

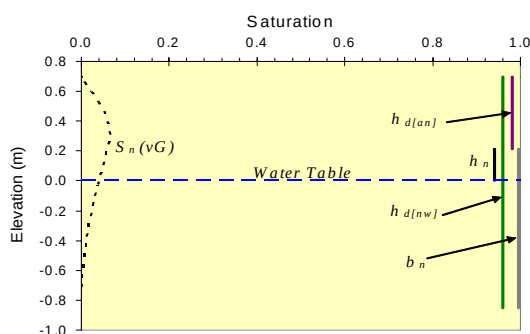
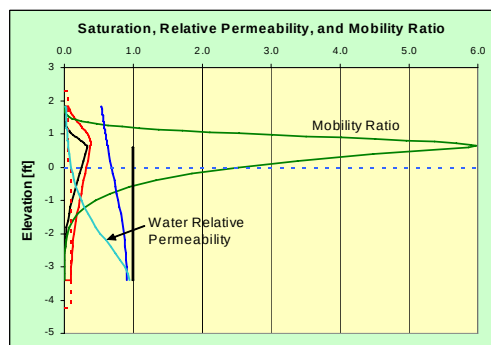


# LNAPL Distribution and Recovery Model (LDRM)

## Volume 1: Distribution and Recovery of Petroleum Hydrocarbon Liquids in Porous Media

Regulatory and Scientific Affairs Department

API PUBLICATION 4760  
JANUARY 2007





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## PREFACE

This manuscript (Volume 1) provides background information supporting formulation of the American Petroleum Institute LNAPL Distribution and Recovery Model (LDRM), and is presented as a supplement to API Publication Number 4682, *Free-Product Recovery of Petroleum Hydrocarbon Liquids*, which was published in June 1999, and to API Publication Number 4729, *Models for Design of Free-Product Recovery Systems for Petroleum Hydrocarbon Liquids; A User's Guide and Model Documentation*, which was published in August 2003 and included in the API Interactive LNAPL Guide, Version 2.0. Model scenarios are described for free-product hydrocarbon liquid recovery using single- and dual-pump well systems, skimmer wells, vacuum-enhanced well systems, and trenches. Information on LNAPL distribution in porous media and possible LNAPL movement is discussed, and the basic modeling equations are provided. Use of the LDRM software to compute LNAPL recovery rates, volumes and times is discussed, and example applications are provided in a companion document (Volume 2), which also documents model testing and evaluation. The API LDRM software can be downloaded from API's website at: [groundwater.api.org/lnapl](http://groundwater.api.org/lnapl).

# TABLE OF CONTENTS

| <u>Section</u> | <u>Page</u>                                                                                  |
|----------------|----------------------------------------------------------------------------------------------|
| 1              | INTRODUCTION.....1                                                                           |
| 1.1            | Background and Objectives.....1                                                              |
| 1.2            | Scenarios for Free-Product Hydrocarbon Liquid Recovery.....1                                 |
| 1.2.1          | Scenarios for Recovery Well Systems.....2                                                    |
| 1.2.2          | Scenario for LNAPL Recovery Using Trenches.....3                                             |
| 1.3            | Overview.....4                                                                               |
| 2              | LNAPL DISTRIBUTION.....5                                                                     |
| 2.1            | Capillarity in Porous Media .....5                                                           |
| 2.1.1          | Surface Tension, Wettability and Capillary Pressure .....5                                   |
| 2.1.2          | Capillary Pressure Curves .....6                                                             |
| 2.1.3          | Residual LNAPL Saturation .....7                                                             |
| 2.1.4          | Spreading Coefficients .....10                                                               |
| 2.1.5          | Leverett Assumptions .....11                                                                 |
| 2.2            | Capillary Pressure Curve Models .....11                                                      |
| 2.2.1          | Fitting Models to Capillary Pressure Curve Data .....12                                      |
| 2.2.2          | Pore-Size Distribution Curves .....13                                                        |
| 2.2.3          | Capillary Scaling Relationships .....15                                                      |
| 2.3            | Forces in Multiphase Fluid Systems .....15                                                   |
| 2.4            | LNAPL Distribution and Monitoring Wells .....17                                              |
| 2.4.1          | Fluid Levels in Monitoring Wells .....17                                                     |
| 2.4.2          | Distribution of Capillary Pressure .....18                                                   |
| 2.4.3          | LNAPL Saturation Distributions .....19                                                       |
| 2.4.4          | “Initial” LNAPL Saturation Values and Residual<br>LNAPL Saturation .....21                   |
| 2.4.5          | LNAPL Capillary Rise .....22                                                                 |
| 2.4.6          | Calculation of LNAPL Saturation Distribution from<br>Monitoring-Well LNAPL Thickness .....23 |
| 2.4.7          | Free-LNAPL and Recoverable-LNAPL Specific Volume .....24                                     |
| 3              | LNAPL MOVEMENT.....26                                                                        |
| 3.1            | LNAPL Movement and Darcy’s Law .....26                                                       |
| 3.1.1          | Darcy’s Law .....26                                                                          |
| 3.1.2          | NAPL Relative Permeability: Burdine and Mualem Equations .....27                             |
| 3.1.3          | Comparison of Relative Permeability Models .....29                                           |
| 3.2            | LNAPL Vertical Migration through Fine-Grain Soil .....30                                     |
| 3.2.1          | Effect of Vertical Gradients on LNAPL Saturation .....30                                     |
| 3.2.2          | Critical Downward Hydraulic Gradient .....31                                                 |
| 3.3            | LNAPL Lateral Migration and Liquid Free-Product Recovery .....31                             |
| 3.3.1          | Lateral Migration of LNAPL to Pristine Soils .....32                                         |
| 3.3.2          | LNAPL Mobility Ratio .....37                                                                 |
| 3.3.3          | LNAPL-Layer Volume Flux .....38                                                              |
| 3.3.4          | Vacuum-Enhanced Recovery .....41                                                             |

