LNAPL Volume and Mobility Estimation to Assess When to Stop Active Recovery

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Presentation Outline

- Introduction , Issue and Importance
- LNAPL Migration & Concept in Subsurface
- Properties that affect LNAPL Volume and Mobility
- Study Methodology
- Case Studies (Site A Louis & Site B David)
  - Background: History and Remedial System
  - LNAPL and Soil Properties
  - Volume and Mobility Estimates
  - Remedial System Performance/ Final LNAPL
- Sensitivity Analysis
- Conclusions

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Introduction

- **Application of the API Interactive LNAPL Guide to estimate the volume and mobility of LNAPL at two former petroleum fuel storage facilities:**
  - **Site A impacted by Gasoline/Diesel**
  - **Site B impacted by Jet Fuel**

- **The Interactive LNAPL Guide is a web available system that includes:**
  - **educational information**
  - **assessment tools**
  - **other useful info on LNAPL**

Issue and Importance

- In the past decade, complete LNAPL removal was considered fundamental to site closure
- This was before understanding:
  - LNAPL movement and removal limitations
  - LNAPL plume stability/Natural attenuation
- More recently, industry/consultants started to ask:
  - What is the practical extent of LNAPL removal?
  - When can LNAPL be declared immobile and not likely to impact surrounding areas?
- This study aimed at finding answers to these questions for two sites

LNAPL Migration in Subsurface

Major Factors of influence:

- **LNAPL properties**
  - **Density**
  - **Viscosity**
  - **Interfacial and surface tension**
- **Soil Properties**
  - **Soil texture/porosity**
  - **Permeability**
  - **Capillary pressure vs saturation**

After API, 2003

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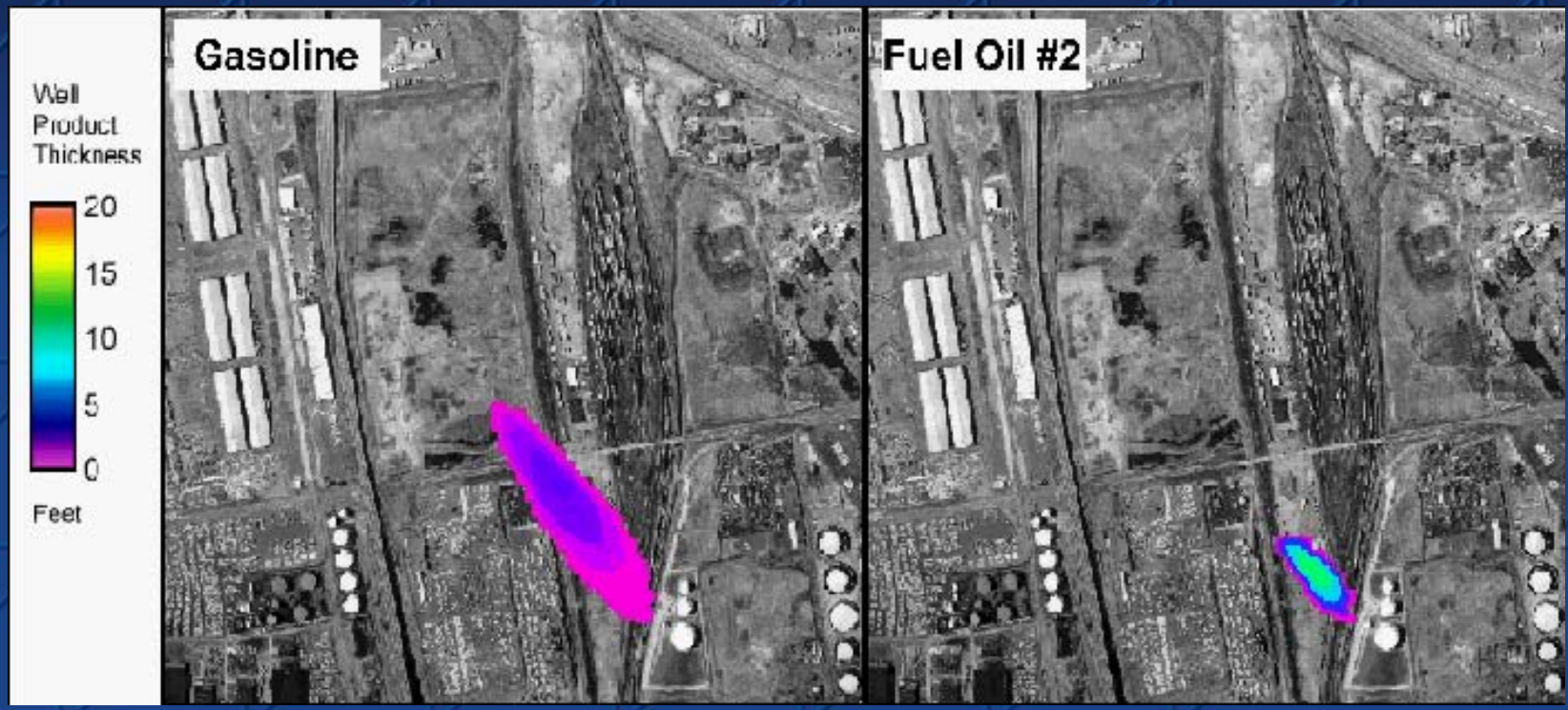
Effect of LNAPL Properties

