

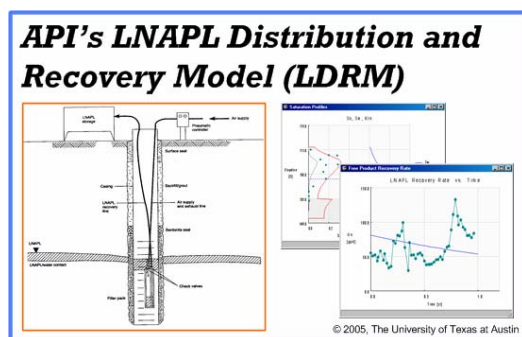


LNAPL Distribution and Recovery Model (LDRM)

Volume 2: User and Parameter Selection Guide

Regulatory and Scientific Affairs Department

API PUBLICATION 4760
JANUARY 2007



Data Input

Thickness, Elevations, Vertical gradient	
Maximum Monitoring Well LNAPL Thickness [ft]	5.000
Ground Surface Elevation [ft]	25.000
Water table Elevation [ft]	22.000
Water Vertical gradient (+ for upward)	0.000
Fluid Characteristics	
LNAPL density [gm/cc]	0.800
LNAPL viscosity [cp]	2.000
Air/Water surface tension [dyne/cm]	65.000
Air/LNAPL surface tension [dyne/cm]	25.000
LNAPL/Water surface tension [dyne/cm]	15.000
Relative Permeability Model (Burdine is default)	
Use Mualem Model for Layer	☐ Layer 1
Soil Characteristics	
Porosity	0.400
Hydraulic Conductivity [ft/d]	5.000
Van Genuchten "N"	3.500
Van Genuchten "a" [ft ⁻¹]	2.000
Irreducible water saturation	0.250
Residual LNAPL saturation	0.100
Residual LNAPL Factor	0.300

OK Cancel

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PREFACE

This manuscript documents use 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*. This manuscript is Volume 2 of a two volume series providing background and user information for LDRM. Guidance on use of the model is provided, along with information to help in parameter selection. The appendix presents results from an independent analysis of model performance. The API LDRM software can be downloaded from API's website at: 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	USER GUIDE
2.1	Workspace Setup 6
2.2	Starting the Application..... 7
2.3	Data Input Window 9
2.4	Menu Items 10
2.4.1	Add Field Data 13
2.4.2	LNAPL Recovery..... 15
2.4.3	Graphs Output..... 17
2.4.4	LNAPL Residual Saturation Models and Residual F-Factor Options 24
2.4.5	Piecewise Linear Model Breakpoint Options 25
2.4.6	Smear Correction Option 27
2.5	Model Output Options..... 29
2.5.1	Screen Output to the Main Application Window 29
2.5.2	File Output from LDRM Application 30
3	PARAMETER SELECTION AND PROBLEM SOLVING GUIDE 32
3.1	Objectives and Overview..... 32
3.2	Oil Recovery Experiences: Oilfield Production versus LNAPL Recovery 33
3.3	Parameter Limitations..... 34
3.4	Model Conceptualization 36
3.5	Multiphase Parameter Selection 38
3.5.1	Background to Multiphase Parameter Databases 38
3.5.2	Introduction to the API LNAPL Parameters Database..... 39
3.6	Example Problems 41
3.6.1	Problem #1: Simple Skimming Recovery Evaluation..... 43
3.6.1.1	Parameter Selection 43
3.6.1.2	Example Problem #1 Execution 44
3.6.2	Problem #2: Optimizing Remedial Options..... 49
3.6.2.1	Parameter Selection 49
3.6.3	Problem #3: Parameter Bracketing Problem 53
3.6.3.1	Parameter Selection Using the API LNAPL Parameter Database... 54
3.6.3.2	Example Problem #3: Execution 59
3.6.3.3	Problem #3: Conclusion 64
3.6.4	Problem #4: Case Study: LNAPL Recovery in Glacial Outwash Sands (Adapted from API Publication #4715)..... 66
3.6.4.1	Problem Overview 66
3.6.4.2	Data Summary..... 67
3.6.4.3	Model Conceptualization Summary..... 68
3.6.4.4	Example Problem #4 Execution 69
3.6.4.5	Example Problem #4 Conclusions 76
4	REFERENCES..... 77
APPENDIX A	REVIEW OF THE LNAPL DISTRIBUTION & RECOVERY MODEL MATHEMATICAL VERIFICATION, CODE FIXES, & SENSITIVITY..... 79