|       |                                                                              |    |
|-------|------------------------------------------------------------------------------|----|
| 3.3.5 | LNAPL Recovery Using Skimmer Wells .....                                     | 44 |
| 3.3.6 | Recovery of LNAPL from Beneath Fine-Grain<br>Zones Using Skimmer Wells ..... | 44 |
| 3.3.7 | LNAPL Recovery Using Trenches .....                                          | 45 |
| 4     | LNAPL CONTINUITY .....                                                       | 47 |
| 4.1   | Continuity Equations for Regions of Capture .....                            | 47 |
| 4.2   | Model Parameterization and Integration .....                                 | 48 |
| 5     | REFERENCES .....                                                             | 51 |

# LIST OF FIGURES

| <u>Figure</u>                                                                                                                                                | <u>Page</u> |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------|
| 1.1 Monitoring well LNAPL thickness, $b_n$ .....                                                                                                             | 2           |
| 1.2 Recovery well system with 7 recovery wells showing the radius of capture .....                                                                           | 3           |
| 1.3 Simple Trench System for LNAPL Recovery .....                                                                                                            | 4           |
| 2.1 Interfacial energy associated with molecular attraction in the liquid phase .....                                                                        | 5           |
| 2.2 Contact angle and wettability .....                                                                                                                      | 6           |
| 2.3 Soil capillary pressure curve showing primary drainage, imbibition, and<br>scanning characteristic curves .....                                          | 7           |
| 2.4 LNAPL residual saturation under normal field conditions .....                                                                                            | 8           |
| 2.5 LNAPL residual saturation increases with initial LNAPL saturation (after<br>Kueper et al, 1993) .....                                                    | 9           |
| 2.6 LNAPL residual saturation depends on initial LNAPL saturation (from Johnston<br>and Adamski, 2005) .....                                                 | 9           |
| 2.7 LNAPL drop located on an air-water interface .....                                                                                                       | 10          |
| 2.8 Measured capillary pressure curve .....                                                                                                                  | 12          |
| 2.9 Fitted capillary pressure curve models (a) Burdine and (b) Mualem relations.....                                                                         | 13          |
| 2.10 Pore size distribution curves (a) fine-grain soil and (b) fine sand soil .....                                                                          | 14          |
| 2.11 Distribution of fluid saturation among various pore sizes .....                                                                                         | 15          |
| 2.12 Fluid elevations within an LNAPL monitoring well .....                                                                                                  | 17          |
| 2.13 Capillary pressure distribution near the water table, including the capillary fringe.....                                                               | 18          |
| 2.14 Capillary pressure distribution in the presence of LNAPL .....                                                                                          | 19          |
| 2.15 Calculated water and LNAPL saturation distributions based on two<br>different LNAPL-thickness values .....                                              | 24          |
| 2.16 LNAPL specific volume and recoverable volume curves .....                                                                                               | 25          |
| 3.1 Two-phase NAPL relative permeability for Burdine and Mualem models .....                                                                                 | 30          |
| 3.2 LNAPL distribution showing effect of vertical hydraulic gradient .....                                                                                   | 31          |
| 3.3 Water saturation curves predicted by vG and BC models .....                                                                                              | 34          |
| 3.4 LNAPL saturation distribution predicted using the Brooks and Corey<br>capillary pressure model with $b_n > b_{n[crit]}$ .....                            | 36          |
| 3.5 Limiting LNAPL saturation distribution (none) predicted using the Brooks<br>and Corey capillary pressure model with $b_n > b_{n[crit]}$ .....            | 37          |
| 3.6 LNAPL/water mobility ratio .....                                                                                                                         | 38          |
| 3.7 LNAPL and groundwater flow to a well .....                                                                                                               | 40          |
| 3.8 Air flow to a vacuum-enhanced recovery well with leakage from the<br>atmosphere across the shallow vadose zone .....                                     | 41          |
| 3.9 LNAPL recovery using a skimmer well .....                                                                                                                | 44          |
| 3.10 LNAPL trapped beneath FGZ and skimmer-well recovery .....                                                                                               | 45          |
| 4.1 Radius of capture based on continuity for the six wells on the left, and<br>based on radius of influence for a single well on right side of figure ..... | 47          |