Release of 1 M US Gal (4 ML) in sand for 5 years



After API, 2003

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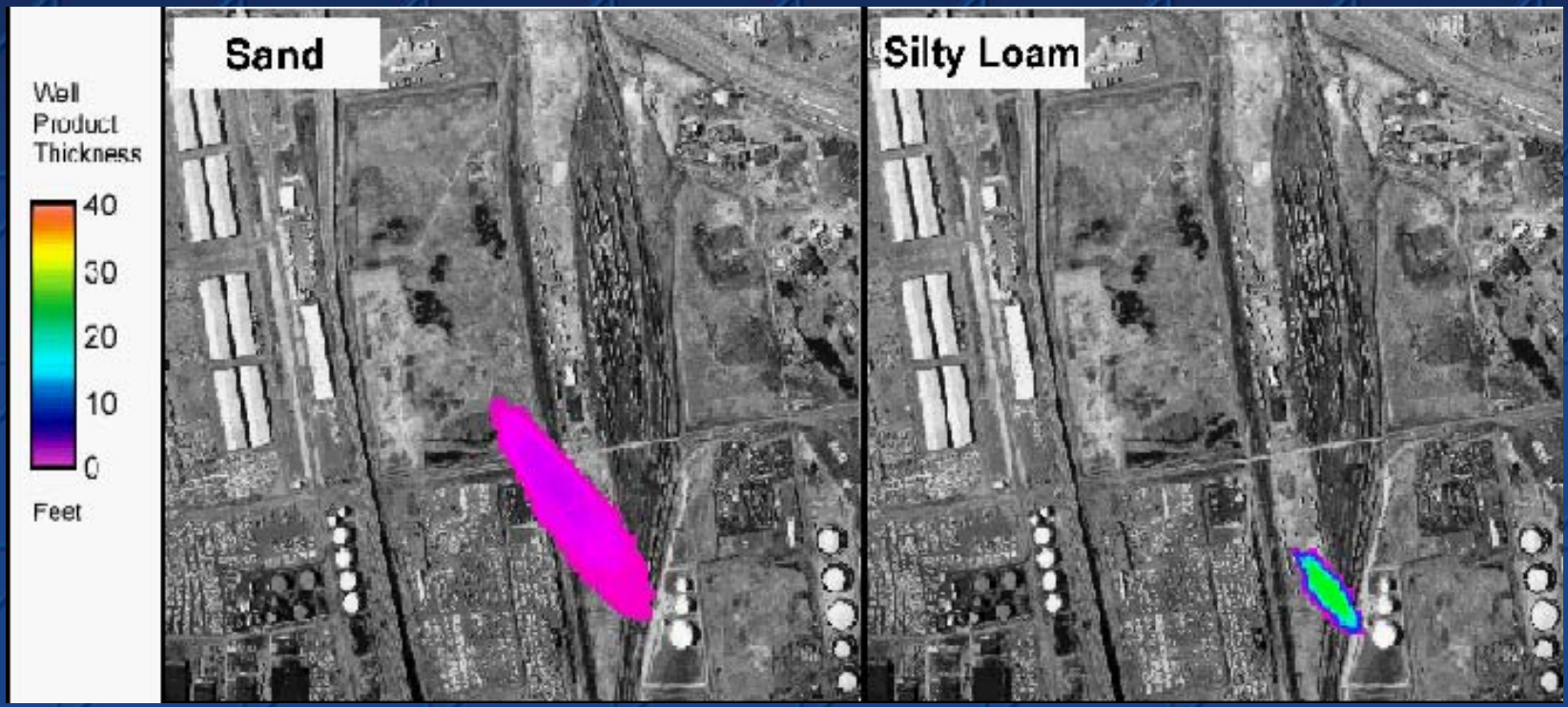
Effect of Soil Properties

Release of 1 M US Gal (4 ML) of gasoline for 5 years



After API, 2003

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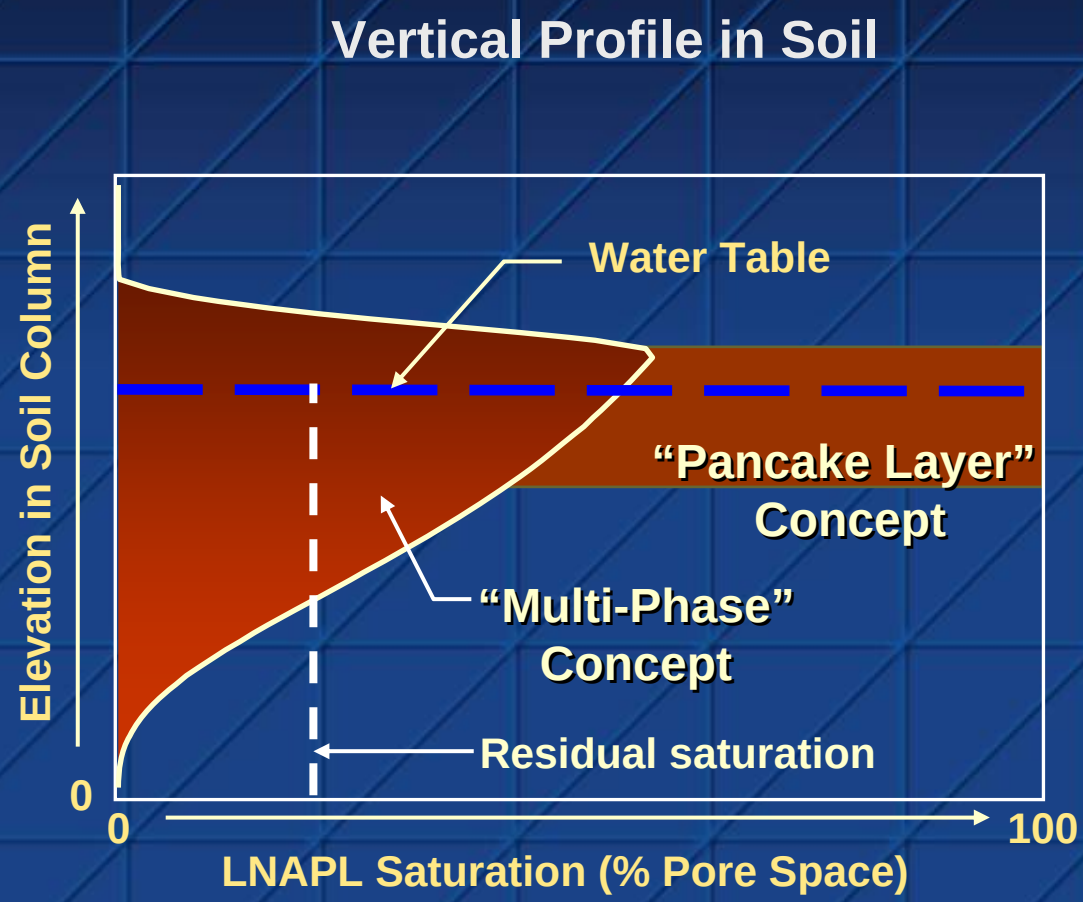
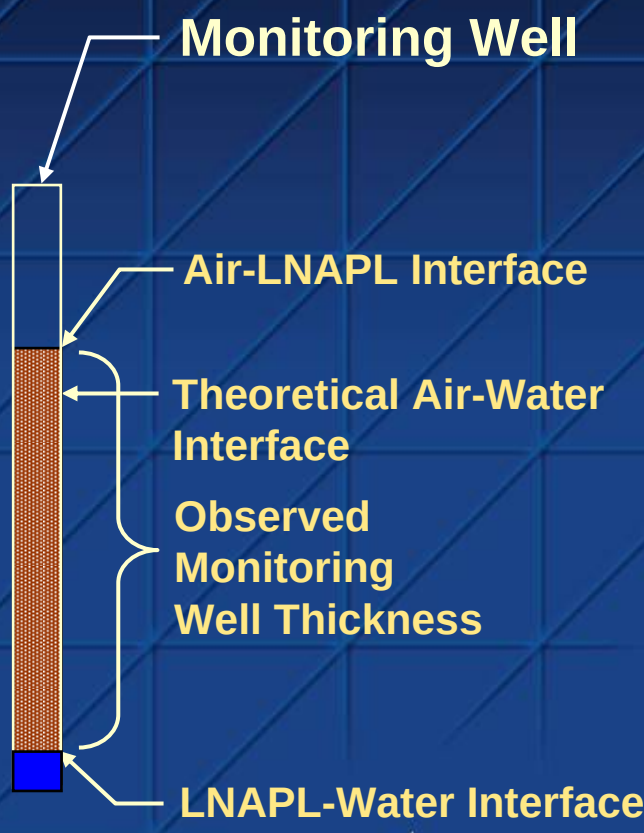
Concept of LNAPL in Subsurface





