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Techniques Used to Evaluate Potential LNAPL Mobility

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Overview

- ◆ **Introduction**
- ◆ **Theory**
- ◆ **Assessment Method**
- ◆ **Output**
- ◆ **Results**
- ◆ **Discussion**
- ◆ **Conclusions**



Introduction

Objective:

To apply a risk management approach to LNAPL encountered at a former refinery property

- Presence of LNAPL in monitoring wells not necessarily equal to unacceptable migration risk
- Aim is to quantify relative migration risk
- When is remediation/control necessary?

Monitoring data from two (2) wells used to demonstrate approach.



Introduction

Site Details:

- **Affected area approximately 15 hectares**
- **Several LNAPL types (naphtha to heavy oil)**
- **Glacial till and glaciofluvial/fluvial sands, gravel and cobbles overlying granitic bedrock**
- **Hydraulic and topographical gradient variable (<0.5% to >10%)**
- **Depth to water variable (<2m to >18m below grade)**

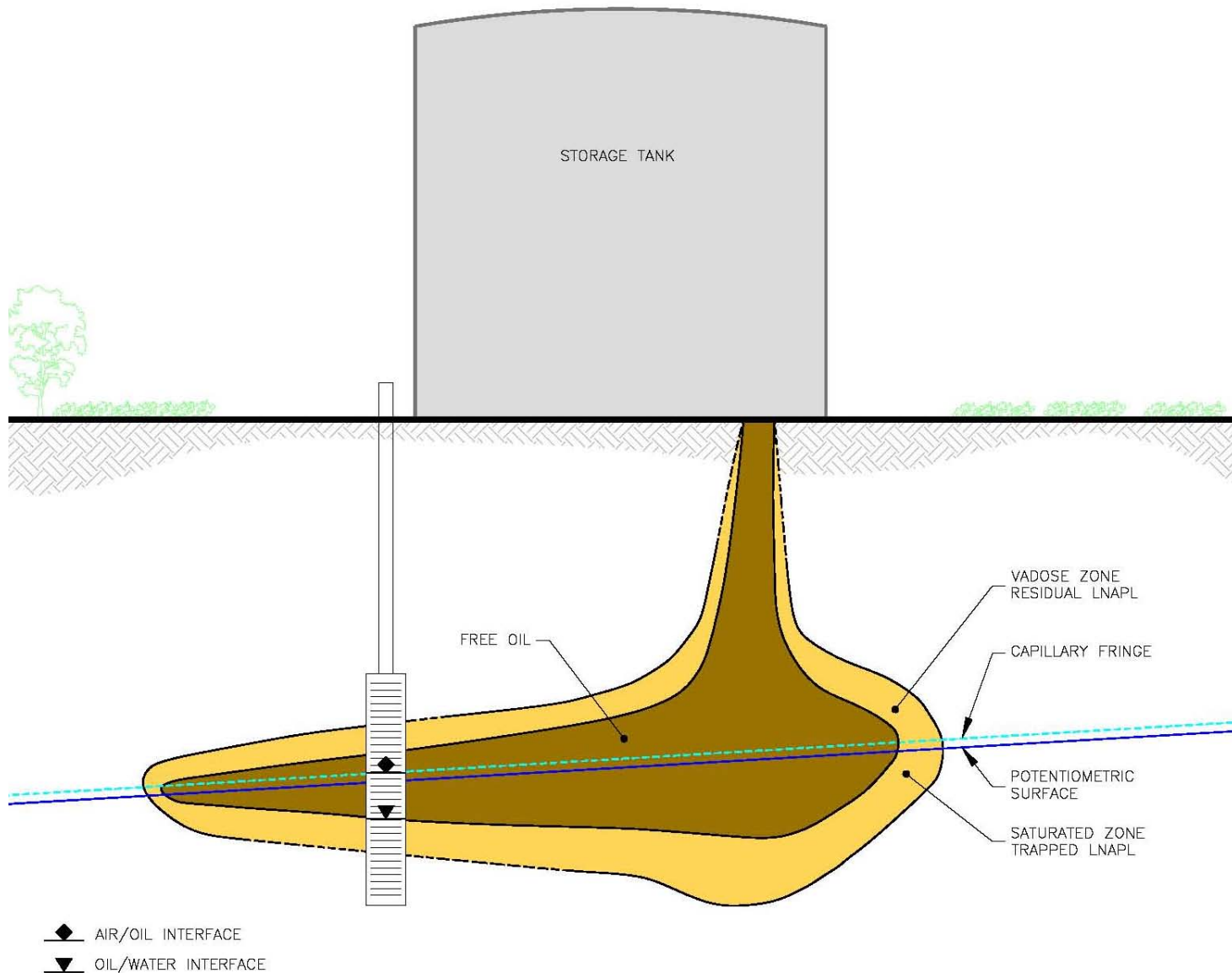


Theory

- ◆ **LNAPL distribution in a unit surface area of soil depends on the following:**
 - **Pore size distribution**
 - **Fluid densities**
 - **Capillary pressures**
 - **Interfacial tensions**



Example LNAPL Release Area



Theory

- ◆ **Multiphase distribution of air/oil/water exists within the soil profile**
- ◆ **Distinct LNAPL layer NOT formed above capillary fringe (i.e. full oil saturation not reached in soil profile)**
- ◆ **A LNAPL affected area consists of partial oil saturations with varying magnitude throughout**



Assessment Method

- ◆ **Spreadsheet analytical model was developed to estimate vertical hydrocarbon distribution and volumes from well fluid levels**
- ◆ **Solves vertically integrated capillary pressure equations presented in Parker et al (1994)**



Input Parameters

- ◆ **Soil properties**
 - Van Genuchten parameters, hydrocarbon retention fractions, hydraulic conductivity
- ◆ **Fluid properties**
 - Density, viscosity, surficial tensions
- ◆ **Well data**
 - Max/min fluid elevations in well, gradient



Example Mobility Spreadsheet

NAPL VOLUME ESTIMATION FROM APPARENT PRODUCT THICKNESS (after Parker et al., 1994)

Author: Don Burnett

