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Morrow Environmental

Techniques Used to Evaluate Potential LNAPL Mobility

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Overview

- Introduction
- Theory
- Assessment Method
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- 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

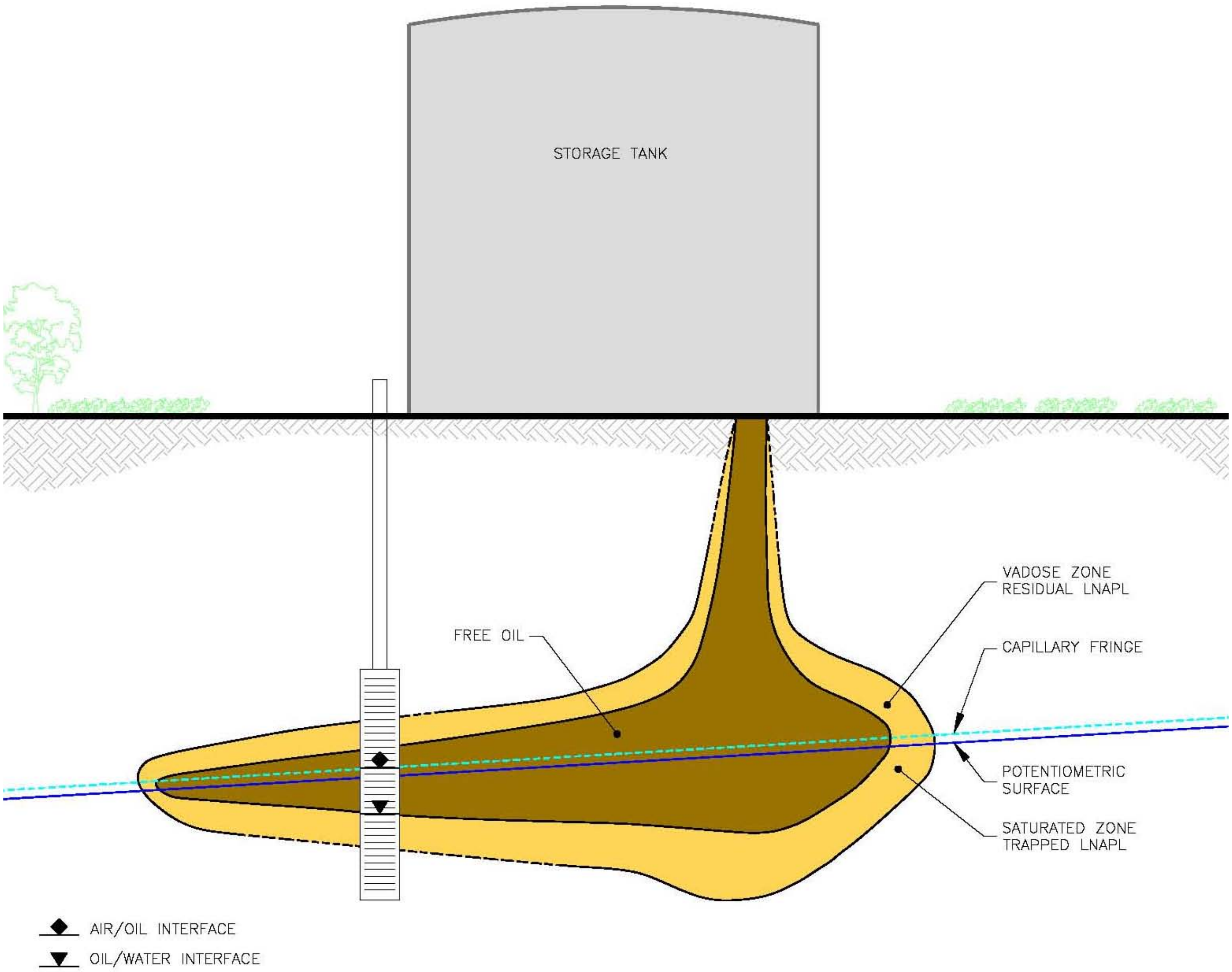
Site Details:

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

Revision Date: 2004 06 29

Project Number:	V2-226	**Location:**	Former Refinery Property
Well Number:	A	**Monitoring Date:**	Maximum APT
NAPL Type/Sample:	LNN	**Soil Type/Sample:**	Coarse Sand
Assessed By:	DAF	**Date:**	2005 09 30