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 (Modified from Lefebvre, 2000)	3
1.3 Simple Trench System for LNAPL Recovery	4
2.1 Example Setup Folder Showing Project Workspace	6
2.2 API LDRM Logo	7
2.3 Terms and Conditions Window	7
2.4 Initiation Message Box	8
2.5 Standard Open File Dialog	8
2.6 Project Setup Dialog that Appears Only When “New” Simulation is Selected	9
2.7 Data Input Window for a 1 Layer Model	10
2.8 Standard File Menu Items	10
2.9 Data Menu Items	11
2.10 Recovery Menu Items	11
2.11 Graphs Menu Items	12
2.12 Options Menu Items	12
2.13 Help Menu Items	13
2.14 Input Field Data Options Message Window	14
2.15 Data Transfer Control Message Box	14
2.16 Application Folder with “field_data.csv” Spreadsheet	14
2.17 “field_data.csv” Spreadsheet with Data	15
2.18 Well Recovery Systems Data Entry Window	16
2.19 Interceptor Trench Data Entry Window	17
2.20 Data Input Window for Two-Layer Soil	18
2.21 Saturation Profiles Graph Output	18
2.22 Specific Volume/Transmissibility Graph Output	19
2.23 Free Product Thickness Graph Output	20
2.24 Drawdown/Buildup Graph Output	21
2.25 LNAPL Recovery Rate Graph Output	22
2.26 LNAPL Recovery Volume Graph Output	23
2.27 LNAPL Thickness Dialog Box for Later-Time Distributions	23
2.28 LNAPL Distribution Graph Output	24
2.29 Three Different LNAPL Residual Saturation Model Representations	25
2.30 LNAPL Distribution Output Graph with Variable LNAPL Residual Saturation	25
2.31 Pick Break Points: $bn1$, $bn2$ Message Box	26
2.32 Piecewise Linear Model Representation with Alternative Breakpoints (Compare with Figure 2.22)	26
2.33 Initial LNAPL Saturation Distribution for Example with Smearing Option Selected	27
2.34 New LNAPL Layer Saturation Distribution Following Drawdown of the Water Table Using the Smear Correction Option	28
2.35 Summary Output Variables Written to the Main Window of the LDRM Application	30
2.36 Leading Part of the LDRM Simulation Output File	31
3.1 Simple Conceptual Site Model	37
3.2 Complex Cross-Section Showing Heterogeneity (Based on Combined Coring & Geophysics), Along with the Water Table Elevation Range and Site Investigation Locations	37
3.3 Startup Box, with Selection Shown	43
3.4 Startup Box, with Selection Shown	44