Morrow Environmental Consultants Inc.

Note: Data to be input or modified by user is coloured **Magenta**

Revision Date: 2004 06 29

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Project Number: V2-226

Well Number: A

NAPL Type/Sample: LNN

Assessed By: DAF

Location: Former Refinery Property

Monitoring Date: Maximum APT

Soil Type/Sample: Coarse Sand

Date: 2005 09 30

<u>Soil Properties</u>	<u>Symbol</u>	<u>Value</u>	<u>Units</u>	<u>Equation</u>	<u>Comments</u>
porosity	ϕ	0.33			site-specific or use data on Properties sheet
water saturation at field capacity	S_m	0.27			site-specific or use data on Properties sheet
air saturation at field capacity	$1-S_m$	0.73			
retention factor above water table	f_{og}	0.3		f_{og} varies from 0.2 to 0.5, median 0.3; higher for viscous fluids and	
hydrocarbon retention above water table	S_{og}	0.059		$S_{og}=f_{og}S_m(1-S_m)$	heterogeneous soils
retention factor below water table	f_{or}	0.3		f_{or} varies from 0.2 to 0.5, median 0.3; higher for viscous fluids and	
hydrocarbon retention below water table	S_{or}	0.219		$S_{or}=f_{or}(1-S_m)$	heterogeneous soils
	R_{ow}	2.33		$R_{ow} = (1-S_m)/S_{or} - 1$	
Van Genuchten parameter - drainage	α	3.87 /m			site-specific or use data on Properties sheet
Van Genuchten parameter	n	1.620			site-specific or use data on Properties sheet
Van Genuchten parameter	m	0.38		$m=1-1/n$	
Saturated Hydraulic Conductivity	K_{sw}	1.3E-04	m/s	11.6 m/day	site-specific or use data on Properties sheet
<u>Fluid Properties</u>					
oil specific gravity	ρ_{ro}	0.765			site-specific or use data on Properties sheet
specific gravity contrast	$(1-\rho_{ro})$	0.235		$(1-\rho_{ro})$	
oil dynamic viscosity at 15 C	η_o	0.79	centipoise		site-specific or use data on Properties sheet
oil-water viscosity ratio	η_{ro}	0.7		$\eta_{ro} = \eta_o/\eta_w$	water = 1.14 cp at 15 C
oil surface tension	σ_{ao}	22.9	dynes/cm		site-specific or use data on Properties sheet
oil/water interfacial tension	σ_{ow}	19.1	dynes/cm		site-specific or use data on Properties sheet
water surface tension	σ_{aw}	41	dynes/cm		water surface tension
air-oil scaling coefficient	β_{ao}	1.8		σ_{aw}/σ_{ao}	
oil-water scaling coefficient	β_{ow}	2.1		σ_{aw}/σ_{ow}	$\beta_{ow} \sim 1/(1-1/\beta_{ao})$

