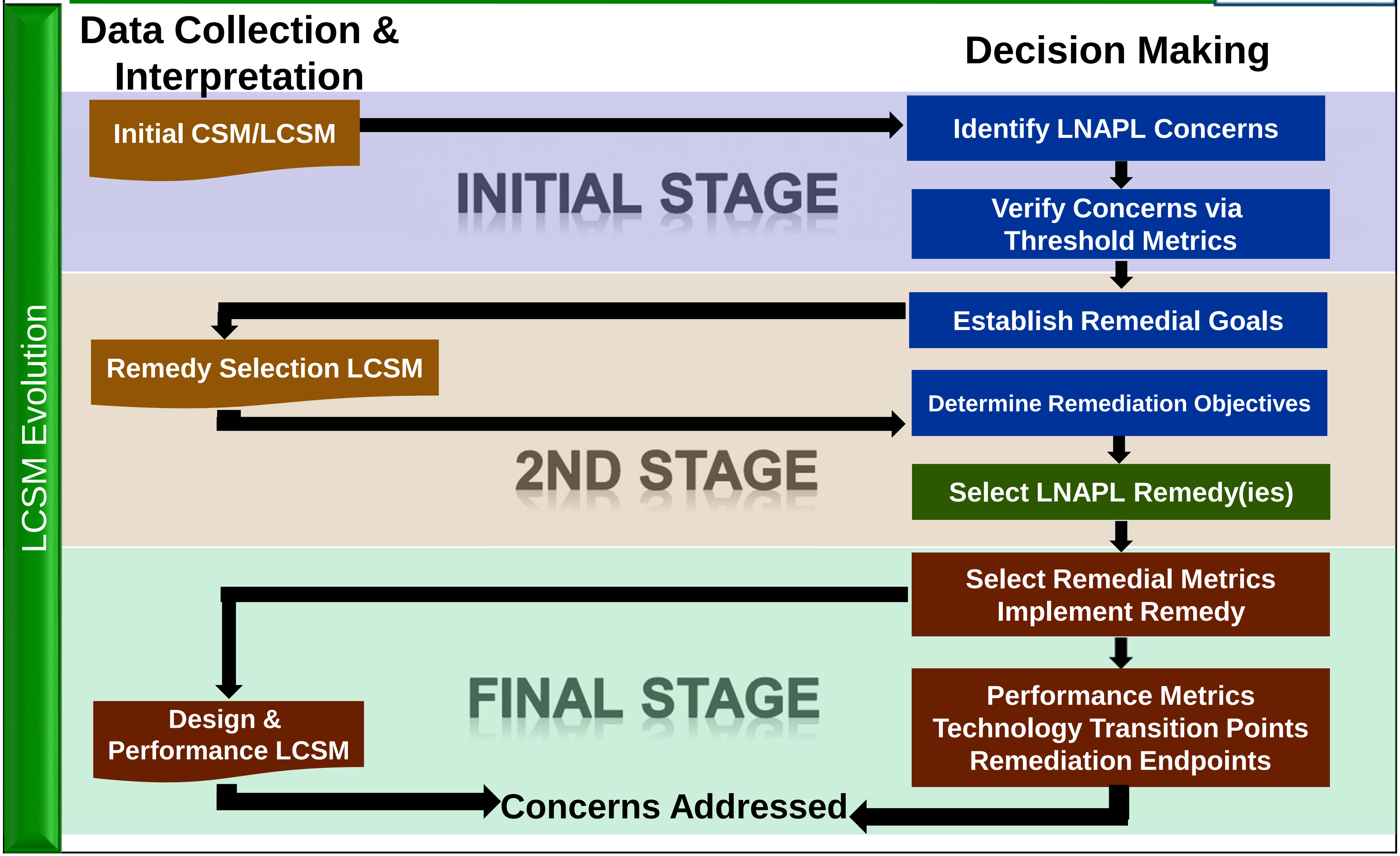


Figure 4-1, LNAPL-3

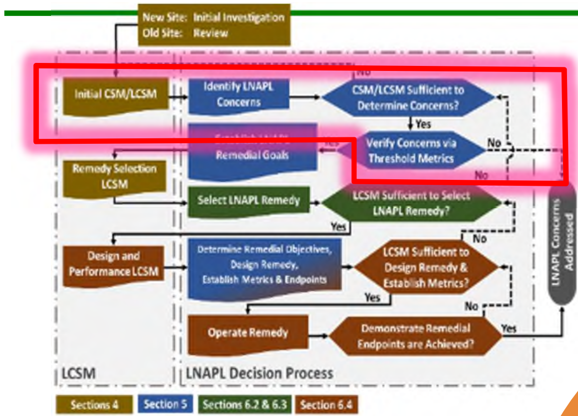
Data Collection & Evaluation is Parallel with Decision Making