## LIST OF SYMBOLS

|                |                                                                       |
|----------------|-----------------------------------------------------------------------|
| $A_c$          | area extent of region of capture for well or trench                   |
| $A_j$          | performance coefficient in LNAPL recovery models                      |
| $b$            | aquifer thickness                                                     |
| $b_a$          | screened interval for air flow above the water table                  |
| $b_n$          | monitoring well LNAPL thickness                                       |
| $b_{nw}$       | LNAPL thickness in well, constrained by fine-grain-zone               |
| $b_w$          | depth beneath the water table of groundwater flow to a well or trench |
| $d$            | mean grain-size diameter                                              |
| $D_n$          | LNAPL specific volume                                                 |
| $f_{ar}$       | mass flux of air in radial direction                                  |
| $f_{az}$       | mass flux of air in vertical direction                                |
| $f_r$          | residual LNAPL f-factor (fraction of initial LNAPL saturation)        |
| $f_{rs}$       | residual LNAPL f-factor (saturated zone)                              |
| $f_{rv}$       | residual LNAPL f-factor (vadose zone)                                 |
| $g$            | gravitational constant                                                |
| $h$            | fluid head                                                            |
| $h_c$          | capillary pressure head                                               |
| $h_d$          | displacement pressure head (air-water)                                |
| $h_{d[an]}$    | air-LNAPL displacement pressure head                                  |
| $h_{d[nw]}$    | LNAPL-water displacement pressure head                                |
| $h_{[an]}$     | air-LNAPL capillary pressure head (equivalent water head)             |
| $h_{[nw]}$     | LNAPL-water capillary pressure head (equivalent water head)           |
| $J_a$          | air-phase hydraulic gradient                                          |
| $J_n$          | LNAPL hydraulic gradient                                              |
| $J_w$          | water hydraulic gradient                                              |
| $J_{wz}$       | vertical water hydraulic gradient (positive upward)                   |
| $k$            | intrinsic permeability                                                |
| $K_n$          | LNAPL hydraulic conductivity                                          |
| $K_{ns}$       | LNAPL saturated hydraulic conductivity                                |
| $k_{ra}$       | air relative permeability                                             |
| $k_{rn}$       | LNAPL relative permeability                                           |
| $K_{ws}$       | water saturated hydraulic conductivity                                |
| $k_{rw}$       | water relative permeability                                           |
| $\hat{k}$      | upward unit vector                                                    |
| $L_T$          | length of LNAPL recovery trench                                       |
| $M$            | van Genuchten $M$ parameter                                           |
| $m_{r[nw]}$    | LNAPL-water mobility ratio ( $= k_{rn}/(k_{rw}\mu_r)$ )               |
| $\dot{m}_{ar}$ | mass rate of flow of air in radial direction                          |
| $n$            | porosity                                                              |
| $N$            | van Genuchten $N$ parameter                                           |
| $p$            | fluid pressure                                                        |
| $p_a$          | air pressure                                                          |
| $p_c$          | capillary pressure                                                    |

|             |                                                             |
|-------------|-------------------------------------------------------------|
| $p_{c[an]}$ | air-LNAPL capillary pressure                                |
| $p_{c[nw]}$ | LNAPL-water capillary pressure                              |
| $p_n$       | LNAPL pressure                                              |
| $p_{nC}$    | LNAPL pressure at radius of capture ( $R_C$ )               |
| $p_{nW}$    | LNAPL pressure at radius of well ( $R_W$ )                  |
| $p_w$       | water pressure                                              |
| $p_{wI}$    | water pressure at radius of influence ( $R_I$ )             |
| $p_{wW}$    | water pressure at radius of well ( $R_W$ )                  |
| $p(r_c)$    | fraction of pores of size $r_c$                             |
| $q_n$       | LNAPL volume flux (Darcy velocity)                          |
| $Q_n$       | LNAPL discharge                                             |
| $q_{nz}$    | LNAPL vertical volume flux (positive upward)                |
| $q_w$       | water volume flux (Darcy velocity)                          |
| $Q_w$       | water discharge                                             |
| $R_c$       | radius of capture                                           |
| $R_n$       | LNAPL recoverable volume                                    |
| $\bar{r}$   | mean radius of curvature of interface between fluid phases  |
| $S_e$       | effective (reduced) saturation                              |
| $S_{e[t]}$  | effective total liquid saturation                           |
| $S_{e[w]}$  | effective water saturation                                  |
| $S_n$       | LNAPL saturation                                            |
| $S_{ni}$    | initial LNAPL saturation                                    |
| $S_{nr}$    | LNAPL residual saturation                                   |
| $S_{NW_r}$  | non-wetting phase residual saturation                       |
| $S_{n/aw}$  | spreading coefficient for LNAPL across air-water interface  |
| $S_w$       | water saturation                                            |
| $S_W$       | wetting phase saturation                                    |
| $S_{wi}$    | initial water saturation                                    |
| $S_{wr}$    | irreducible water saturation                                |
| $S_{W_r}$   | wetting phase residual saturation                           |
| $T_n$       | LNAPL-layer transmissibility                                |
| $U_n$       | LNAPL unit flux                                             |
| $U_w$       | water unit flux                                             |
| $W_T$       | width of LNAPL lens extending away from the recovery trench |
| $z$         | elevation                                                   |
| $z_{an}$    | air-LNAPL interface elevation in monitoring well            |
| $z_{aw}$    | water table elevation                                       |
| $z_{FGZ}$   | elevation of facies interface with fine-grain-zone          |
| $z_{gs}$    | ground surface elevation                                    |
| $z_{max}$   | maximum elevation of free LNAPL (due to capillary rise)     |
| $z_{nw}$    | LNAPL-water interface elevation in monitoring well          |
| $z_r$       | reference elevation                                         |
| $z_{wt}$    | elevation of water table                                    |
| $z_{12}$    | elevation of interface between soil layers 1 and 2          |
| $z_{23}$    | elevation of interface between soil layers 2 and 3          |