3.5	Input Parameters Controlling the LNAPL Distribution at Vertical Equilibrium.....	45
3.6	Results chart of Specific Volumes/Transmissibility for the Given Problem. Recall that D_n is the specific volume, and R_n is the recoverable volume. T_n is the LNAPL transmissibility. Paralleling that is a linearized “fit” that can be tuned by the user as discussed in the text.....	46
3.7	Input Parameters for Skimming Recovery Portion of Problem #1	47
3.8	Summary Output for Skimming Recovery Using the Constant Residual Saturation Option (Original Problem Definition)	48
3.9	Summary Output for the F-factor Residual Saturation Conditions, with Other Parameters Being the Basic Skimming Simulation.....	49
3.10	Data Input Screen for a Recovery Time of 2 Years	51
3.11	Results for Vacuum-Assisted Skimming	52
3.12	Site-specific Grain Size Data—Sample 1	55
3.13	Site-specific Grain Size Data—Sample 2	55
3.14	Capillary Fit Parameters for Samples with Soil Description.....	56
3.15	Capillary Fit Parameters for Given Conductivity Range	58
3.16	Grain Size Curves, Site Samples versus Database Samples	59
3.17	Initial Data Input Screen for Example Problem #3	60
3.18	Saturation Profiles for Data Input in Figure 3.17.....	61
3.19	Saturation Profile for $\alpha = 3.5 \times 10^{-2}$ 1/cm and $N = 2.25$	61
3.20	Saturation Profile for $\alpha = 7.8 \times 10^{-2}$ 1/cm and $N = 1.50$	62
3.21	Data Input Screen for Example Problem #4	69
3.22	Saturation Profile for Example Problem #4 Input Data	70
3.23	Recovery Input Data for Example Problem #4	71
3.24	Drawdown/Buildup Screen for Example Problem #4.....	71
3.25	Data Input for Model with Two Layers	72
3.26	Drawdown/Buildup for 2-Layer Model.....	73
3.27	LNAPL Recovery Rate versus Time	74
3.28	LNAPL Recovery Volume versus Time.....	75

LIST OF TABLES

<u>Table</u>	<u>Page</u>
3.1 USDA Soil Types and Multiphase Parameters (from M.G. Schaap, U.S. Salinity Lab, 1999). Where: N is the number of samples; θ_r is the residual volumetric moisture content; θ_s is the saturated volumetric moisture content (total porosity); $\log(\alpha)$ is the log of the van Genuchten model α parameter; $\log(n)$ is the log of the van Genuchten model N parameter; and K_s is the log of the saturated hydraulic conductivity. Abbreviations: S = sand; C = clay; L = loam; Si = silt.....	39
3.2 Results of Initial Optimization Simulations.....	51
3.3 Results for Vacuum-Assisted Skimming	51
3.4 Results of the Smear Zone Correction Problem	52
3.5 Site-Specific Grain Size Data.....	55

EXECUTIVE SUMMARY

This document provides user and parameter selection guidance for application of the American Petroleum Institute LNAPL Distribution and Recovery Model (LDRM). This is Volume 2 of a two volume series; the first volume provides background information on distribution and recovery of petroleum hydrocarbon liquids in porous media, and is intended as an LNAPL primer. Section 1 of this volume discusses earlier releases of the API LNAPL Recovery Model and describes the new features of the current release of the model software application that is associated with this document series. Model scenarios (wells and trenches) are also described. Section 2 is a detailed guide to use of the LDRM software application. Workspace setup, program initiation, and data entry are described. The various menu items which provide the basic navigation tools through the application are discussed. Model options are described and model output using graphical screen output and text files are presented. Section 3 provides background information on model conceptualization, parameter selection (and limitations), and problem solving using the LDRM. Four example problem applications are presented which highlight model use, parameter estimation using the API LNAPL Parameters Database, and limitations of scenario-based models.

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 Publ 4682 describes two (Excel spreadsheet) models that may be used to characterize the subsurface distribution and mobility of liquid hydrocarbon (lighter-than-water nonaqueous phase liquids, LNAPL), 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 in API Publ 4682 are described 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 objective of the present manuscript is to provide necessary background and user information for application of scenario-based models describing LNAPL liquid recovery. Volume 1 of this two-volume series provides model background information including the effects of capillarity in porous media, distribution of LNAPL saturation under conditions of vertical equilibrium, potential movement of LNAPL liquid, and mathematical model formulation and solution. The model scope is similar to that presented in API Publ 4729, though the model formulation has been generalized and additional capabilities have been added. The present Volume 2 describes model implementation through a single executable program. This is a User Guide and includes information and guidance on parameter selection and model testing.

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.

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 ρ_n (see Section 2 of Volume 1).