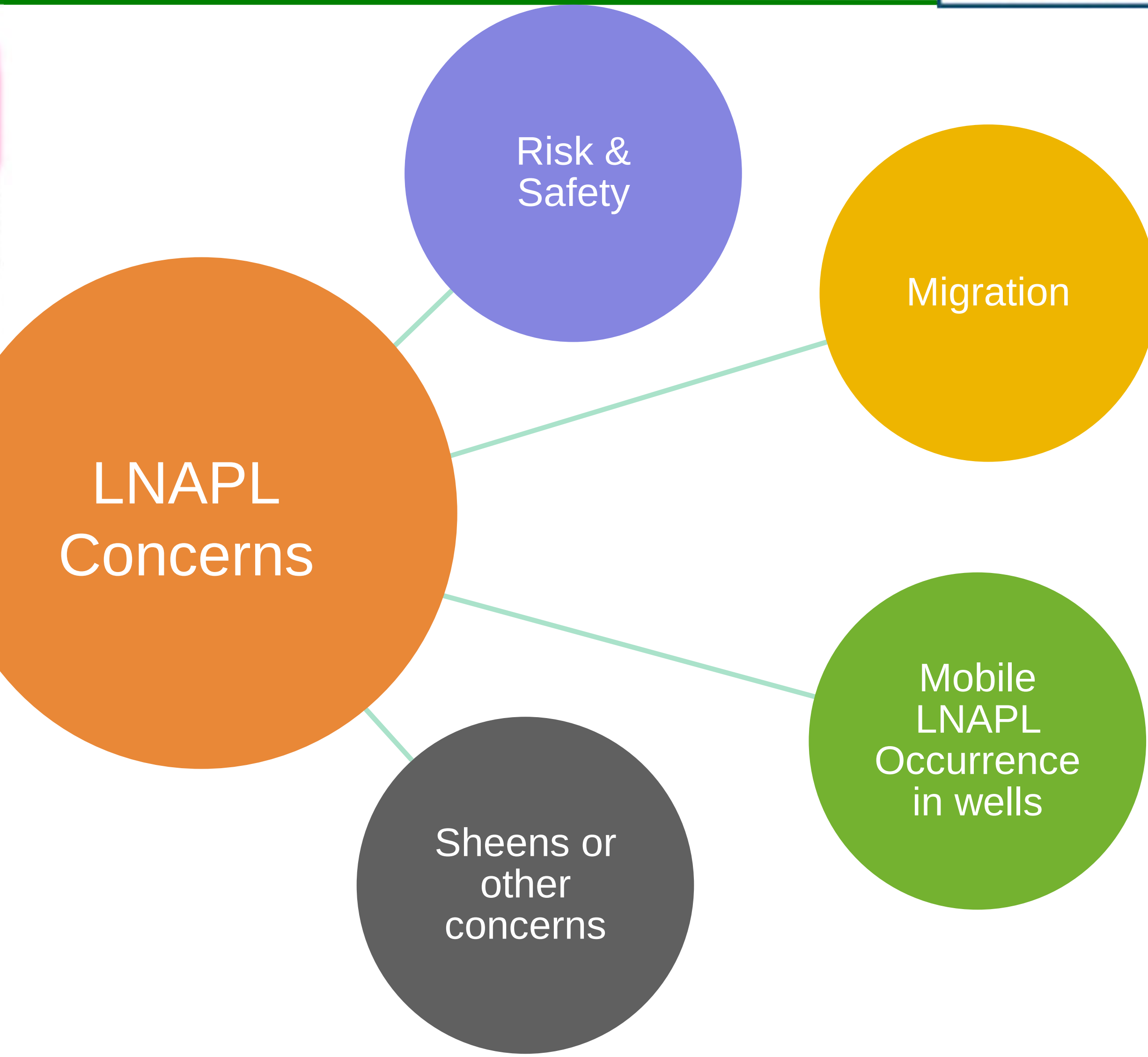


LNAPL Concerns

The Initial LCSM identifies specific LNAPL concerns

Initial LCSM





Initial LCSM

- Overall, the Concerns portion of the LCSM are typically well developed and mature
- Recent improvements in this area include
  - PVI (PVI IBT)
    - Screening distances (ITRC, 2015)
  - Natural Source Zone Depletion
  - Plume stability & NSZD (IBT#1)
  - LNAPL transmissivity to improve understanding of recoverability as related to maximum extent practicable
  - Sheens – Related Appendix in LNAPL Update document
- Ongoing Development
  - TPH guidance is being updated
- Recommended completeness test for Initial LCSM
  - LCSM should be able to inform a series of typical questions
  - Amount of detail for a given question is decided by asking "is there sufficient understanding to enable **Decision Making?"**

What is Needed for the Initial LCSM Consistently Needed or Possibly Needed?

- Receptors – NEED to understand where they are relative to plume
- Extent of impacts – NEED to understand if receptors are affected
- Migration – NEED to understand if existing impact extent will change
- LNAPL Occurrence in wells – Regulatory driven NEED
- Hydraulic Conductivity – Typically not needed to evaluate Concerns. Site Specific – for Concerns and Often Needed in Remediation
- Distribution of LNAPL and dissolved/vapor within the extent of Impacts – Typically not needed to evaluate concerns, Site Specific – for Concerns and Often Needed in Remediation

The Concerns LCSM Litmus Test

- The questions provided:
  - Are typical of multiple guidance (ASTM, CRCcare, IPECA, EPA)
  - Encourage a systematic framework to develop an LCSM
  - Encourage a systematic thought process to help confirm the completeness of the LCSM
  - Only apply to the Initial LCSM & may not be sufficient to select a remedy

1. Is current and future land use known?
2. Does the potential for preferential pathways exist?
3. How does stratigraphy relate to affecting impacts and potential migration?
4. Is the source and extent of the LNAPL known?
5. Are dissolved or vapor issues expected based on LNAPL composition?
6. Are dissolved or vapor plumes characterized?
7. Do soil or groundwater concentrations exceed criteria?
8. Are exposure pathways complete or incomplete?
9. Is the LNAPL body stable?
10. Is the mobile LNAPL hydrogeologic condition known?