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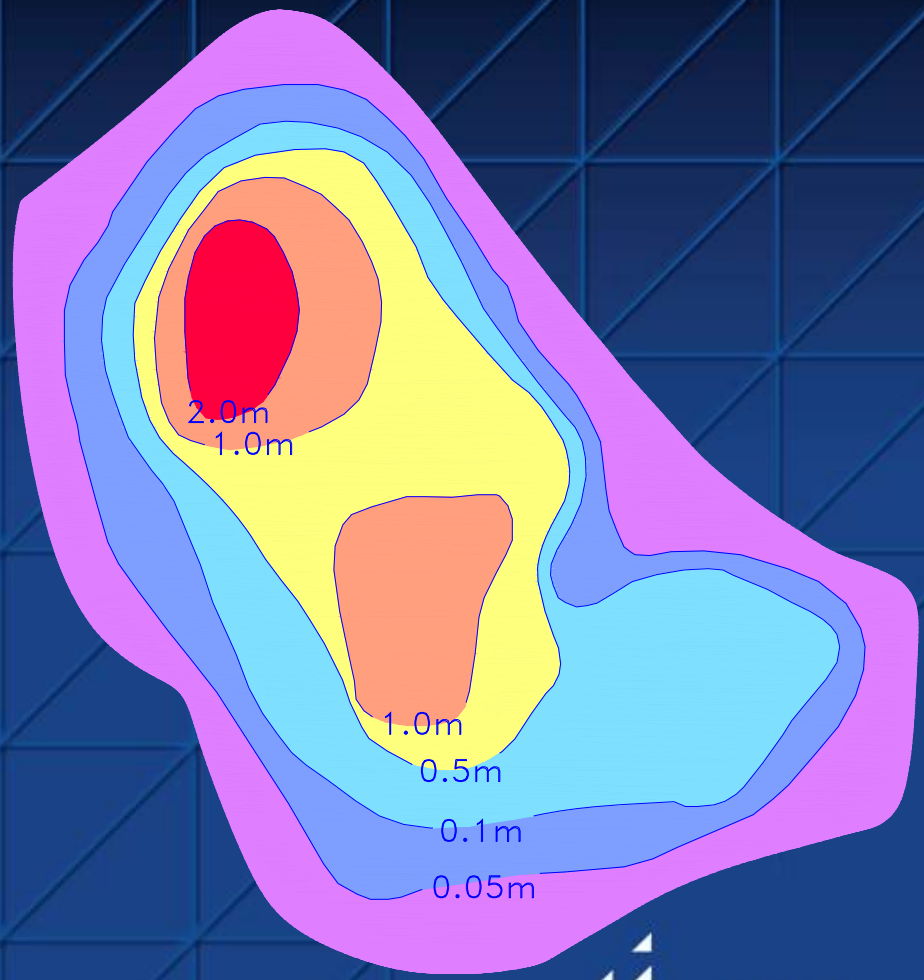
Methodology - LNAPL Volume

- **Well product thicknesses contoured and areas calculated**
- **An LNAPL saturation profile for each contour interval (average product) is defined using soil and LNAPL properties based on LNAST from API**
- **By integration of the saturation profile over the contour area, the volume of LNAPL is calculated**



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Methodology - LNAPL Mobility

- **The inherent mobility of an LNAPL in a porous medium is calculated using (API, 2003):**

$$M = \frac{k\, kr_{LNAPL}\, \rho_{LNAPL}\, g}{\mu_{LNAPL}\, n\, S_{LNAPL}} = \frac{K_{LNAPL}}{n\, S_{LNAPL}}$$

where:

k	: permeability of the porous media (L^2)
kr_{LNAPL}	: relative permeability of the porous media to LNAPL (varies with S_{LNAPL}) (dimensionless)
ρ_{LNAPL}	: density of LNAPL (M/L^3)
g	: gravitational constant (L/T^2)
μ_{LNAPL}	: dynamic viscosity of LNAPL (M/LT)
n	: porosity of the porous media (dimensionless)
S_{LNAPL}	: fraction of pore space saturated with LNAPL (dimensionless)
K_{LNAPL}	: LNAPL conductivity (L/T)

Case Study – Site A Background

- **Former Bulk Fuel Plant**
- **LNAPL discovered on-site in 1998 (Gasoline/Diesel)**
- **Geology: Fine sand**
- **Hydrogeology:**
  $K = 10^{-5} – 10^{-6}$ m/s
  Groundwater flow to southwest (5-25 m/y)
- **Remedial Technologies**
  1999-2001: Manual Product Bailing
  2001-2005: Dual-Phase High Vacuum Extraction (DPVE)