Soil Properties	Symbol	Value	Units	Equation		Comments
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	$1\text{-}S_m$	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		$S_{or}\sim f_{or}(1-S_m)$		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 Conductivty	K_{sw}	1.3E-04	m/s	11.6	m/day	site-specific or use data on Properties sheet
Fluid Properties						
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

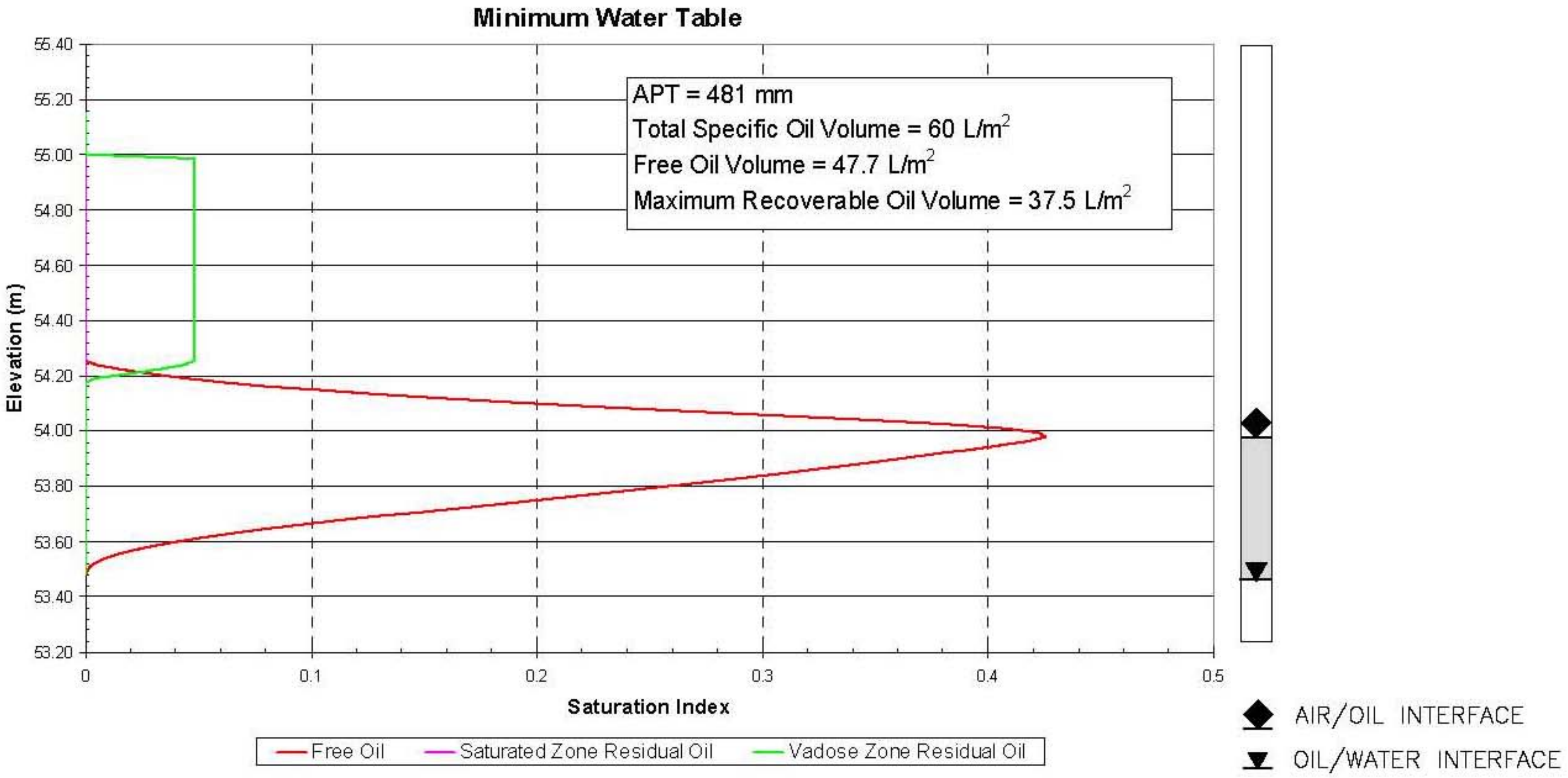
Oil Volume Estimates

Estimated free oil specific volume	V_{of}	**21.8**	**L/m²**		
estimated saturated zone trapped oil specific volume	V_{or}	0.40	L/m²		
estimated vadose zone residual oil specific volume	V_{og}	18.11	L/m²		
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	m²/s	0.62123	m²/day
Local Hydraulic Gradient	i	5.0E-02	m/m		
estimated oil flux	$T_o * i$	31.1	L/day/m		