The Amount of Knowledge

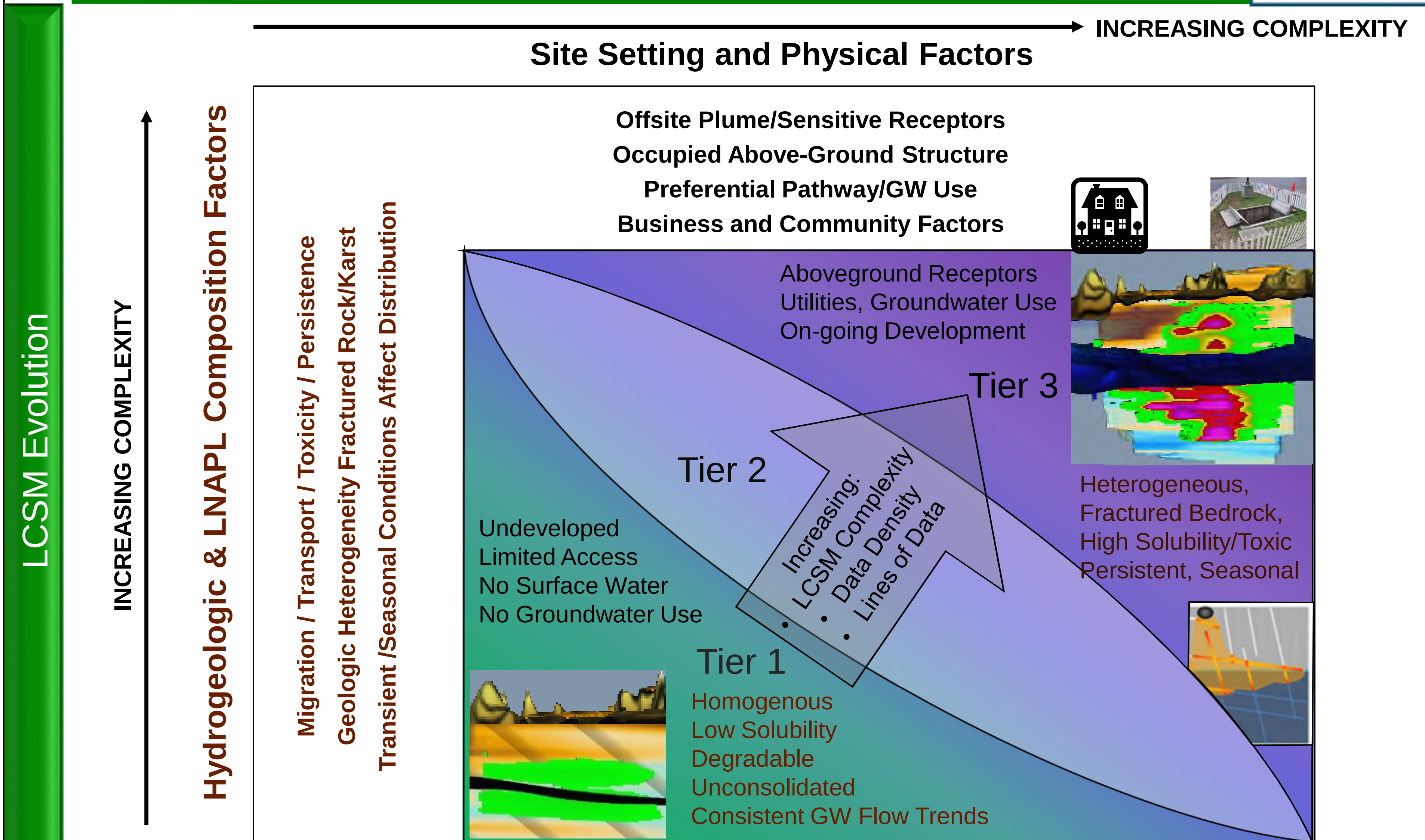


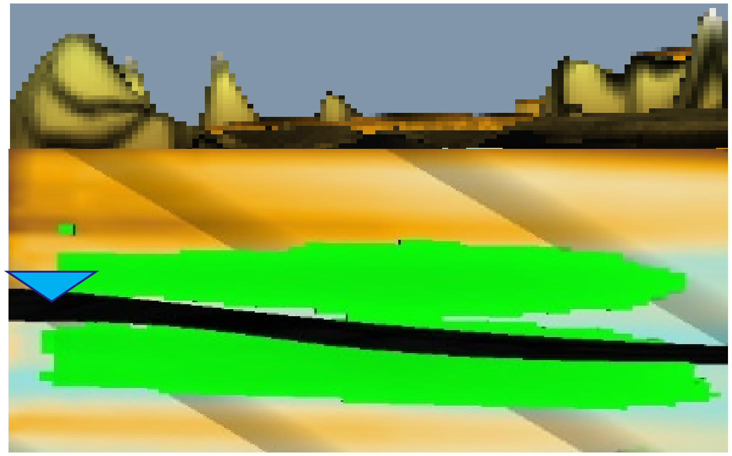
Figure 4-2, LNAPL-3 (adapted from ASTM 2014)

Tier 1 vs. Tier 3

Tier 1 Retail – Diesel in Sand

- 10 – 15 feet to Water-table
- Dissolved plume contained onsite (MNA)
- Mobile LNAPL in wells – T_n 1.0 ft^2/day
- LNAPL is not under any buildings
- Release occurred 10+ years ago

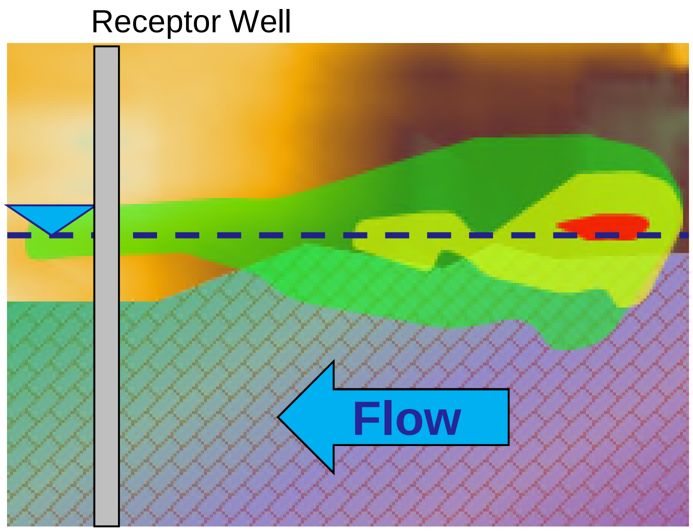
- Well Defined Remedial Concerns
- No risk, Tn above but close to 0.8 ft^2/day



Tier 3 Retail – Gasoline Interbedded Soil Over Bedrock

- Water- Table 15-20 ft. depth
- Fractured bedrock at ~25 ft depth,
- Down gradient receptors - 30 year old bedrock screened wells exhibit impacts
- LNAPL is off-site in unconsolidated soil

- What are remaining questions for the LCSM?
    - Likely requires nest well pairs (unconsolidated bedrock) for dissolved delineation



Summary
Initial LCSM and The Decision

- Is there sufficient information for a given question to support identification of Concerns?
- Is additional site characterization required for evaluating the Concerns LCSM?
  - Initial characterization activities may go beyond collecting data for concerns
  - Combining mobilizations for concerns and remedial selection characterization may improve efficiency at sites where remediation is already known to be needed
  - Collecting remedial-technology-focused characterization data at more complex sites may result in incomplete data collection, or less efficient data collection

Learning Objectives

1. Become familiar with LNAPL decision process and key terms:
    - LNAPL Concerns
    - Remedial Goals
    - Remediation Objectives