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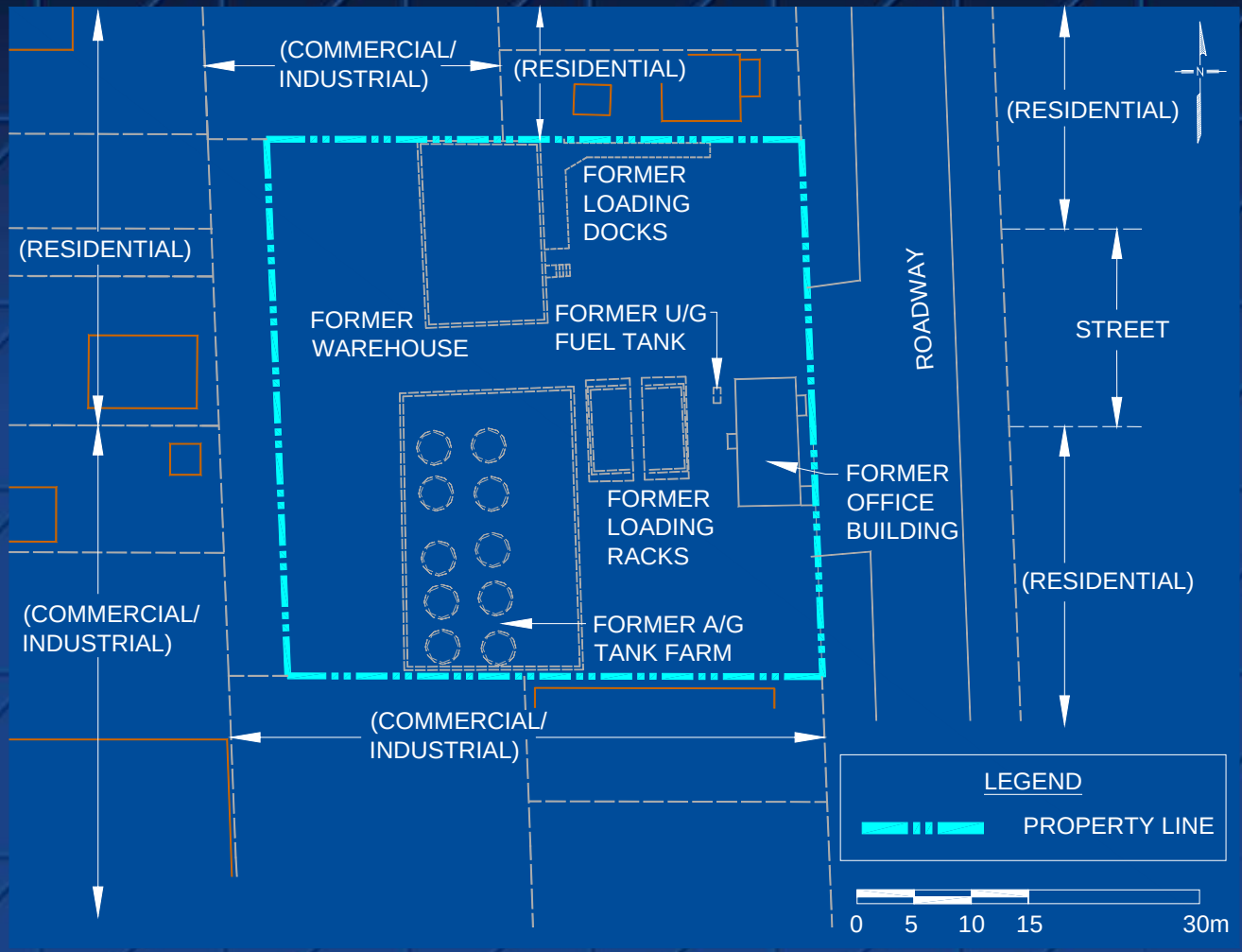
Site A - Layout and Surrounding Use



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Site A - LNAPL and Soil Properties

- **LNAPL Properties based on Analytical Results**

  LNAPL = Diesel Fuel (~80%) and Gasoline (~20%) Mixture

  ρ = 0.81 g/ml, μ = 1.7 cP, σ_{ow}= 27.9 mN/m, σ_{ao}= 25.6 mN/m,

- **Soil Properties based on Huntley & Beckett (2002) and LNAPL Guide Default Program Parameters**

  Fine Sand

  Van Genuchten α = 7.5 m^{-1}, n = 1.9

  Residual Water Saturation = 0.32

  LNAPL Residual Saturation = 0.20

  Total Porosity = 0.43

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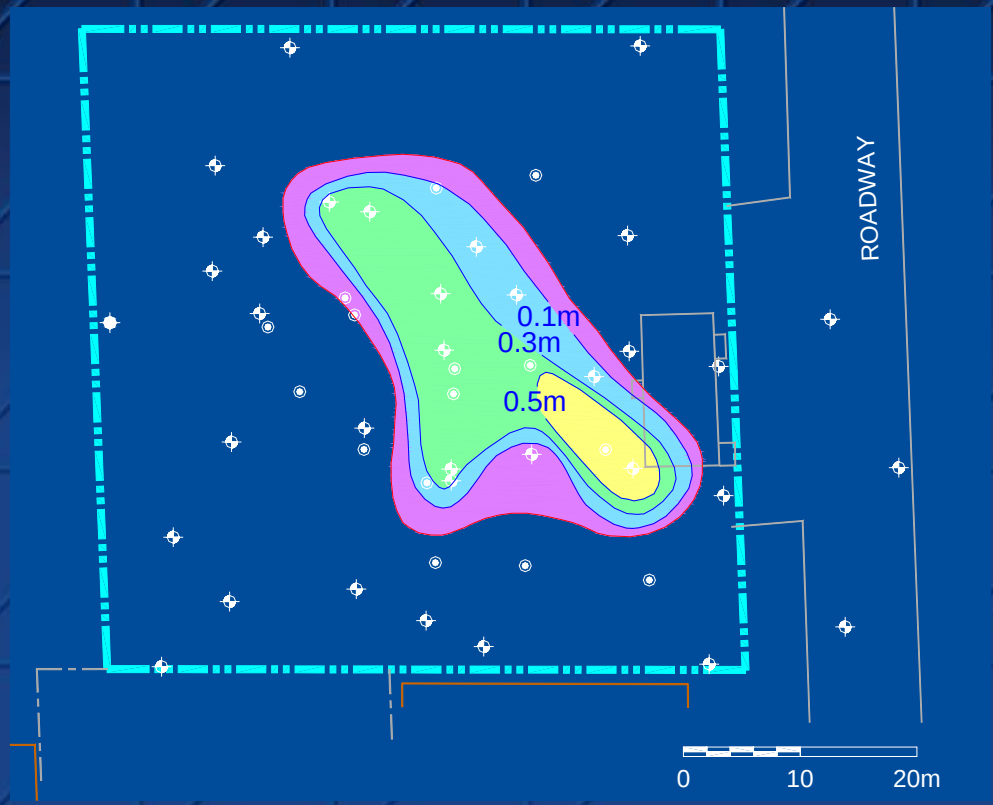
Site A - Initial LNAPL Volume/Mobility