|                 |                                                                                     |
|-----------------|-------------------------------------------------------------------------------------|
| $\alpha$        | van Genuchten $\alpha$ parameter                                                    |
| $\alpha_{an}$   | vG- $\alpha$ air-LNAPL scaling relationship for interfacial tension plus buoyancy   |
| $\alpha_{[an]}$ | vG- $\alpha$ air-LNAPL scaling relationship for interfacial tension                 |
| $\alpha_{nw}$   | vG- $\alpha$ LNAPL-water scaling relationship for interfacial tension plus buoyancy |
| $\alpha_{[nw]}$ | vG- $\alpha$ LNAPL-water scaling relationship for interfacial tension               |
| $\beta$         | recoverable volume slope parameter                                                  |
| $\eta$          | LNAPL transmissibility slope parameter                                              |
| $\theta_c$      | contact angle                                                                       |
| $\lambda$       | Brooks and Corey pore size distribution index                                       |
| $\mu$           | dynamic viscosity                                                                   |
| $\mu_a$         | air dynamic viscosity                                                               |
| $\mu_n$         | LNAPL dynamic viscosity                                                             |
| $\mu_r$         | LNAPL-water viscosity ratio ( $\mu_r = \mu_n/\mu_w$ )                               |
| $\mu_w$         | water dynamic viscosity                                                             |
| $\xi$           | LNAPL transmissibility intercept parameter                                          |
| $\rho_a$        | air density                                                                         |
| $\rho_n$        | LNAPL density                                                                       |
| $\rho_r$        | LNAPL-water density ratio ( $\rho_r = \rho_n/\rho_w$ )                              |
| $\rho_w$        | water density                                                                       |
| $\sigma_{an}$   | air-LNAPL surface tension                                                           |
| $\sigma_{aw}$   | air-water surface tension                                                           |
| $\sigma_{nw}$   | LNAPL-water interfacial tension                                                     |
| $\chi$          | recoverable volume intercept parameter                                              |

## EXECUTIVE SUMMARY

This document provides background information necessary to characterize the behavior of LNAPL in porous media with regard to performance of LNAPL liquid recovery technologies. The scope of information is selected to support model assumptions and development for the API LNAPL Distribution and Recovery Model (LDRM) which simulates the performance of proven hydraulic technologies for recovering free-product petroleum liquid releases to groundwater. This manuscript (Volume 1) and its companion manuscript (Volume 2) supplement API Publication Number 4682 and 4729, and document the LDRM software models for design and analysis of liquid free-product recovery systems using single- and dual-pump wells, vacuum-enhanced wells, skimmer wells, and trenches.

The scenario-based models for recovery wells and trenches are described in Section 1. Section 2 provides necessary background information for characterizing the vertical distribution of LNAPL located near the water table under conditions of vertical equilibrium. Capillarity, capillary pressure curves, and LNAPL residual saturation are discussed. The capillary pressure curve model presented by van Genuchten is presented, along with scaling relationships that allow the model representation to be applied with different multiphase fluid systems. Hubbert's relationships for forces in multiphase fluid systems are presented. These are important in understanding how water-enhanced and vacuum-enhanced recovery systems create hydraulic gradient within the LNAPL phase causing its movement to a well or trench. The relationship between LNAPL thickness in a monitoring well and fluid pressure and capillary pressure within a formation is discussed in some detail. This relationship, when combined with a capillary pressure curve model, allow one to estimate LNAPL accumulations within the porous medium from monitoring well thickness measurements. Significant parameters are identified. Calculation of LNAPL specific volume and LNAPL recoverable volume as a function of LNAPL thickness in a well is discussed.

Section 3 concerns possible LNAPL movement. Darcy's law is presented for LNAPL flow, and the Burdine and Mualem LNAPL relative permeability models are discussed. The effect of vertical hydraulic gradient in fine-grain soil on LNAPL saturation is described, and the critical vertical gradient at which LNAPL is displaced to accumulate beneath fine-grain soil is identified. Potential lateral migration of LNAPL is discussed. For lateral migration into pristine soils, capillary pressure curve models that include a finite displacement pressure should be used, and it is shown that LNAPL plumes are stable towards lateral spreading (an LNAPL plume will stop spreading even though LNAPL has a positive head). The vertical distribution of LNAPL mobility ratio is examined to show LNAPL is much more mobile in the upper part of the capillary fringe than groundwater. The LNAPL-layer transmissibility is introduced to calculate the LNAPL-layer volume flux. The lateral flow equations for LNAPL to wells and trenches are developed for water-enhanced and vacuum-enhanced systems, and for skimmer wells.

Section 4 shows how the continuity principle applied with regions of capture can be used, when combined with the LNAPL recoverable volume and transmissibility functions, to predict performance of LNAPL liquid recovery systems. Model parameterization and integration are discussed, and the basic equations of LDRM are presented.

# 1 INTRODUCTION

## 1.1 BACKGROUND AND OBJECTIVES

The American Petroleum Institute (API) Publication Number 4682, *Free-Product Recovery of Petroleum Hydrocarbon Liquids* (Charbeneau et al., 1999), provides an overview of recovery technologies for petroleum hydrocarbon liquids that are released to the subsurface environment and accumulate near the water table. The primary recovery technologies include skimmer wells that produce hydrocarbon liquids and single- and dual-pump wells that produce both water and hydrocarbon liquids. Hydrocarbon liquid recovery rates may also be enhanced by applying a vacuum pressure to the well to increase the gradient towards the well within the hydrocarbon layer. API 4682 describes two (Excel spreadsheet) models that may be used to characterize the subsurface distribution of liquid hydrocarbon (lighter-than-water nonaqueous phase liquids, LNAPL) in a single homogenous soil layer and to calculate the potential recovery rate and time using single- and dual-pump wells, and vacuum-enhanced wells.