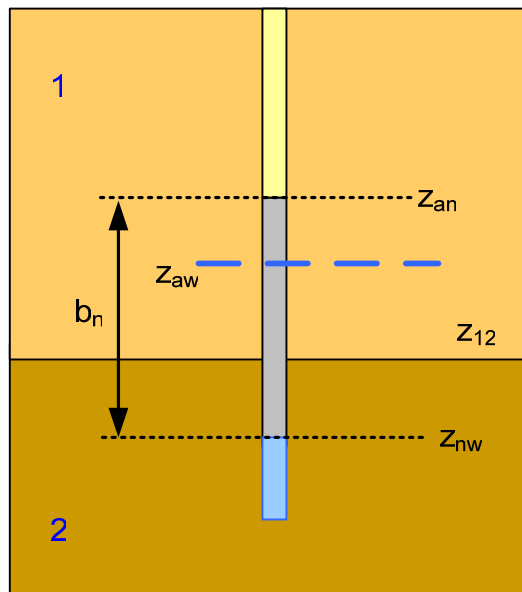


Figure 1.1—Monitoring Well LNAPL Thickness, b_n

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_w ; the van Genuchten parameters N and α ; and the irreducible water saturation, S_{wr} . Selection of residual LNAPL saturation values remains an elusive issue, and various options are described in Section 2.4.4. Fluid properties include the LNAPL density, ρ_n (it is assumed that the water density is 1 g/cm^3), and the water and LNAPL surface and interfacial tensions, σ_{aw} , σ_{an} , and σ_{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 is typically on the order of 30 – 40 feet) limits the radius of capture. For skimmer wells, the radius of capture is limited to a greater but unknown extent, which is probably on the order of 10 – 30 feet.

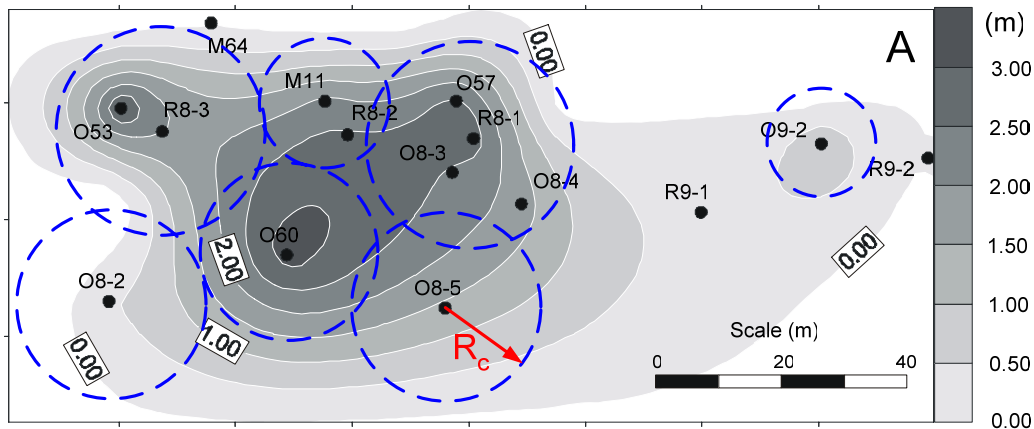


Figure 1.2—Recovery Well System with 7 Recovery Wells Showing the Radius of Capture.
Scale on Right Side Shows Measured LNAPL Thickness in Wells.
(Modified from Lefebvre, 2000)

The data required for analysis of recovery-well-system performance includes the radius of capture for the well, the LNAPL viscosity (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.