- Volume/Mobility estimated using site monitoring data collected prior to DPVE
- Spring 1999 LNAPL thickness and area:
  Up to ~0.9 m (680 m²)
- Total estimated volume of LNAPL initially present in the plume:
  Approx. 13,000 L
- Highest LNAPL mobility:
  0.8 m/day at S_{LNAPL} = 0.4



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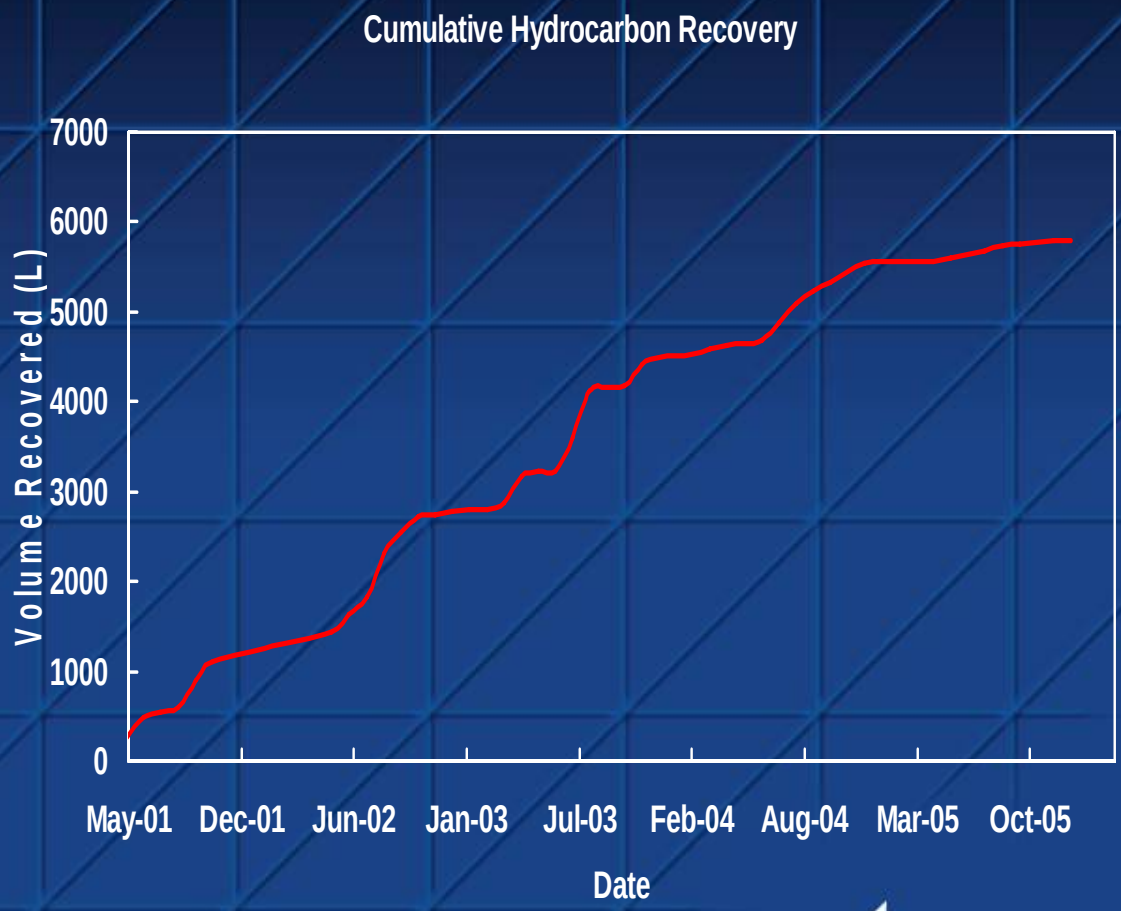
Site A - Remedial System Performance

DPVE started 2001

Initial DPVE hydrocarbon recovery rate **~20 L/day**

Total volume recovered **~5,800 L (45%)**

Final DPVE hydrocarbon recovery rate **<2 L/day**



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Site A – Final LNAPL Distribution

LNAPL areal extent reduced considerably to

~100 m² (680 m²)

By 2005, LNAPL thickness in wells reduced to:

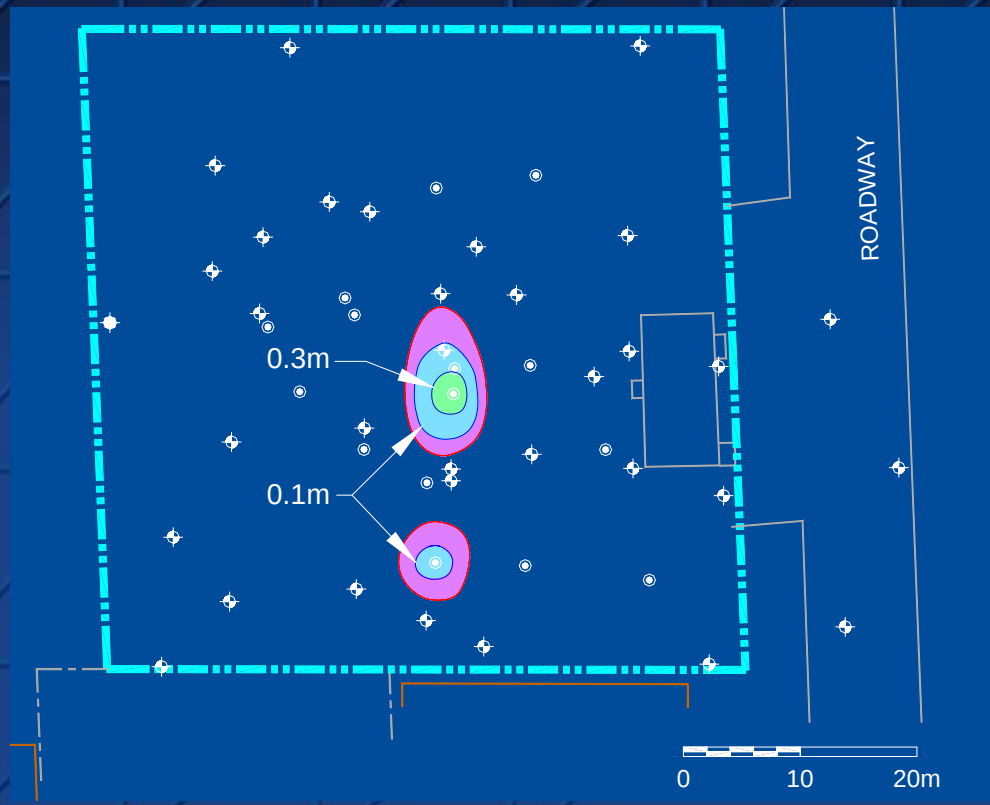
~0.45 m or less (~0.9 m)

Highest LNAPL mobility:

0.2-0.4 m/day at S_{LNAPL}= 0.1-0.2

(0..8 m/day at S_{LNAPL}= 0.4)

Majority of LNAPL below residual and essentially immobile



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Case Study – Site B Background

- **Former Airport Fuel Storage Facility**
- **LNAPL discovered on-site in 1998 (Jet A-1 Fuel)**
- **Geology: Fine sand**
- **Hydrogeology**
  K = 2 x 10^{-6} m/s
  Almost flat gradient (no clear groundwater flow direction – divide)
- **Remedial Technologies**
  - 1998-2002: Manual Product Bailing
  - 2002-2006: Low Vacuum Enhanced Product Skimming

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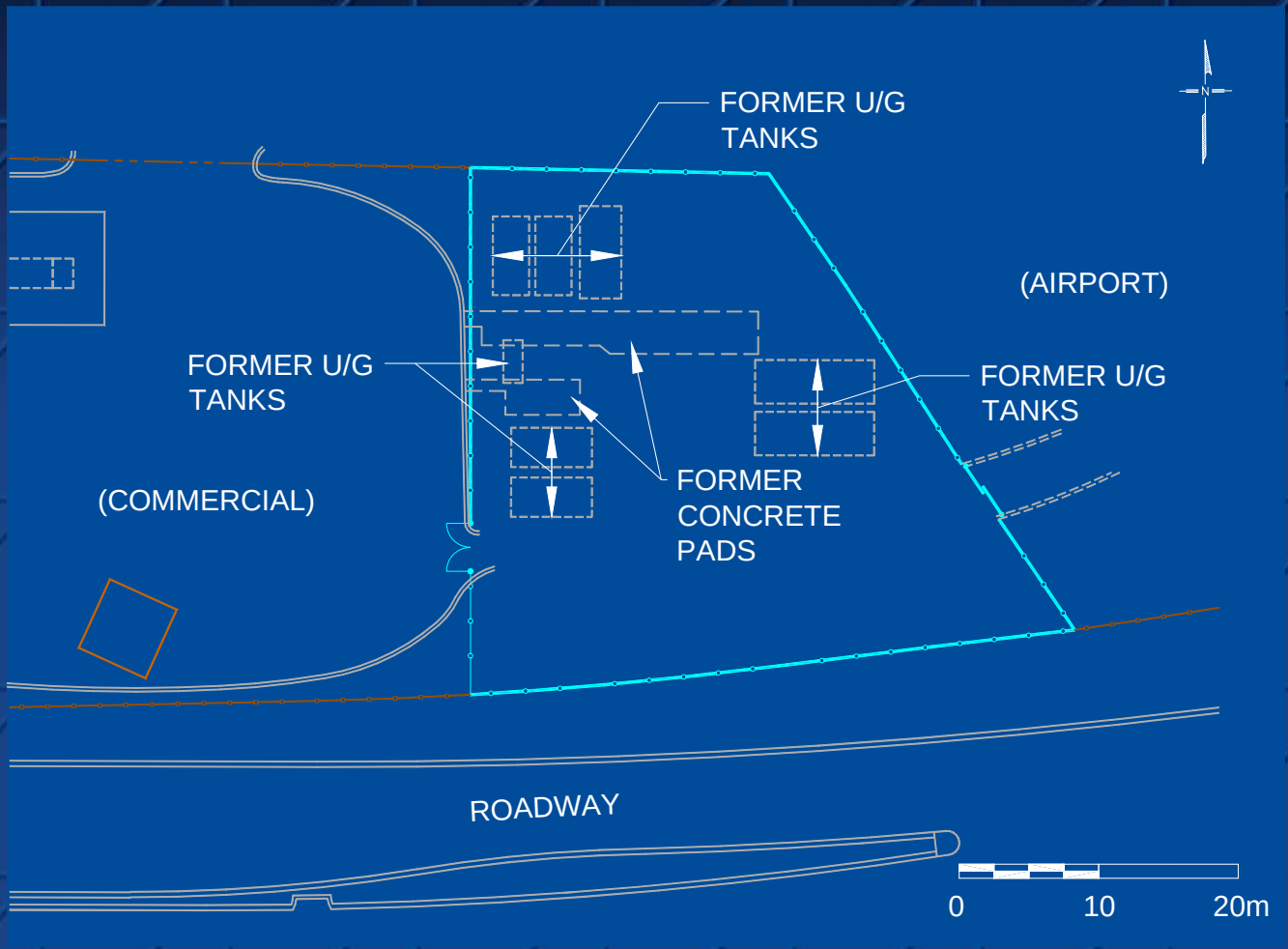
Site B - Layout and Surrounding Use