API Publication Number 4729, *Models for Design of Free-Product Recovery Systems for Petroleum Hydrocarbon Liquids* (Charbeneau, 2003) describes scenario-based models for LNAPL liquid recovery using skimmer wells, water and vacuum enhanced recovery wells, and trenches. Soil capillary pressure characteristics are described using the van Genuchten (1980) capillary pressure model (soil characteristics and LNAPL distribution are described in API 4682 using the Brooks and Corey (1964) capillary pressure model). Implementation of the models through use of four separate spreadsheets is presented, based on single or two-layer heterogeneity, and on selection of relative permeability model (Burdine, 1953, or Mualem, 1976).

The present documentation supports release of the *LNAPL Distribution and Recovery Model (LDRM)* by API which supersedes API 4682 and API 4729 through development of a more general modeling framework with up to three soil layers. The objective of the present manuscript (Volume 1) is to provide necessary background information to support modeling assumptions and development of scenario-based models describing LNAPL liquid recovery. The scope of the material presented documents the quantitative framework on which the LNAPL distribution and recovery model is based. A more general discussion of LNAPL topics is presented in the *API Interactive LNAPL Guide* (2004). Huntley and Beckett (2002) discuss the effects of LNAPL recovery on dissolved plumes. Model implementation through a single executable program and model testing are described in a companion document (Volume 2).

## 1.2 SCENARIOS FOR FREE-PRODUCT HYDROCARBON LIQUID RECOVERY

Proven technologies for free-product recovery of petroleum hydrocarbon liquids are described in API 4682. Models to provide quantitative estimates of system performance must necessarily be based on simplifying assumptions that will not be applicable to all field conditions. Nevertheless, the models provide insight and guidance that should be helpful in technology selection and system design, and in analysis of system performance. The model scenarios for well systems and trenches are discussed separately.

For this model formulation, the subsurface porous media is assumed to be laterally homogeneous, but can have up to three distinct layers (numbered with Layer 1 on top) with different soil characteristic and permeability parameters. The vertical transition between layers is assumed to be abrupt. An example two-layer soil system is shown in Figure 1.1. This figure shows a monitoring well with an LNAPL layer located between the air-NAPL interface  $z_{an}$  and the NAPL-water interface  $z_{nw}$ . The total monitoring well LNAPL thickness is  $b_n$ . The elevation of the abrupt transition between the upper and lower soil layers is designated  $z_{12}$ . The elevation of the water table is designated  $z_{aw}$ . While the water table is not present because of the LNAPL layer, its elevation is easily determined from the elevations  $z_{an}$  and  $z_{nw}$ , and the LNAPL density  $\rho_n$  (see Section 2).

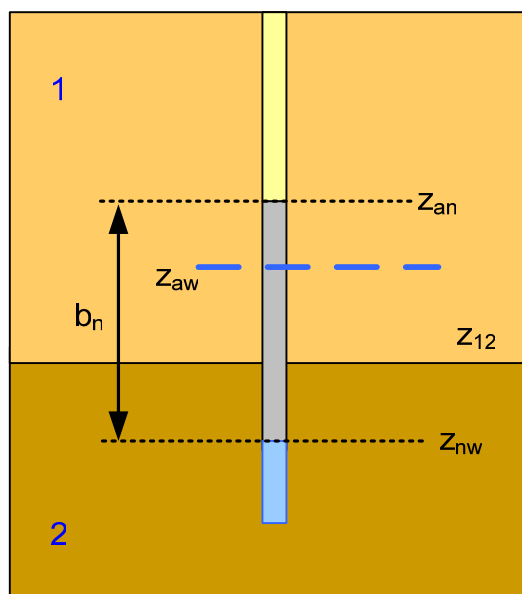


Figure 1.1—Monitoring well LNAPL thickness,  $b_n$

The soil texture characteristics that must be defined for each layer of the porous medium include the porosity  $n$ ; the (water phase) hydraulic conductivity  $K_{ws}$ ; the van Genuchten parameters  $N$  and  $\alpha$ ; and the irreducible water saturation,  $S_{wr}$ . Selection of residual LNAPL saturation values remains an elusive issue, and various options are described in Section 2. Fluid properties include the LNAPL density,  $\rho_n$  (it is assumed that the water density is  $1 \text{ g/cm}^3$ ), and the water and LNAPL surface and interfacial tensions,  $\sigma_{aw}$ ,  $\sigma_{an}$ , and  $\sigma_{nw}$ .

### 1.2.1 Scenarios for Recovery Well Systems

The basic scenario for free-product recovery using well systems is the same for single- and dual-pump wells, vacuum-enhanced wells, and skimmer wells. The performance of each well is characterized in terms of its radius of capture  $R_c$ , with a typical scenario shown in Figure 1.2. This figure depicts a plan view of an LNAPL lens (in gray color) with 7 recovery wells located so that the pattern of wells with their radius of capture will cover most of the area of the lens. For single- and dual-pump well systems, the radius of capture could extend out to the radius of influence (water production) of the well. For vacuum-enhanced systems, the radius of influence of the vacuum extraction well (which, because of air leaking from the ground surface, is

typically on the order of 30 feet – 40 feet) limits the radius of capture. For skimmer wells, the radius of capture is also limited to probably 10 feet – 30 feet, depending on the soil characteristics.