Example Mobility Spreadsheet Cont'd

Well Data

elevation of air/oil interface in well	Z_{ao}	53.955 m		measured field value
elevation of oil/water interface in well	Z_{ow}	53.441 m		measured field value
apparent oil thickness in well	H_o	0.514 m	$H_o = Z_{ao} - Z_{ow}$	
calculated min. soil hydrocarbon thickness	D_o	0.814 m	$D_o = \rho_{ro} * \beta_{ao} * H_o / (\beta_{ao} * \rho_{ro} - \beta_{ow}(1 - \rho_{ro}))$	
calculated potentiometric elevation	Z_{aw}	53.834 m	$Z_{aw} = Z_{ow} + \rho_{ro} * H_o$	calculated water table elevation
elevation of historical minimum Z_{ow}	Z_{ow}^{min}	53.415 m		base of hydrocarbon smear zone in soil
elevation of historical maximum Z_{ow}	Z_{ow}^{max}	55.072 m		top of hydrocarbon smear zone in soil
water table rising?	rise	0	1=true, 0=false	1 for rising, 0 for falling
effective α parameter	α_e	3.87	$\alpha_e = (1 + \text{rise}) * \alpha$	$\alpha_i = 2\alpha$ (Kool and Parker, 1987)
vertical step for integration	ΔZ	0.017 m		integrates over 100 slices

Oil Volume Estimates

Estimated free oil specific volume	V_{of}	21.8 L/m²	
estimated saturated zone trapped oil specific volume	V_{or}	0.40 L/m ²	
estimated vadose zone residual oil specific volume	V_{og}	18.11 L/m ²	
Estimated total oil specific volume	V_o	40.3 L/m²	
Theoretical maximum recoverable oil specific volume	$V_o - V_{og(max)}$	10.9 L/m²	
estimated maximum free oil conductivity	$K_{o(max)}$	3.8E-05 m/s	
estimated average free oil conductivity	$K_{o(avg)}$	1.4E-05 m/s	
estimated free oil transmissivity	T_o	7.2E-06 m ² /s	0.62123 m ² /day
Local Hydraulic Gradient	i	5.0E-02 m/m	
estimated oil flux	$T_o * i$	31.1 L/day/m	