More Learning Objectives

2. Understand three classes of LNAPL remediation objectives:
   - Mass Recovery
   - Phase Change
   - Mass Control

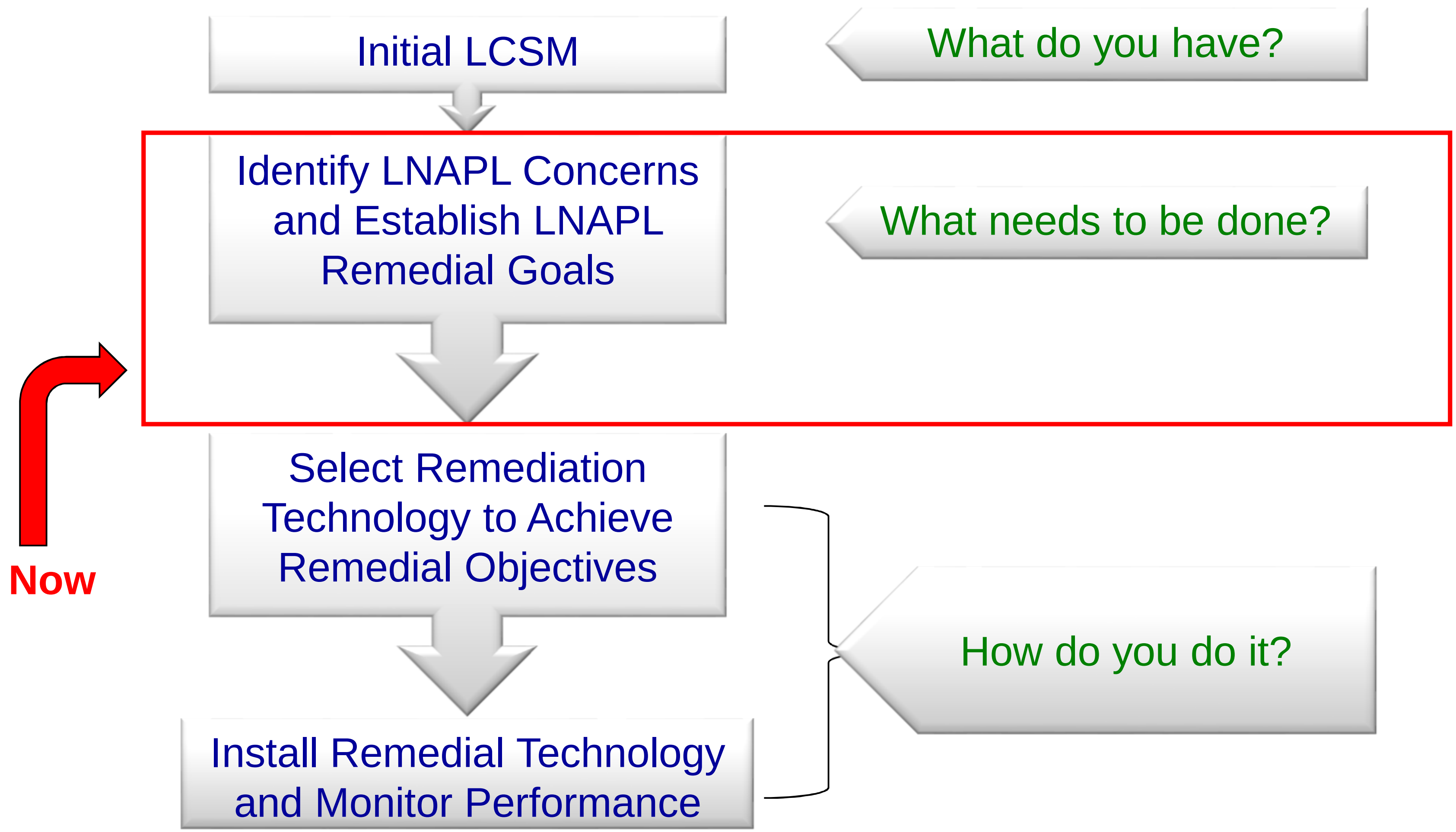
   To apply ITRC framework for LNAPL remedial technology selection

And More Learning Objectives

3. Understand how metrics are applied:
   - Threshold Metrics for verifying or eliminating LNAPL concerns
   - Performance Metrics for assessing remedy effectiveness, and determining when remediation endpoints have been met