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Site B - LNAPL and Soil Properties

- **LNAPL Properties based on Analytical Results**

  LNAPL = Jet A-1

  ρ = 0.81g/ml, μ = 1.6 cP, σ_{ow}= 25.2 mN/m, σ_{ao}= 26.6 mN/m,

- **Soil Properties based on Huntley & Beckett (2002) and LNAPL Guide Default Program Parameters**

  Fine Sand

  Van Genuchten α = 7.5 m^{-1}, n = 1.9

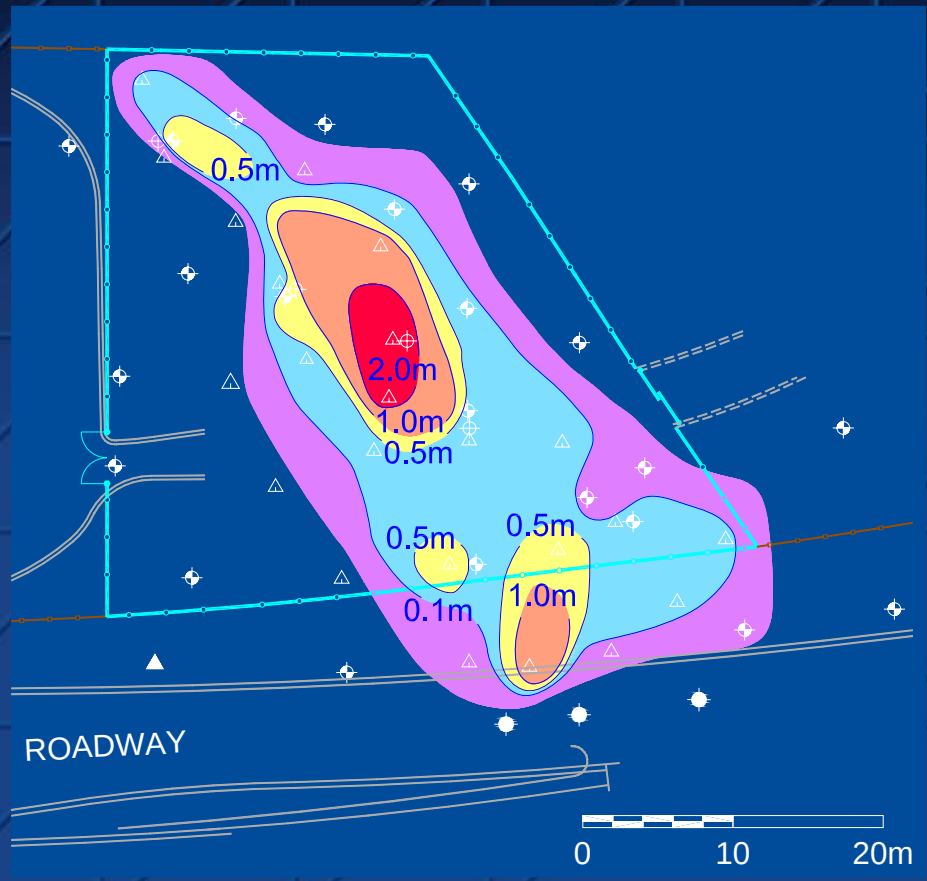
  Field residual water saturation = 0.32

  LNAPL field residual saturation = 0.2

  Total porosity = 0.43

Site B – Initial LNAPL Volume/Mobility

- Volume/Mobility estimated using site monitoring data collected prior to skimming
- Spring 2002 LNAPL thicknesses and area:
  Up to ~ 2.4 m (1150 m²)
- Total estimated volume of LNAPL initially present in the plume:
  Approx. 67,000 L
- Highest LNAPL mobility:
  0.2 m/day at S_{LNAPL} = 0.6



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Site B - Remedial System Performance

Vacuum skimming started in 2002 at low vacuum followed by moderate vacuum in 2003

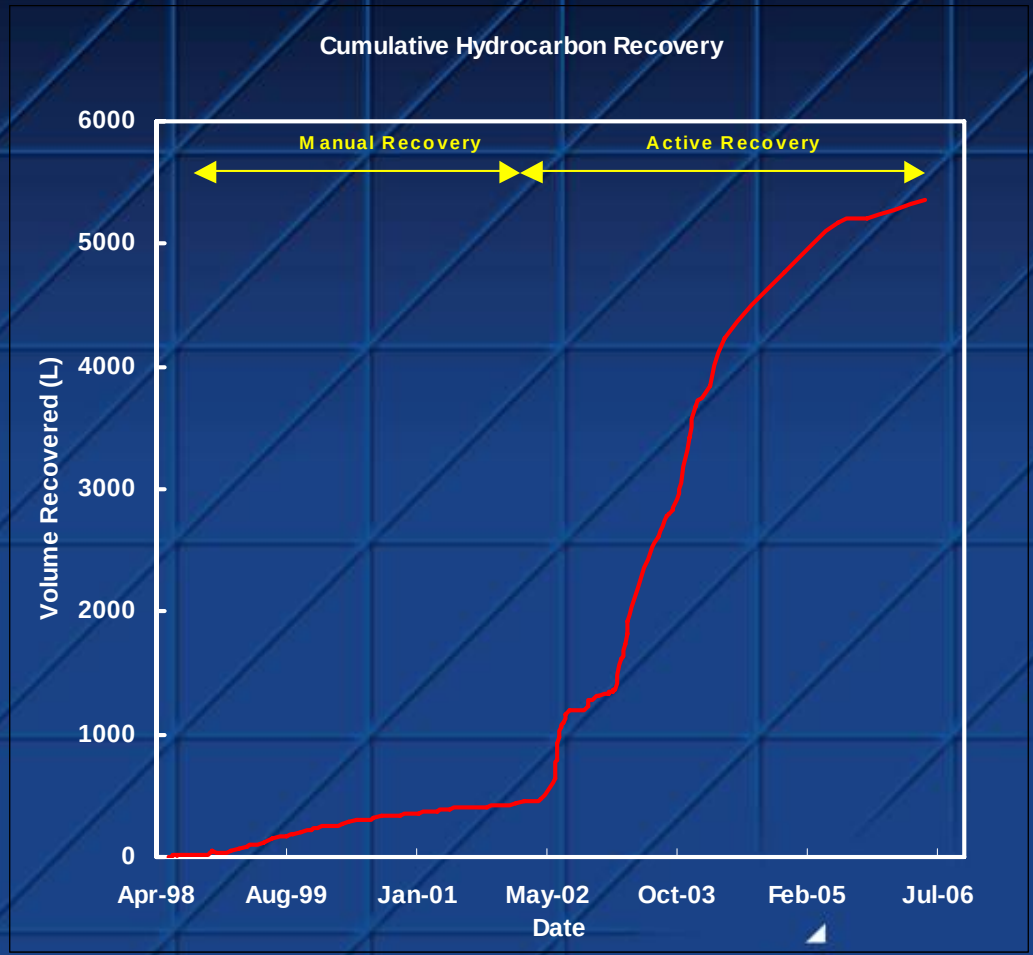
Vacuum skimming recovery rate ~ **7 L/day**