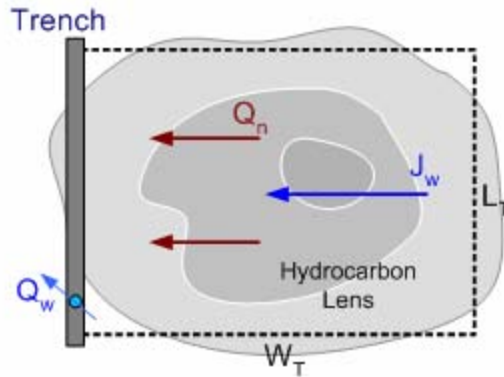


Figure 1.3—Simple Trench System for LNAPL Recovery

1.3 OVERVIEW

The new features included in this release of the API LDRM include the following:

- the model is a single, stand-alone executable application,
- one may select either US Customary or metric units,
- soil heterogeneity may be represented through use of 1, 2 or 3 soil layers,
- soil profile data may be represented either as elevation above a datum or as depth below the ground surface,
- the capability for simulating LNAPL smearing associated with water table drawdown has been added,
- three different representations for LNAPL residual saturation are available, and the user may change between representations during a modeling session,
- the effects of vertical hydraulic gradient through surface fine-grain soil layers on LNAPL distribution and recovery may be represented,
- either the Burdine or Mualem relative permeability model may be selected for individual soil layers,
- measured field data on LNAPL saturation, LNAPL thickness, LNAPL recovery volume, and LNAPL recovery rate may be added and displayed on model graphical output,
- model formulation through use of the LNAPL layer transmissibility function is both more rigorous and simpler than earlier model formulations,
- the user may more directly specify the breakpoints for the piecewise linear fit of the LNAPL transmissibility and specific volume functions,
- more extensive and useful model output capabilities have also been added.

Section 2 of this document provides detailed user information on application of LDRM. Model setup and data input are described. The user interacts with the application primarily through menu items that are selected on the main application window. These are described in Section 2.4. The method for adding field data is presented in Section 2.4.1, while the steps for simulating LNAPL recovery using wells or trenches are described in Section 2.4.2. Seven different graphical outputs are described in Section 2.4.3. Use of the different models for representing LNAPL residual saturation are discussed in Section 2.4.4, while selection of piecewise linear model breakpoints are described in Section 2.4.5. Section 2.4.6 discusses use of the smear correction option. Section 2.5 describes the model output.

Section 3 provides guidance for model conceptualization, parameter selection, and problem solving using the LDRM. Section 3.2 compares experience with oilfield production of hydrocarbon liquids with LNAPL recovery for environmental management. Section 3.3 discusses limitations that may be associated with LDRM input parameters. Section 3.4 discusses model conceptualization while Section 3.5 describes methods for parameter estimation when detailed site data is limited. Finally, Section 3.6 provides four example problems showing model application, methods for parameter estimation and bracketing, and an example where the scenario-based model might not be appropriate.

2 USER GUIDE

The purpose of this section is to provide information on use of the API LNAPL Distribution and Recovery Model (LDRM) and its various options. Model input and graphical and text output are described. It is shown how field data may be entered and displayed on graphical output for model testing and calibration. Various options are explained and demonstrated. The output file format is also shown.

2.1 WORKSPACE SETUP

The API LNAPL Distribution and Recovery Model (LDRM) consist of a single executable application that runs with the Windows [™] operating system. It is assumed that the user is familiar with Windows, menus, the mouse, and folders for storage of files. The user should create a folder for storage of work and copy the executable application (LDRM.exe) to a desired location within the file structure (such as the primary work folder). Any additional input/output/data files that are supplied with the application should also be copied into the work folder. Subfolders can be created for each individual project. When running LDRM, the default folder for opening active projects is the folder containing the application, while the default folder for saving output is the active folder from which the input file was opened. An example setup is shown in Figure 2.1.