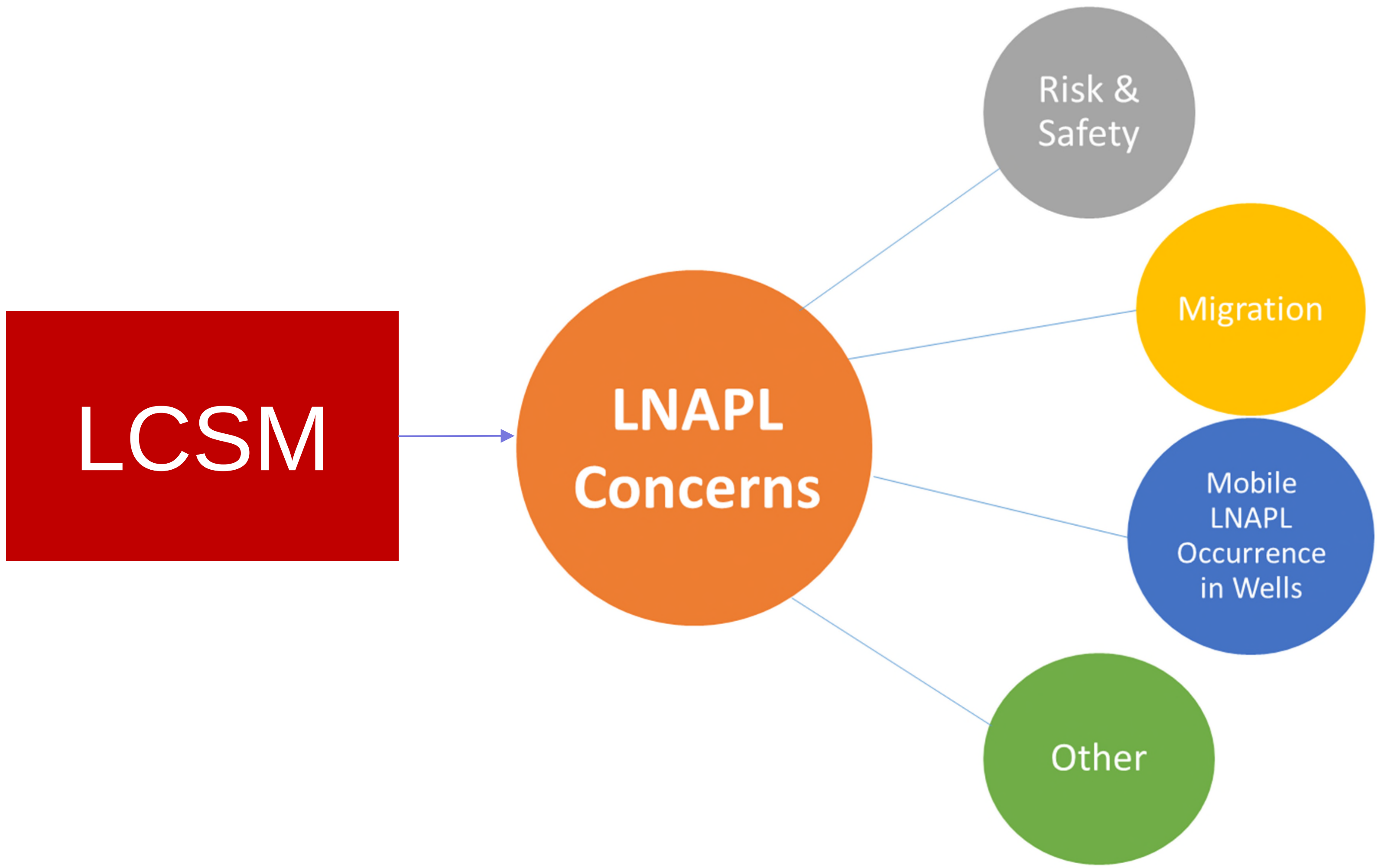
ITRC LNAPL Management

LNAPL Decision Process

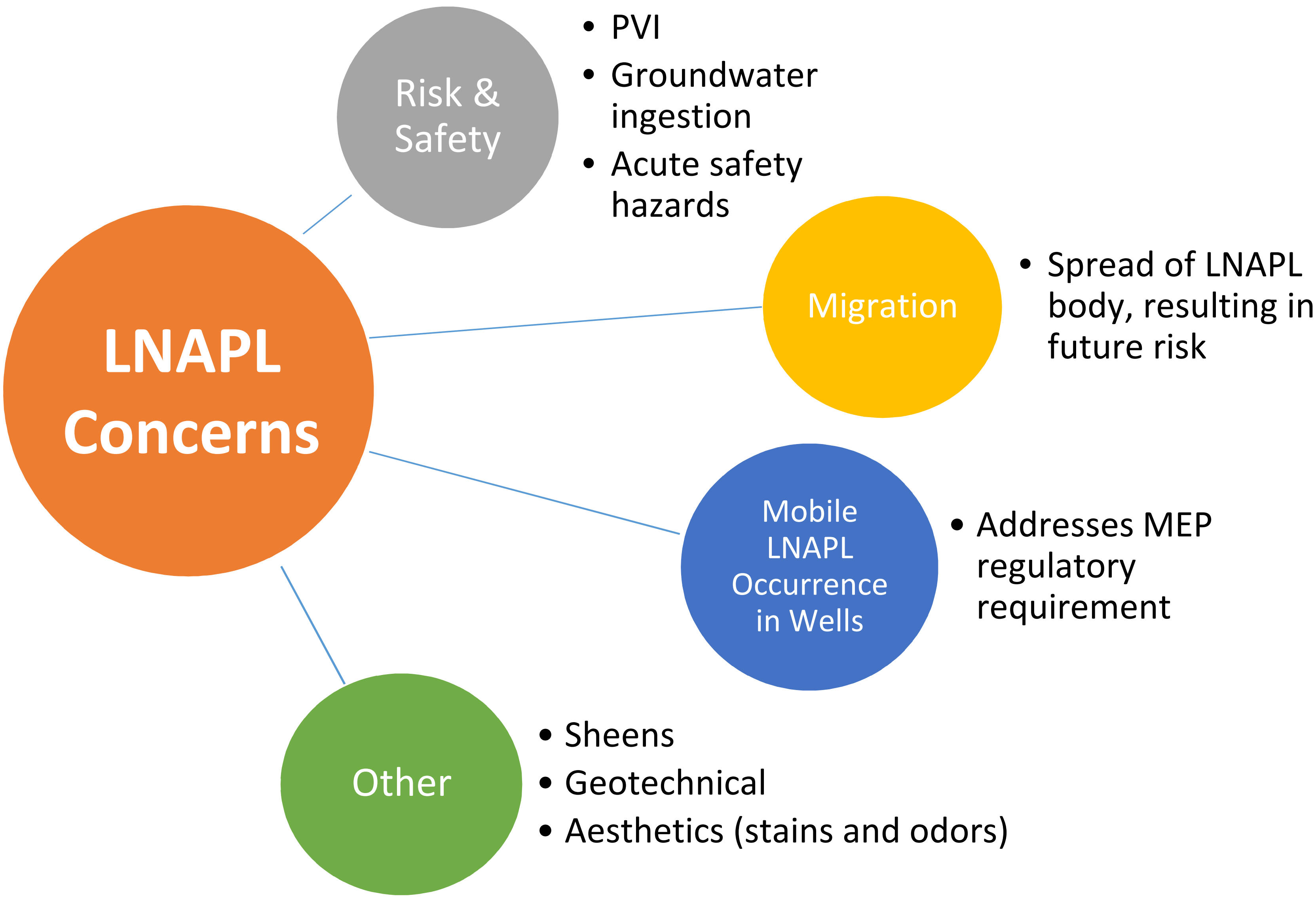


LNAPL Concerns

The LCSM identifies specific LNAPL concerns



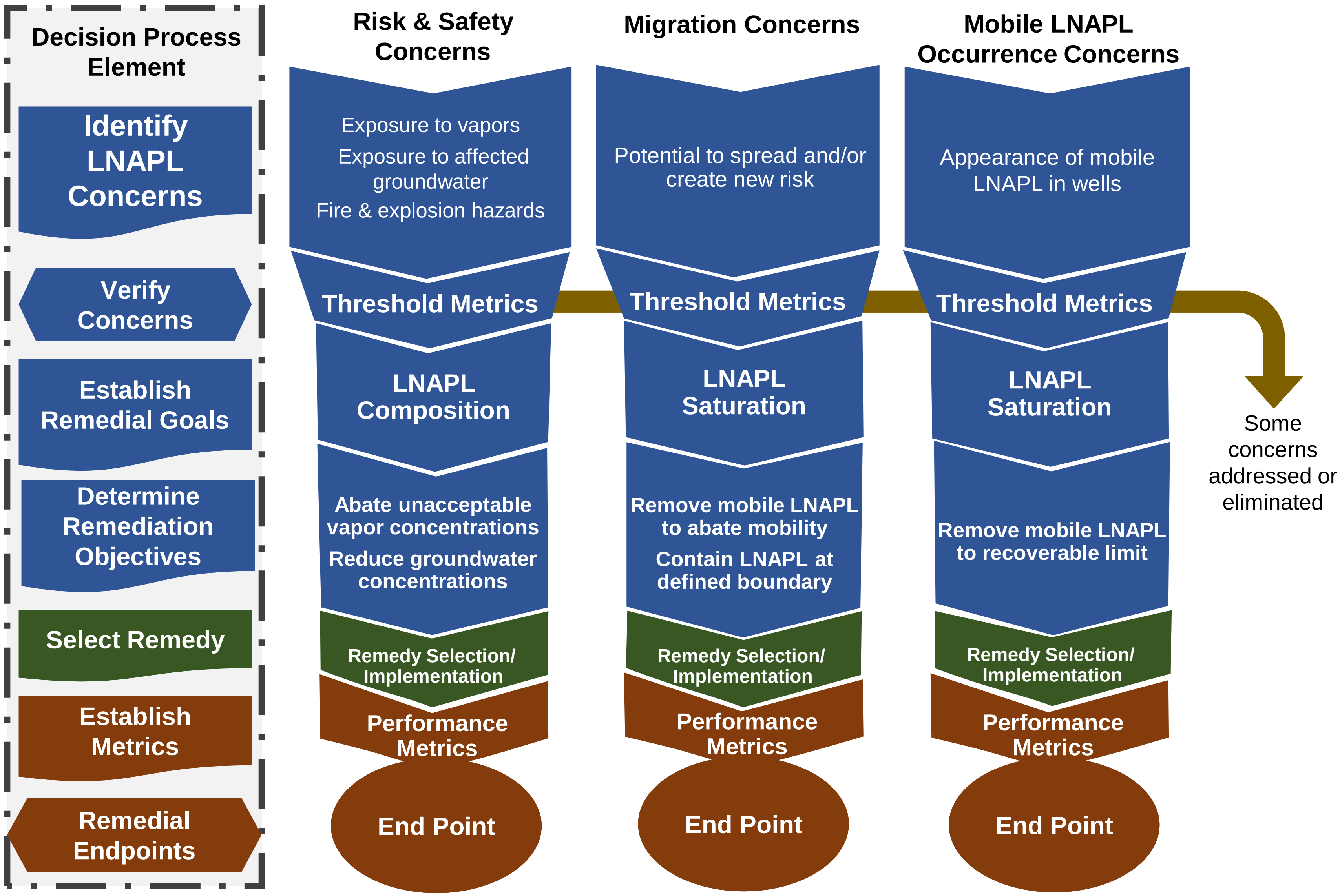
Example LNAPL Concerns



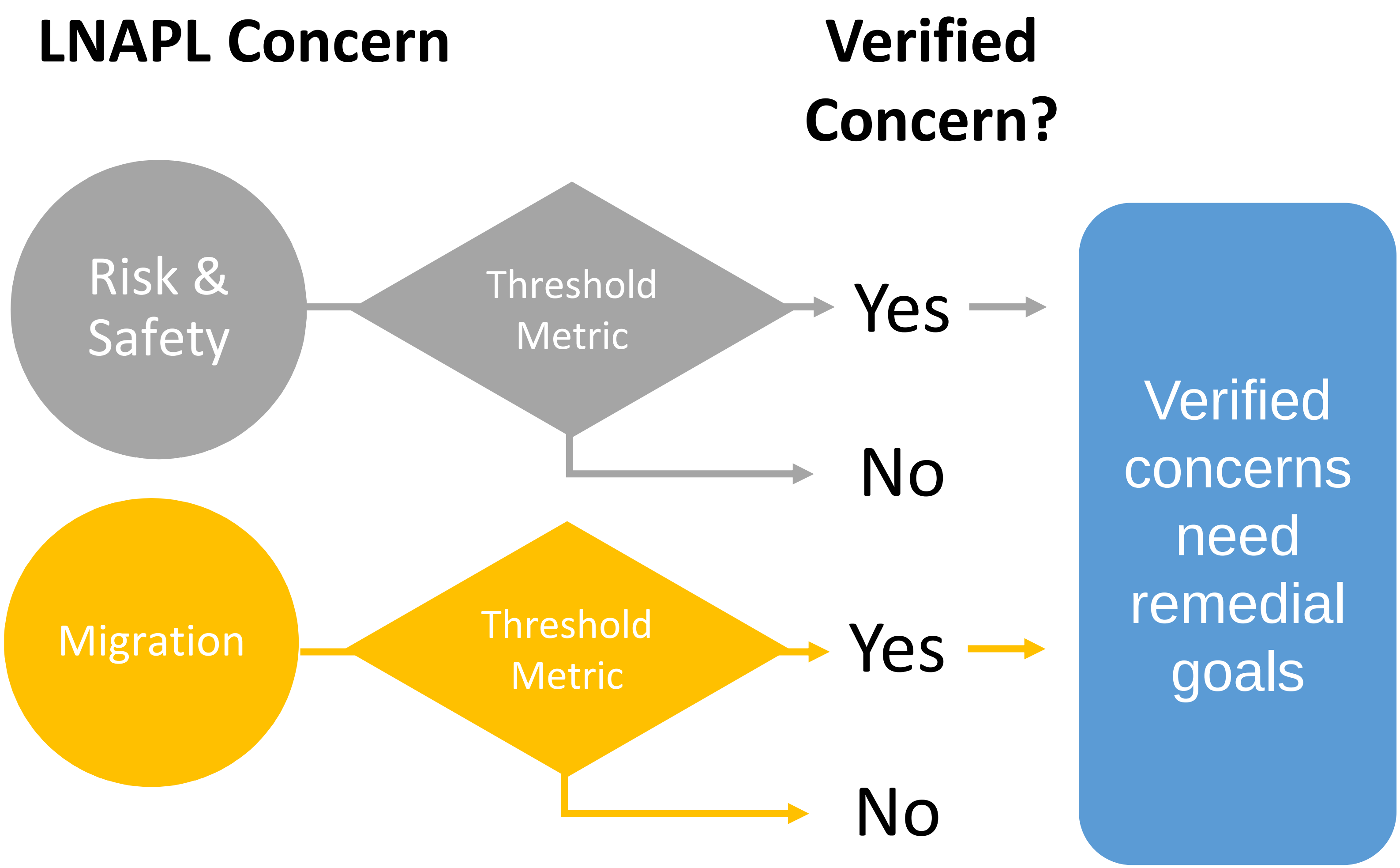
LNAPL Decision Process

Figure 5-1, LNAPL-3

LNAPL Decision Process

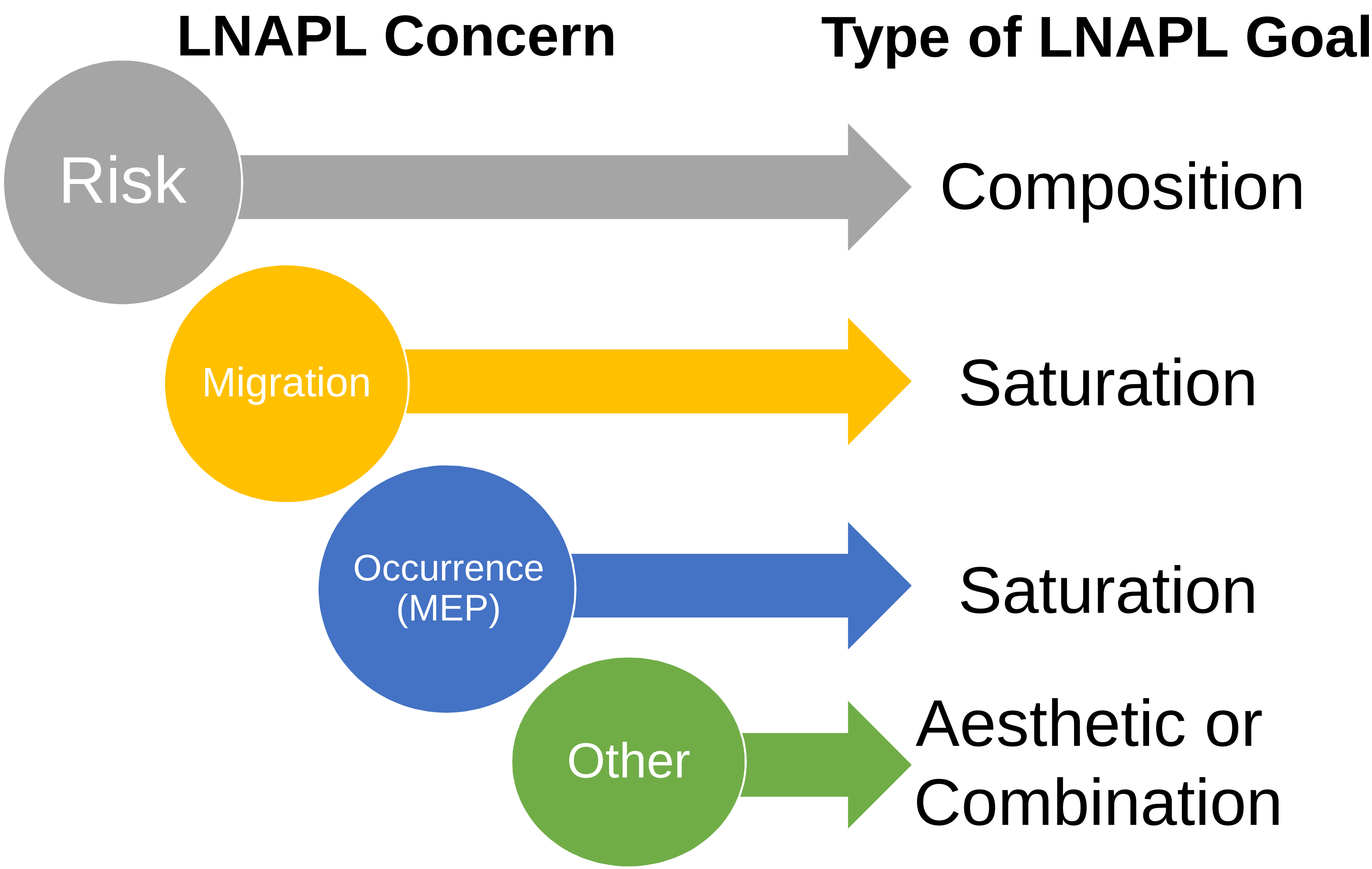