Total volume recovered

~5,500 L (<10%)

Final recovery rate

<0.5 L/day



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Site B – Final LNAPL Distribution

LNAPL areal extent reduced to:

~ **700 m²** (1150 m²)

By 2005, LNAPL thickness in wells reduced to:

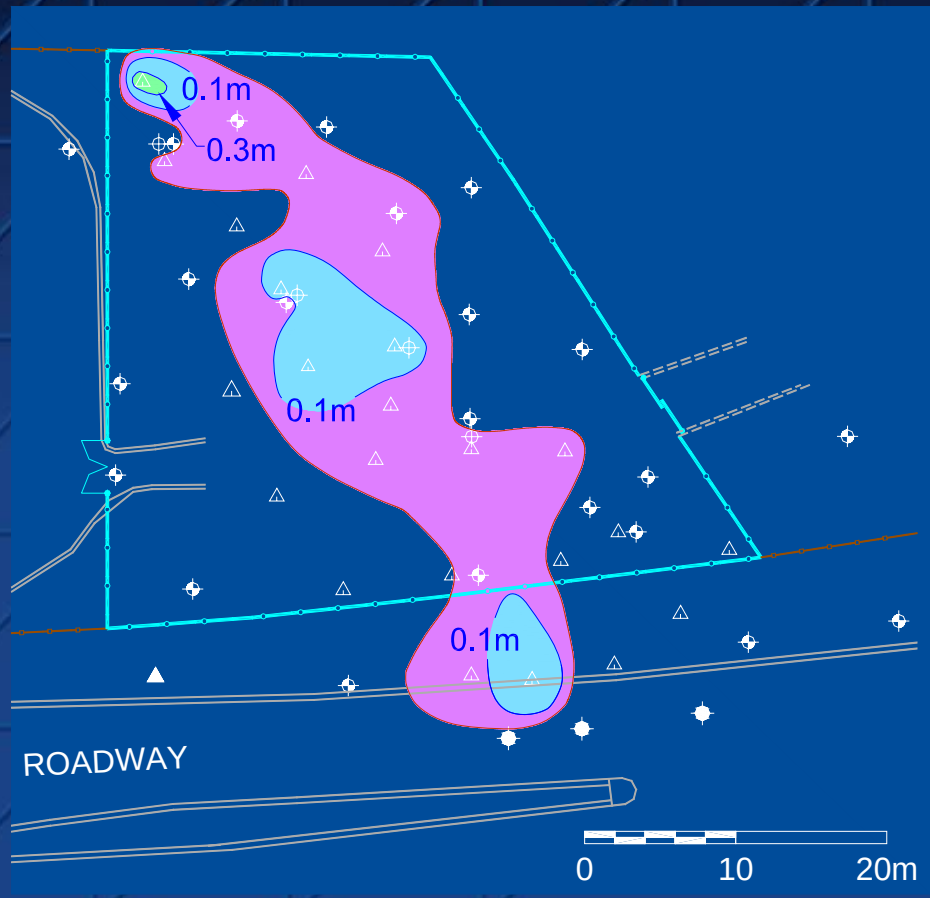
~0.39 m or less (2.4 m)

Highest LNAPL mobility:

0.07 m/day at S_{LNAPL} = 0.24

(0.2 m/day at S_{LNAPL} = 0.6)

Majority of LNAPL essentially immobile in absence of significant thickness and gradient



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Sensitivity Analysis – VG Properties

- LNAPL properties determined by analysis
- Site specific van Genuchten properties not available. Default VG Properties in the LNAPL Guide based on "typical values". Use of "typical" soil capillary properties contributes to variability in volume estimates
- van Genuchten α is inversely related to capillary fringe height with coarse materials displaying relatively high values
- van Genuchten *n* is a function of the pore throat distribution with high values indicating greater pore size uniformity

Sensitivity Analysis – VG Properties

Simulation	VG α m^{-1}	VG n
Base Case – Site A (Huntley & Beckett, 2002)	7.5	1.9
Base Case – Site B (Huntley & Beckett, 2002	7.5	1.9
High (μ+2σ) (coarse materials with uniform sized pore size)	19.8	3.2
Low (μ-3σ) (fine materials with non-uniform pore size)	7.1	1.9

Sensitivity Analysis – Results

	Base Case (L)	High *n* and α (m^{-1}) (L)	Low *n* and α (m^{-1}) (L)
Site A	13,000	27,800	10,000
Site B	67,000	110,000	65,500

LNAPL volume estimate within each contour interval varied by up to a factor greater than 6.
Total volume estimates varied by up to a factor of 3 in the above cases.

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Conclusions

- **Interactive LNAPL Guide an interesting tool to assess LNAPL Volume & Mobility and help substantiate exit criteria for LNAPL recovery**
- **Volume estimates can be sensitive to LNAPL and soil properties and should therefore not be taken as absolute values**
- **In our cases, mobility estimates of 10^{-2}-10^{-1} m/day suggest plume stability under limited gradient**
- **This model provides a secondary line of evidence in addition to field evidence (reduced LNAPL thicknesses, limited recovery rates and plume stability) to support site closure**

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