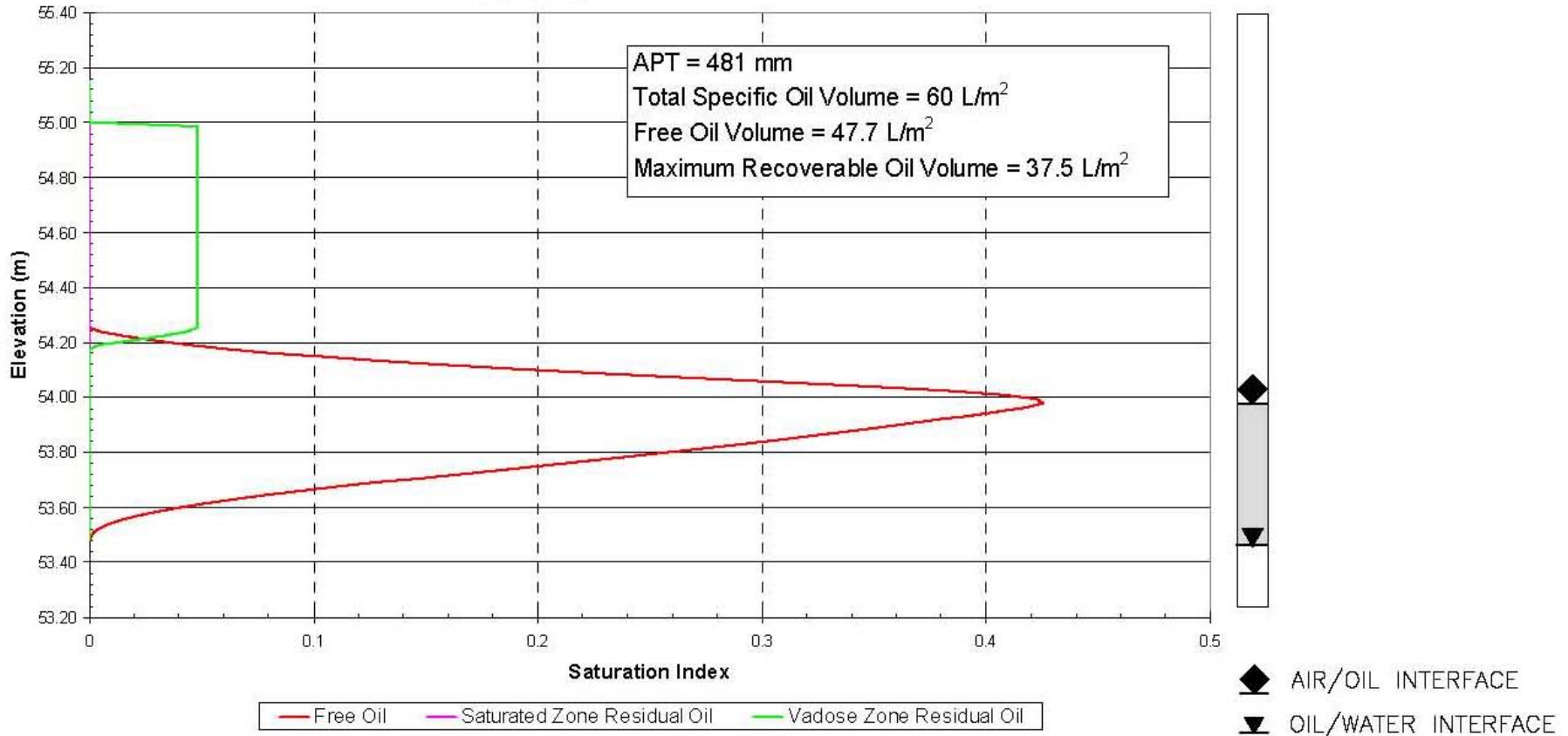
Output

- ◆ **Oil volume estimates per unit surface area**
 - Total oil specific volume
 - Residual oil volume in vadose zone
 - Trapped oil volume in saturated zone
 - Free oil volume
 - Maximum theoretical recoverable oil volume
- ◆ **Oil transmissivity -- used to estimate front migration rate**