Verifying Concerns with Threshold Metrics



LNAPL Remedial Goals

LNAPL Decision Process



Remedial Goal vs. Remediation Objectives

LNAPL Remedial Goal:

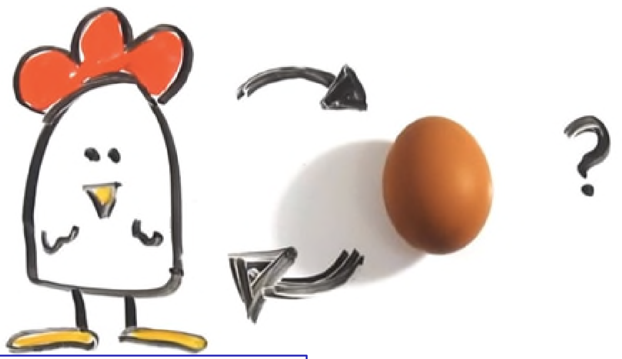
the desired change in LNAPL conditions

- Aspirational… envisioning a future state
- Established before choosing remedy

LNAPL Remediation Objectives:

the actions and desired outcomes that need to occur using the chosen technology

- Tactical… how to get to the goal
- Determined in parallel with remedy selection



These definitions are the *opposite* of what they were in the previous ITRC LNAPL Guide

LNAPL Remedial Goals

Each LNAPL Remedial Goal expresses a desired change in LNAPL conditions

Composition-Based Goals

- Reduce vapor concentrations
- Reduce groundwater concentrations
- Etc.

Saturation-Based Goals

- Reduce LNAPL saturation
- Contain migrating LNAPL
- Etc.