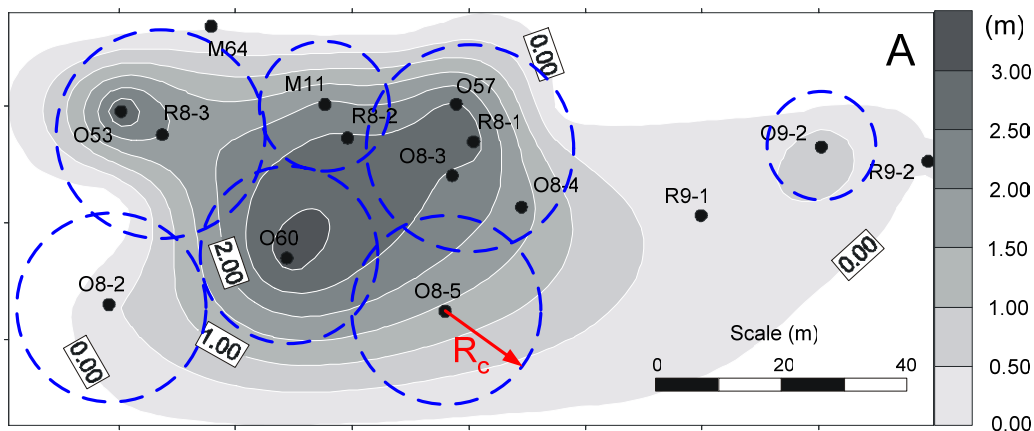


Figure 1.2—Recovery well system with 7 recovery wells showing the radius of capture (modified from Lefebvre, 2000)

The data required for analysis of recovery-well-system performance includes the radius of capture for the well, the LNAPL-water viscosity ratio  $\mu_r$  (the water viscosity is assumed to be 1 cp), and water production rate for a water-enhanced system or wellhead vacuum pressure for a vapor-enhanced system. For a water-enhanced system, the effective depth of penetration of the well into the aquifer must be specified, while for a vacuum-enhanced system, the screened interval of the vadose zone must be given. The effective relative permeability of the vadose zone due to the presence of residual soil water is assumed to be  $k_{ra} = 0.9$ . If zero water production and wellhead pressure are specified, then the well is assumed to function as a skimmer well.

### 1.2.2 Scenario for LNAPL Recovery Using Trenches

The modeling framework may also be used to represent a simple trench recovery system, such as shown in Figure 1.3. The trench has a length  $L_T$  transverse to the direction of groundwater flow. The LNAPL lens is assumed to be of rectangular shape with length  $L_T$  and width  $W_T$ . The natural groundwater hydraulic gradient  $J_w$  is transferred to the LNAPL layer and carries it into the trench where LNAPL is removed by skimmer wells or other technology. The rate of LNAPL discharge into the trench will depend on the effective lens thickness as observed in a monitoring well, soil texture, natural groundwater hydraulic gradient, and whether groundwater is also produced from the trench in order to increase the hydraulic gradient. If the trench cuts across an LNAPL lens, then the upstream and downstream sections of the lens must be analyzed separately, with  $J_w$  being negative on the downstream side.

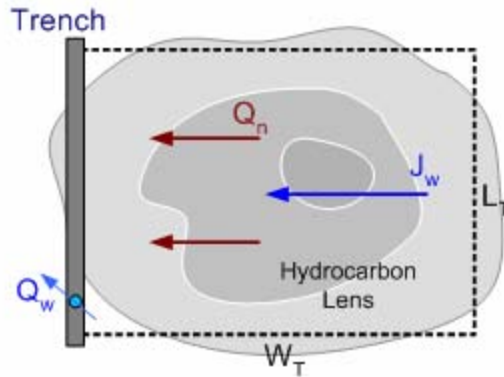


Figure 1.3—Simple Trench System for LNAPL Recovery

### 1.3 OVERVIEW

The models for well and trench recovery systems provide estimates of the recovery volume and rate as a function of time. The mathematical models on which these estimates are based use a simple representation of the LNAPL layer effective saturation and transmissibility. The representation is consistent with the actual formation distributions of LNAPL saturation and relative permeability under conditions of vertical equilibrium, and within the modeling framework, balance of LNAPL volume (continuity) is maintained between the recovered volume and formation LNAPL volume within the well radius of capture or lens rectangular area. Section 2 discusses the effects of capillarity on LNAPL in porous media and the relationship between monitoring well LNAPL thickness and formation LNAPL saturation distribution. The quantity of LNAPL is characterized through functions representing the LNAPL specific volume (integral of the LNAPL volumetric content over the lens thickness) and recoverable specific volume, as a function of monitoring well LNAPL thickness. A key to model simplicity is representation of these relationships through piecewise linear functions.

Section 3 discusses LNAPL relative permeability as a function of multiphase saturation. Both the Burdine (1953) and Mualem (1976) models are used. When combined with the soil hydraulic conductivity, vertical integration of the LNAPL relative permeability distribution is used to characterize lateral movement through the resulting transmissibility function. LNAPL transmissibility is also represented as a piecewise linear function of monitoring well LNAPL thickness.

The mathematical models for predicting free-product recovery are developed in Section 4. These models are based on the free-product thickness that one would observe in a monitoring well in good communication with the formation fluids (water, LNAPL, air). The rate equations for single- and dual-pump wells, vacuum-enhanced wells, skimmer wells, and trench recovery systems depend on the monitoring well LNAPL thickness and on the discharge of formation fluids (water or air). The principle of continuity is applied to predict how the monitoring well LNAPL thickness (and recovery rate) varies as a function of time.

## 2 LNAPL DISTRIBUTION

The purpose of this section is to provide background information on LNAPL behavior in the subsurface environment. This background information is necessary for understanding the distribution of LNAPL liquids under conditions of vertical equilibrium. It includes the effects of capillary forces on the distribution of immiscible fluids in porous media and methods for predicting the formation LNAPL saturation distribution as a function of monitoring well LNAPL thickness. Representation of LNAPL residual saturation is also discussed. Additional information on the effects of capillarity on the behavior of multiphase fluids in porous media may be found in Bear (1972), Corey (1986), and Dullien (1992).