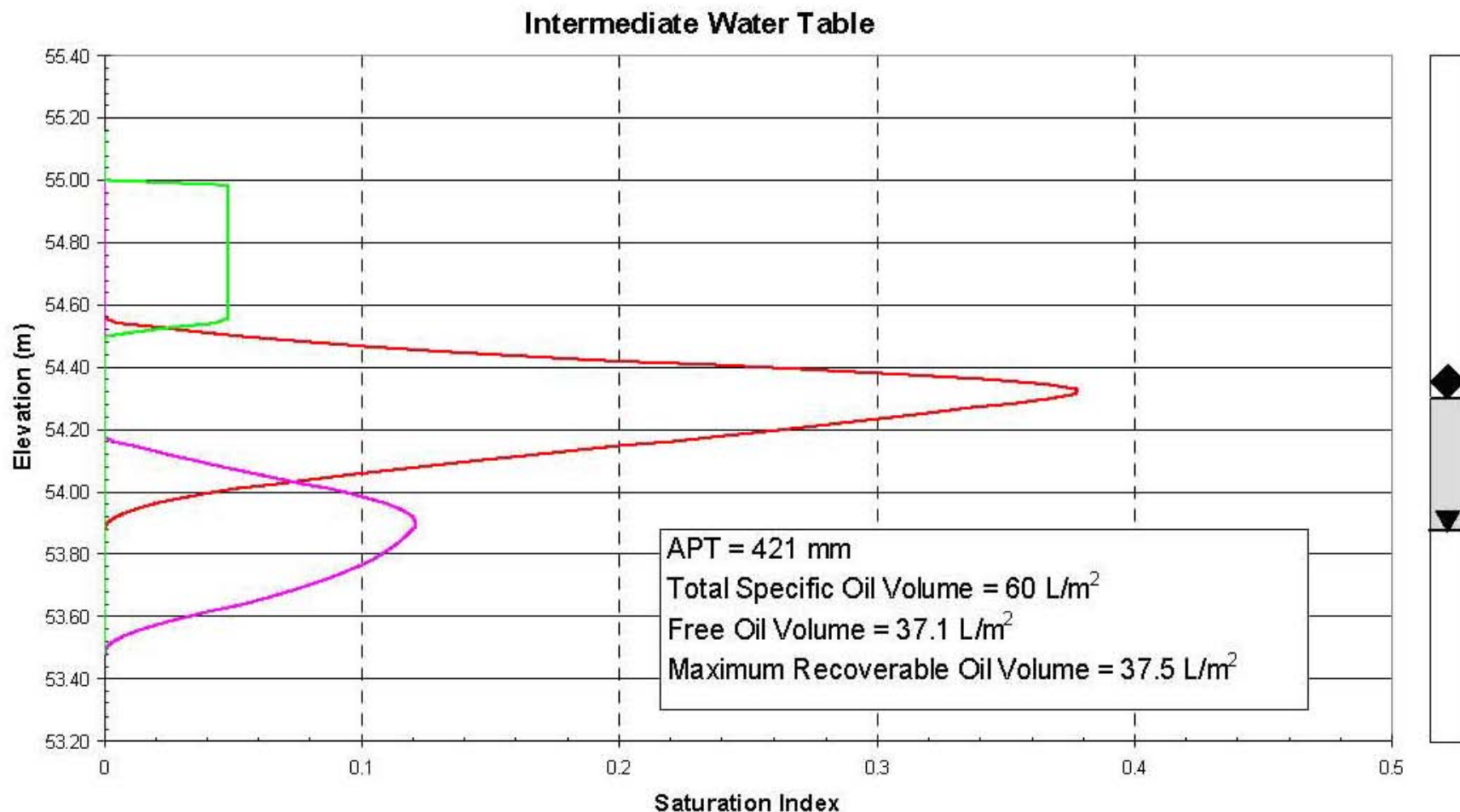


Typical Oil Saturation Curve for Low Water Table

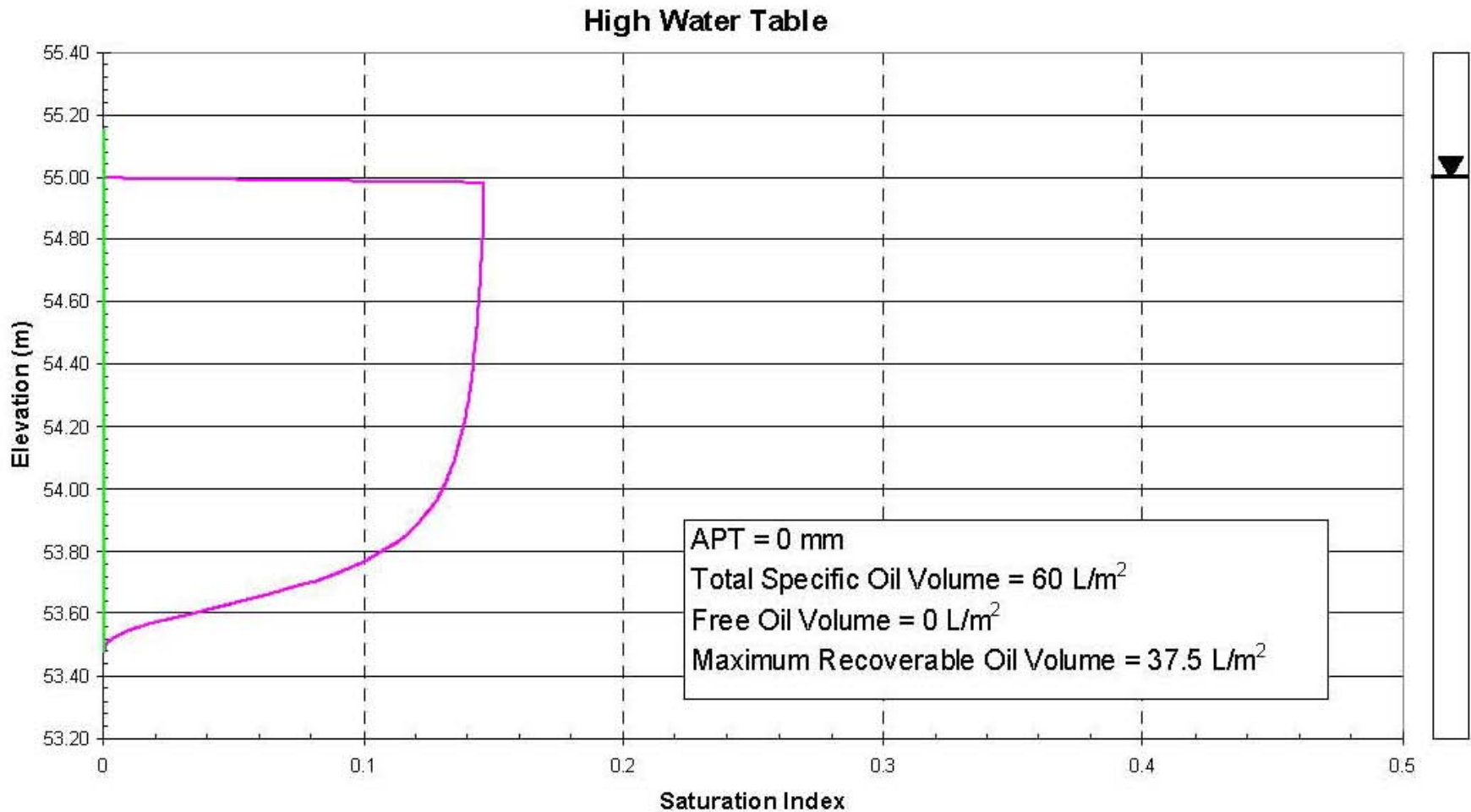
Minimum Water Table



Typical Oil Saturation Curve for Intermediate Water Table



Typical Oil Saturation Curve for High Water Table



Results

Monitoring Well A

Monitoring Date	10/6/2003	11/10/2004	2/22/2005	5/25/2005
Apparent oil thickness in well (m)	0.51	0.38	0.10	0.25
Mobility Estimate Oil Transmissivity (m²/day)	0.55	0.05	0.00	0.01
Bail Test Oil Transmissivity (m ² /day)	0.14	---	---	---
Elevation of air/oil interface in well (m)	53.955	54.408	54.932	54.542
Elevation of oil/water interface in well (m)	53.441	54.030	54.828	54.292
Estimated free oil specific volume (L/m²)	21.8	11.5	0.5	4.6
Estimated saturated zone trapped oil specific volume (L/m ²)	0.40	25.11	58.95	35.909
Estimated vadose zone residual oil specific volume (L/m ²)	16.95	9.46	2.30	8.209
Estimated total oil specific volume (L/m²)	39.2	46.1	61.8	48.7
Theoretical maximum recoverable oil specific volume (L/m²)	9.7	16.7	32.4	19.3
LNAPL Mobility (m/day)	14.1	1.2	0.0	0.2
Estimated Gradient (m/m)	0.05	0.05	0.05	0.05
LNAPL Front Migration (m/day)	0.70	0.06	0.00	0.01

Representative of plume centre.