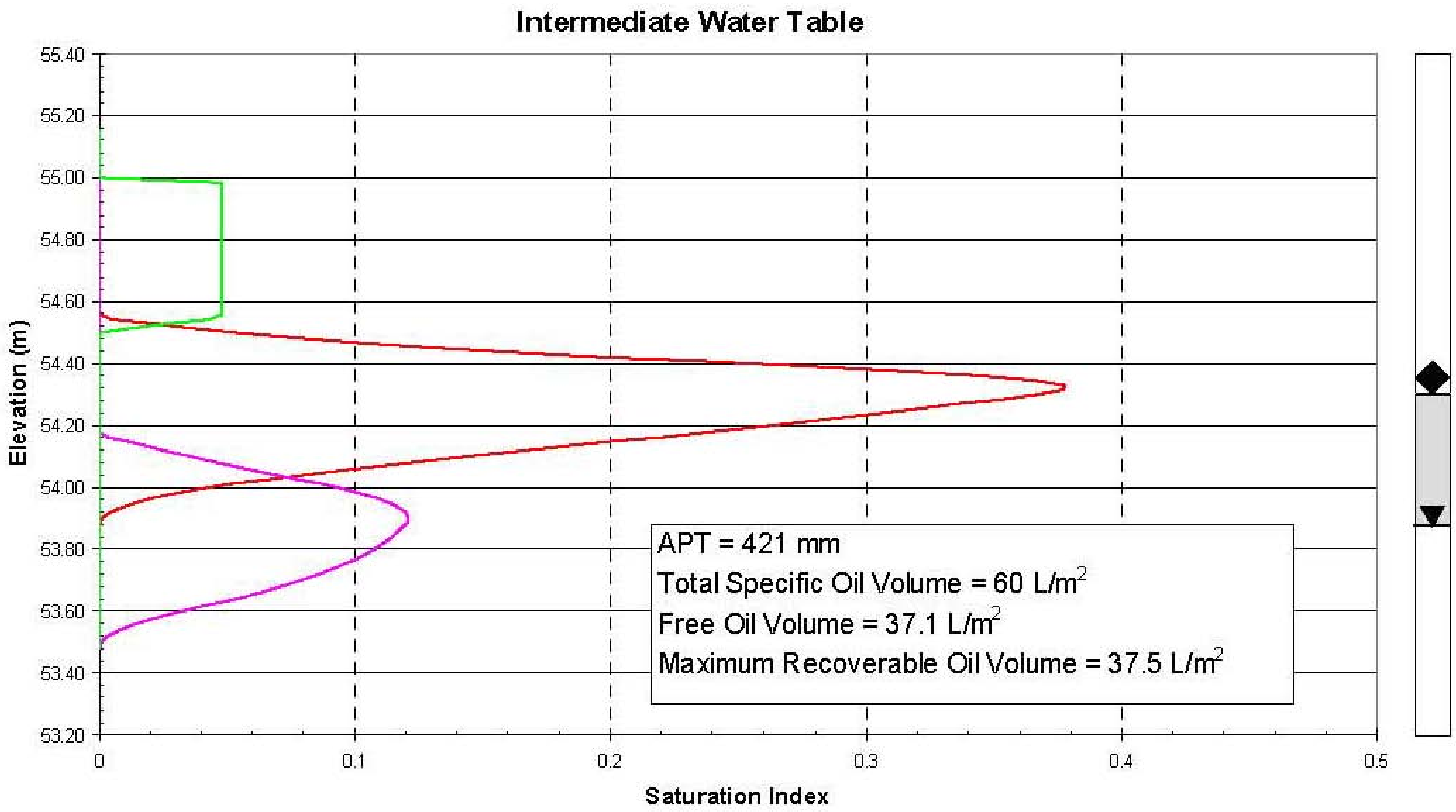
Output

- **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**

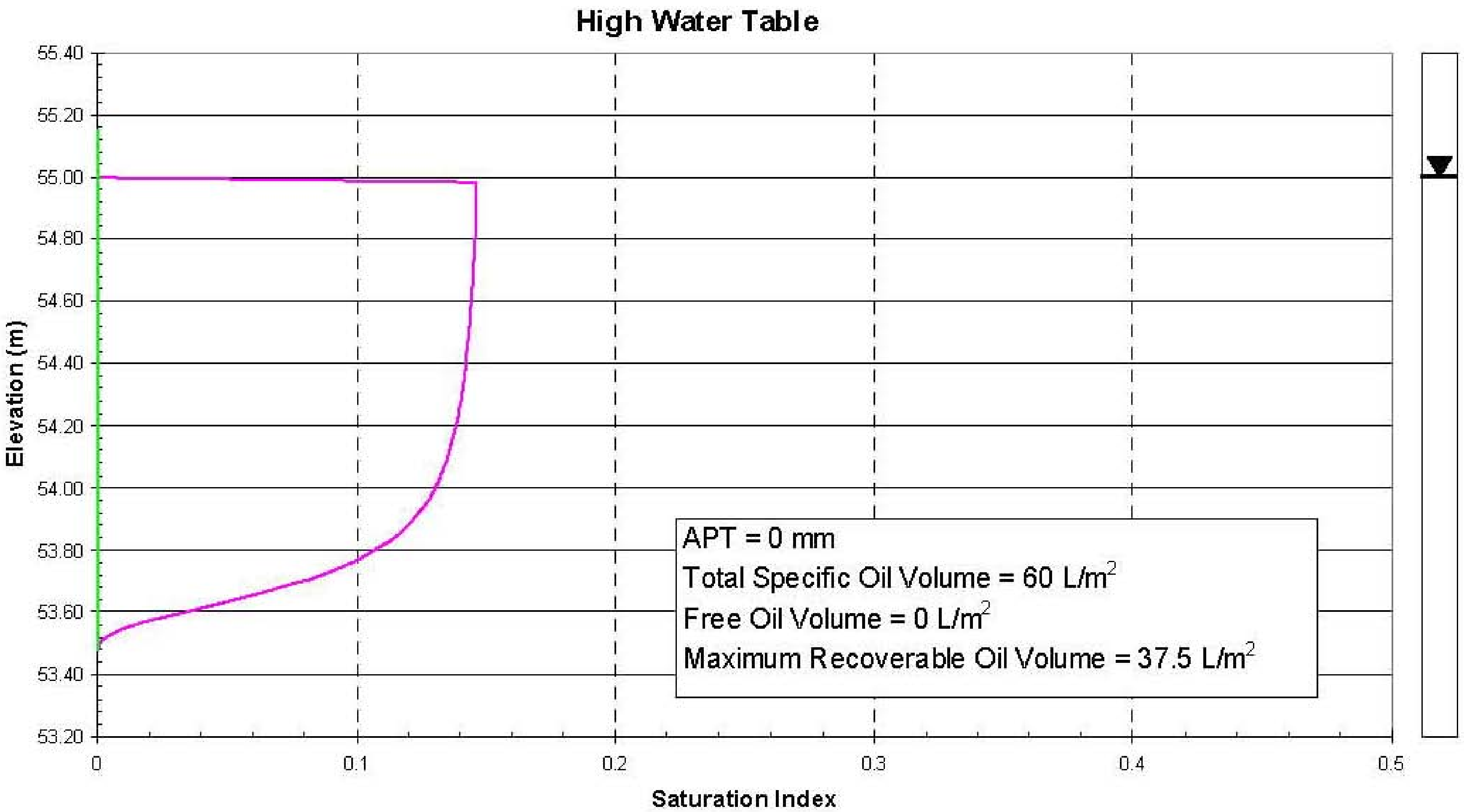
Typical Oil Saturation Curve for Low Water Table



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 (m2/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/m2)	0.40	25.11	58.95	35.909
Estimated vadose zone residual oil specific volume (L/m2)	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	**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 (m2/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/m2)	0.00	97.14	42.27	15.93
Estimated vadose zone residual oil specific volume (L/m2)	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	**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