### 2.1 CAPILLARITY IN POROUS MEDIA

#### 2.1.1 Surface Tension, Wettability and Capillary Pressure

When the pore space of a porous medium is occupied by two or more immiscible fluids, the interface separating fluid phases is the most significant feature. Molecules near this interface have greater energy than molecules within the bulk phase, and the excess interfacial energy makes the interface act as a membrane under tension; the total energy in the system is minimized through minimizing the interfacial area (Hillel, 1980). The source of the interfacial energy (or surface tension) is associated with the attractive forces that exist between molecules in the liquid phase. For molecule *A* within the bulk liquid phase- $\beta$  shown in Figure 2.1, it is attracted equally by neighboring molecules on all sides, resulting in no net force on the molecule associated with molecular attraction. Now consider the molecule at location *B* shown in this figure. It is attracted by neighboring molecules within the bulk phase but not by those in the phase- $\alpha$  [if molecules in phase- $\alpha$  also attracted the molecule from phase- $\beta$ , then the interface would not exist and the phases would be miscible]. There is a net force on the molecule located at *B*. In order for molecules at locations *A* and *B* to change places, the molecule from *A* would have to move against this force field, thus gaining energy. Likewise, the molecule from *B* would move in the direction of the net force, losing energy. Thus molecules near the interface must have greater energy than molecules within the bulk phase. This interfacial energy (per unit area,  $\text{erg/cm}^2$ ) is the same as the surface tension ( $\text{dyne/cm}$ ), and results in capillary phenomena trying to minimize the interfacial area (minimize the free energy of the system at equilibrium).

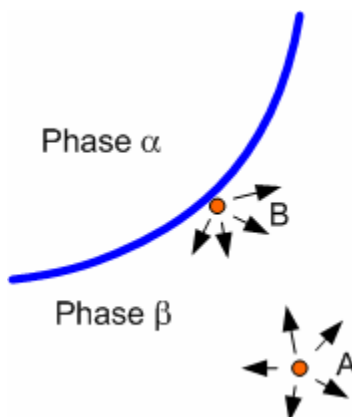


Figure 2.1—Interfacial energy associated with molecular attraction in the liquid phase

Along lines of contact of the interface with a solid phase, the interface will make a contact angle,  $\theta_c$ . The phase with the smaller contact angle preferentially covers the surface, and is called the wetting phase. The contact angle is the angle measure between the solid surface and the interface through the wetting phase, as shown in Figure 2.2. For usual field conditions of interest in environmental investigations, the *wettability* sequence mineral based soil is water  $\rightarrow$  NAPL  $\rightarrow$  air, with water being the most wetting phase for mineral porous media.

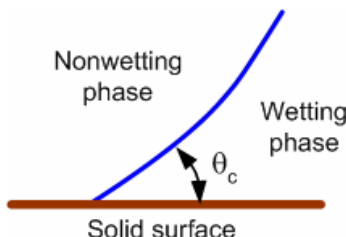


Figure 2.2—Contact angle and wettability

If the interface separating two fluid phases is curved, then there will be a pressure difference across the interface between the phases on either side. This pressure difference is called the *capillary pressure*, and it depends on the interfacial energy (surface tension), contact angle, and mean radius of curvature. The capillary pressure is the excess pressure in the nonwetting phase over the wetting phase, and it may be calculated using the equation of Young (1805) and Laplace (1806) as follows (Adamson, 1982):

$$p_c = \frac{2\sigma \cos(\theta_c)}{\bar{r}} \quad (2.1)$$

In equation (2.1),  $p_c$  is the capillary pressure,  $\sigma$  is the surface tension (interfacial energy), and  $\bar{r}$  is the mean radius of curvature of the interface. In a water-wet porous medium, excess pressure must be applied to the nonwetting phase (air or NAPL) to displace water from the medium, and the capillary pressure is positive. It is assumed that the radius of the pore containing the interface between wetting and nonwetting fluid is the same as the mean radius of curvature.

### 2.1.2 Capillary Pressure Curves

An important characteristic of a porous medium is the relationship between the capillary pressure and wetting fluid saturation (Hillel, 1980). This characteristic is called the *capillary pressure curve* (and it is so important, it is often simply called the “characteristic curve” for the soil). Increases in capillary pressure will force the interfaces between the nonwetting and wetting phase into smaller pore spaces (equation 2-1), and result in a corresponding increase in nonwetting phase saturation and decrease in wetting phase saturation. Likewise, decreases in capillary pressure will allow the interface to move into larger pore spaces, with an increase in wetting phase saturation and decrease in nonwetting phase saturation. Because of the complex system of pore spaces, the sequence upon drainage of pore space is not the same as that upon re-filling, and the capillary pressure curve shows *hysteresis*. This means that the relationship between capillary pressure and saturation is not a single function, but will also depend on the wetting and drainage history of the soil.

The capillary pressure curve is usually measured by starting with a soil that is fully saturated with wetting phase fluid. A nonwetting fluid is introduced at increasing capillary pressures. Time is provided for the fluids to equilibrate within the pore space, and the resulting saturation values are recorded. The capillary pressure is increased until no further reduction in wetting phase saturation is measured. The end-point value is the *wetting-phase residual saturation*,  $S_{wr}$ , and represents the wetting phase fluid that is held tightly at grain contacts and as fluid skins, so that the wetting phase is no longer continuous for flow. The resulting capillary pressure versus saturation curve is called the *drainage curve*. It provides a measure of initial displacement of wetting phase by nonwetting phase. The drainage curve is usually used to characterize the soil.