Remedial Goals must be identified before choosing remedial technology(ies)

LNAPL Remediation Objectives

- LNAPL remediation objectives describe how the goal will be accomplished by the selected technology(ies)
- Remediation objectives state the actions and desired outcomes that need to occur using the chosen technology
- Combined with the agreed-upon endpoint and performance metrics, the remediation objectives becomes SMART

LNAPL Remediation Objectives

LNAPL Decision Process

Mass Recovery

- **Abate** LNAPL body migration **by** removal of LNAPL Mass
- **Remove** mobile LNAPL **to** the MEP
- Etc.

Phase Change

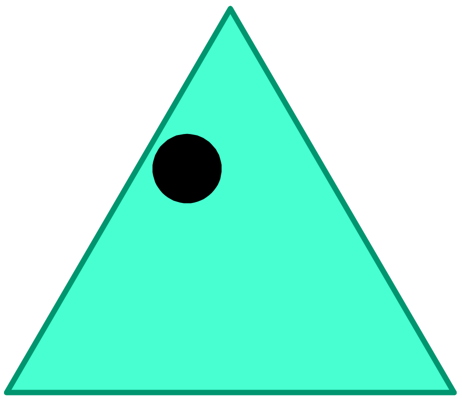
- **Abate** unacceptable vapor accumulations **by** sufficient depletion of volatile constituents from LNAPL
- **Reduce** dissolved concentrations at point of compliance **by** sufficient depletion of soluble constituents from LNAPL
- Etc.

Mass Control

- **Contain** LNAPL **at** a defined boundary
- **Prevent** migration **beyond** a point of compliance
- Etc.

Technology Groups and Objectives

- Mass Control
- Phase Change
- Mass Recovery



Key Point: Some technologies have more than one effect and may serve more than one objective

Choose Remedial Technology(ies), then Identify Performance Metrics & Endpoints

Remedy

- Performance Metrics — These assure effective implementation
- Endpoint — This defines remedial action completion

- Performance Metrics and Endpoints are SMART and technology-specific

Why Are We Focused on the Remedy LCSM

- Development of CSMs for identifying risks, concerns, etc. is fairly mature
- CSMs are also sufficient to identify completion of remediation (i.e., there are no more concerns, risk, etc.)
- Refinement of CSMs for technology Selection, Optimization & Confirmation represent the highest potential for improvement
  - Historically, remedies have been selected based on an incomplete understanding of LNAPL occurrence, nature and remedy performance
  - Remediation has often been driven by LNAPL thickness in wells without considering the relationship between LNAPL thickness and recoverability or the effects of LNAPL recovery on subsurface conditions
- The Remedy Selection LCSM aims to inspire continuation of improvements to CSMs for LNAPL remedy selection

Remedy Selection Needs Improvement
This Starts with the LCSM

- Our concerns are known,
- We know the Remedial Technology Types
- Ok, move ahead with remediation?!? Give it a shot?

- LNAPL in Well
- No Migration

- Insufficient data often exists at end of concerns LCSM to choose a remedy that will achieve remedial goals

Transmissivity Has Improved Remedy Selection

Above Ground

Well with LNAPL

Thickness = 2 feet
T_n = 2 ft²/day
Volume in well = 1.4 gal

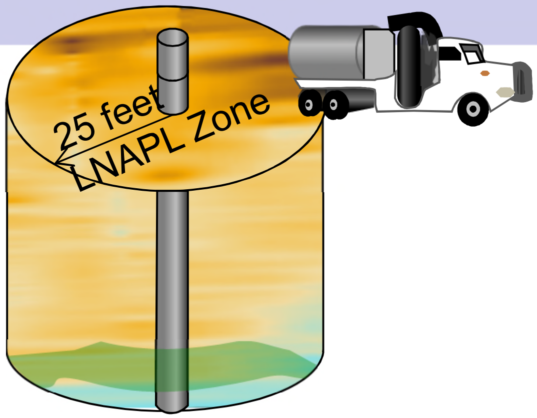
Monthly Vacuum Truck

Drawdown - 2 feet
Time – 1 hour

Monthly Volume Produced
Stored + Induced Flow

1.4 gallons +1.7 =3.1 gal/month
36.2 gal/year

(ASTM E2856-13)



- Vacuum Truck Effort results in 0.4% saturation reduction across 25 foot Radius each year
- 15 years required to reach 0.8 ft²/day
- Active Skimming reaches it in 0.8 years

Below Ground

- 2 feet of Mobile LNAPL interval
- Saturation varies between 8% and 45%
- 8 % Residual Saturation
- 27% Average Mobile Saturation
- 5 feet of Residual Smear Zone

- API LDRM Model with Published Values for soil and LNAPL parameters
- Calibrated to LNAPL Tn field value
- 1 hour of time outside of Field Tn Testing

See Table 4-4 in ITRC LNAPL-3 for Estimation Tools

Remedy Selection Should be Informed by the LCSM not just the Concern

- The concern associated with a gauged LNAPL thickness or a dissolved phase concentration does not indicate how to eliminate it
- This Section will identify approaches to answer
  - Where remediation needs to target
  - Which remedial mechanisms may be effective
  - Improved quantification of these mechanisms prior to implementing a technology

Improved Remedy Selection is Achieved through Understanding

1. Where is the Source Mass?
A. Homogenous Permeable Soil
B. Interbedded within coarser zones that are surrounded by finer grained layers
C. Within low permeability media, secondary porosity, fractures, karst
D. Is the LNAPL source distributed above or below the water-table
2. What Is Nature of the Source?
A. Volatile and/or Soluble
B. Biodegradable
C. Mobile vs Residual Fractions
3. What is Achievable for a Given Technology?
A. Mobility-Based Limit
B. Volatility-Based Limit
C. Solubility-Based Limit
D. Biodegradability-Based Limit
E. Other – Safety, Depth, Sustainability (e.g., community impact, energy/resource use).
E. Design Data – Radius of Treatment, Waste Production/Treatment

Remedy Selection LCSM Questions

1. Where is the Source Mass?

- Identifies where to target remediation
- Identifies Physical factors/limitations to consider for impacted soil
  - Soil Permeability
  - Depth - absolute and relative to water table
- References (See Tables 4.2 in the ITRC LNAPL-3 Document for additional Tools)

Brief Discussion of Tools is Next