Results

Monitoring Well B

Monitoring Date	10/19/2004	2/8/2005	3/11/2005	6/21/2005
Apparent oil thickness in well (m)	0.44	0.00	0.04	0.20
Mobility Estimate Oil Transmissivity (m²/day)	0.09	0.00	0.00	0.00
Bail Test Oil Transmissivity (m ² /day)	---	---	---	---
Elevation of air/oil interface in well (m)	54.37	56.37	55.35	54.77
Elevation of oil/water interface in well (m)	53.93	56.37	55.31	54.57
Estimated free oil specific volume (L/m²)	6.8	0.0	0.0	1.0
Estimated saturated zone trapped oil specific volume (L/m ²)	0.00	97.14	42.27	15.93
Estimated vadose zone residual oil specific volume (L/m ²)	37.34	0.00	19.52	30.62
Estimated total oil specific volume (L/m²)	44.1	97.1	61.8	47.6
Theoretical maximum recoverable oil specific volume (L/m²)	1.0	16.7	18.7	4.5
LNAPL Mobility (m/day)	2.1	0.0	0.0	0.0
Estimated Gradient (m/m)	0.05	0.05	0.05	0.05
LNAPL Front Migration (m/day)	0.10	0.00	0.00	0.00

Representative of plume fringe.

Results

- ◆ **Lowering water table causes increase in mobility potential**
- ◆ **Calculated free oil volumes increase due to LNAPL drainage and increase oil saturation and transmissivity**
- ◆ **Estimated free oil volumes also decrease with a rising water table, which immobilizes LNAPL volumes and reduces oil transmissivity**



Results

- ◆ **Position of water table impacts the effectiveness of LNAPL recovery systems**
- ◆ **Model data also reveals that large volumes of LNAPL are immobilized by smearing due to water level fluctuation**



Discussion

- ◆ **LNAPL front migration rate subject to interpretation**
- ◆ **Oil transmissivity varies with time and space in a LNAPL plume**
- ◆ **Calculated LNAPL migration rates are dependent on when and where they are calculated**



Discussion

- ◆ **LNAPL mobility is measured at its edges, as lateral spreading is of concern**
- ◆ **Front migration rates calculated from monitoring wells away from plume fringe will overestimate migration potential**
- ◆ **Oil volume and saturation decrease to zero at the limit of LNAPL influence**



Discussion

- ◆ **Theoretical maximum recoverability regarded to be more representative evaluation parameter for central wells**
- ◆ **Can be interpreted as a measure of free LNAPL volume available to contribute to migration**



Conclusions

- ◆ **Risk management approach useful in assessing potential LNAPL migration risk at monitoring well locations**
- ◆ **Allows the ability to interpret LNAPL thicknesses measured in the field**
- ◆ **Provides a mechanism for prioritization of effort based on risk management**
- ◆ **Regarded to be a valuable risk communication tool**



Conclusions

- ◆ **Mobility estimates are complicated by oil saturation variability within a LNAPL plume, therefore interpretation is important**
- ◆ **Assessment, characterization and delineation of LNAPL plume regarded to be important when using a risk management approach**
- ◆ **An additional benefit of risk management approach is ability to estimate potentially recoverable volume within LNAPL plume**



Conclusions

Moving Forward:

- ◆ **Continue to build confidence in approach**
- ◆ **Reduce uncertainties in parameter assumptions, specifically soil properties**
- ◆ **Investigate assumptions regarding residual and trapped LNAPL saturations, and smear zone thickness**



Questions & Answers