If the experiment described in the preceding paragraph is continued, with the capillary pressure being lowered starting with wetting-phase residual saturation, then the resulting saturation versus capillary pressure values follow the *imbibition curve*. When the capillary pressure is lowered to zero, the soil will not be fully saturated with the wetting phase fluid. This end-point nonwetting phase saturation is sometimes called the *nonwetting-phase residual saturation*,  $S_{Nwr}$  (though this concept requires further discussion for practical field applications, see below). Figure 2.3 shows a graphical representation of the experiment that has been described. Both the primary drainage and wetting curves are shown. If the drainage-imbibition cycle is stopped and reversed before the residual endpoints are reached, then a *scanning curve* results. Two such curves are also shown in Figure 2.3.

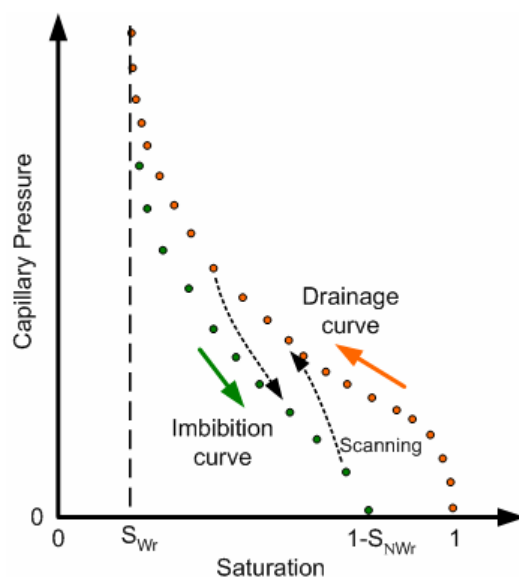


Figure 2.3—Soil capillary pressure curve showing primary drainage, imbibition, and scanning characteristic curves

### 2.1.3 Residual LNAPL Saturation

The nonwetting phase residual saturation shown in Figure 2.3 is a reproducible measure of the capacity of a porous medium to retain nonwetting fluid during re-filling with the wetting phase for a two-phase fluid system. However, such values have little relevance to issues associated with LNAPL in the groundwater environment (Adamski et al., 2003). Typical LNAPL releases result in LNAPL-water capillary pressures which are very much smaller than those required to

produce irreducible water saturations along the primary drainage curve. Most often, maximum LNAPL saturation values observed in the field are less than LNAPL residual values suggested using the experimental procedure suggested by Figure 2.3. Thus many of the literature-reported tabulated values of residual LNAPL saturation are of limited use in environmental remediation applications. For example, an often cited reference is Mercer and Cohen (1990) who report residual LNAPL saturation values ranging from 0.15 to 0.50 for the saturated zone, and 0.10 to 0.20 for the vadose zone. These values are much larger than the maximum LNAPL saturation values measured at industrial facilities with appreciable LNAPL contamination issues (Mark Adamski, BP America, personnel communication, 2004). To be useful, estimates of LNAPL residual saturation must consider the nature of the LNAPL release and the maximum LNAPL saturation values that exist under field conditions.

A typical field situation of an LNAPL release is outlined in Figure 2.4. The location is assumed to be near the water table, and the porous medium is initially saturated with water. As released LNAPL accumulates near the water table, it will develop a pressure greater than that of the neighboring groundwater (positive capillary pressure) and displace water from the medium following the drainage curve. Point A in Figure 2.4 corresponds to the maximum capillary pressure developed by the LNAPL release and results in an ‘initial’ LNAPL saturation  $S_{ni} = 1 - S_{wi}$ . Here, the term “initial” refers to the beginning of the recovery period where water displaces LNAPL from the medium, with capillary pressure-saturation following a scanning curve. During LNAPL recovery, at point B in the figure, the capillary pressure has been reduced to zero and LNAPL will no longer move into a recovery well due to a capillary pressure driving force. The remaining LNAPL saturation, designated  $S_{nr}$ , cannot be recovered using conventional LNAPL hydraulic recovery technologies. The fraction  $S_{nr}$  represents the LNAPL remaining trapped within the formation.

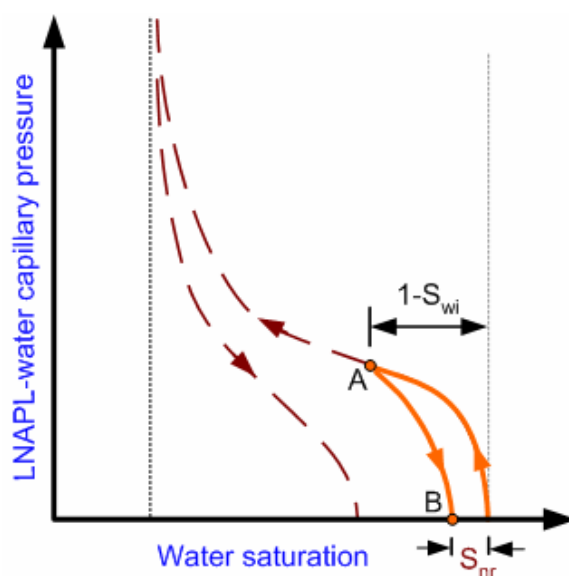


Figure 2.4—LNAPL residual saturation under normal field conditions

While limited theory exists to predict residual LNAPL saturation values,  $S_{nr}$ , from initial saturation values  $(1 - S_{wi}) = S_{ni}$ , there is sufficient empirical data to develop useful predictive models. Data from laboratory column experiments, shown in Figure 2.5, suggests that residual