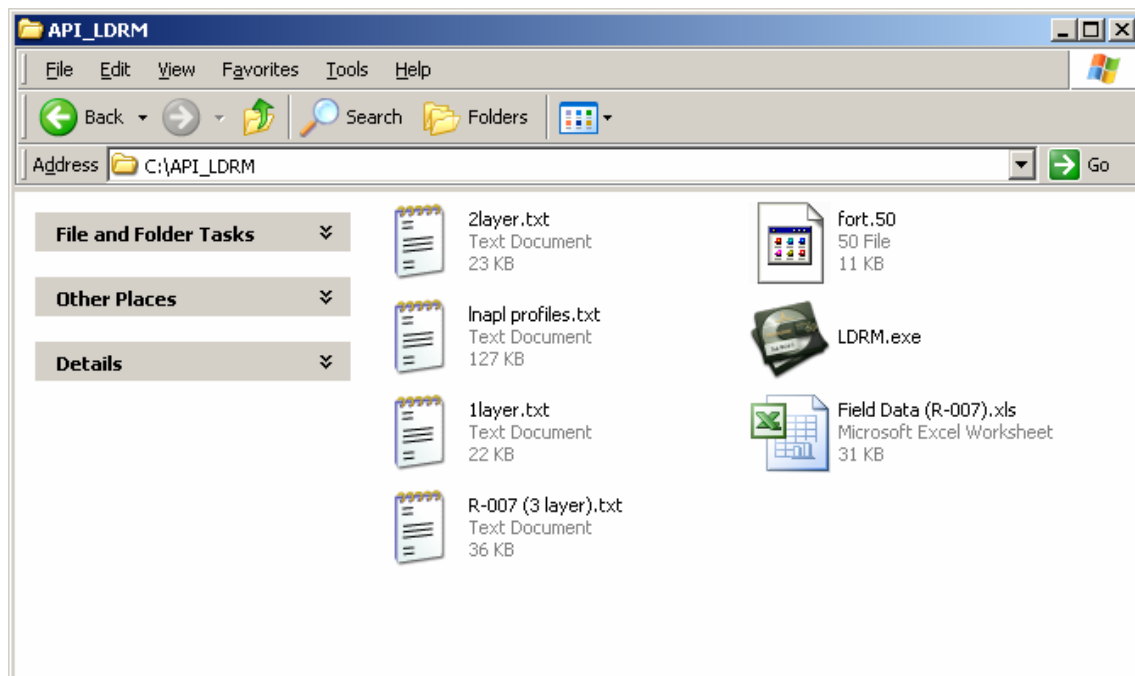


Figure 2.1—Example Setup Folder Showing Project Workspace

2.2 STARTING THE APPLICATION

Like all Windows applications, the LDRM model can be initiated by ‘clicking’ on the executable file icon (LDRM). The user is greeted briefly with the logo shown in Figure 2.2, and then is required to agree to Terms and Conditions of model use before the program is initiated, as shown in Figure 2.3.

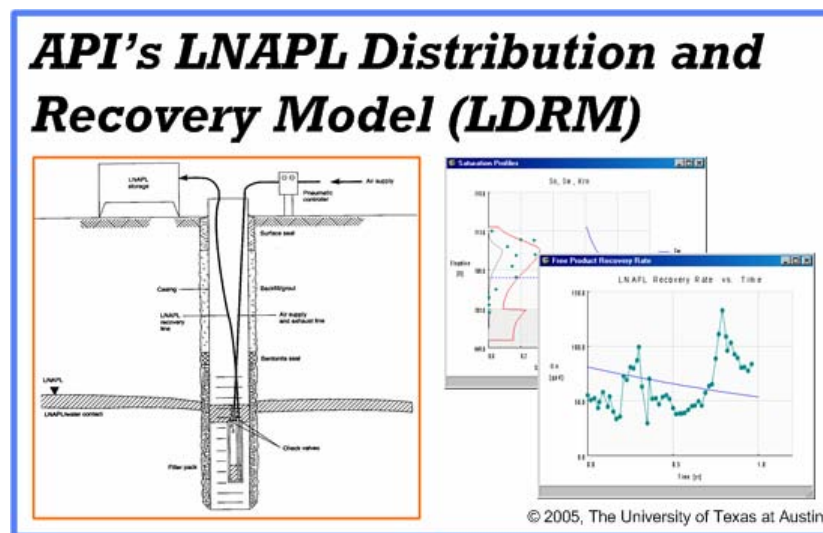


Figure 2.2—API LDRM Logo

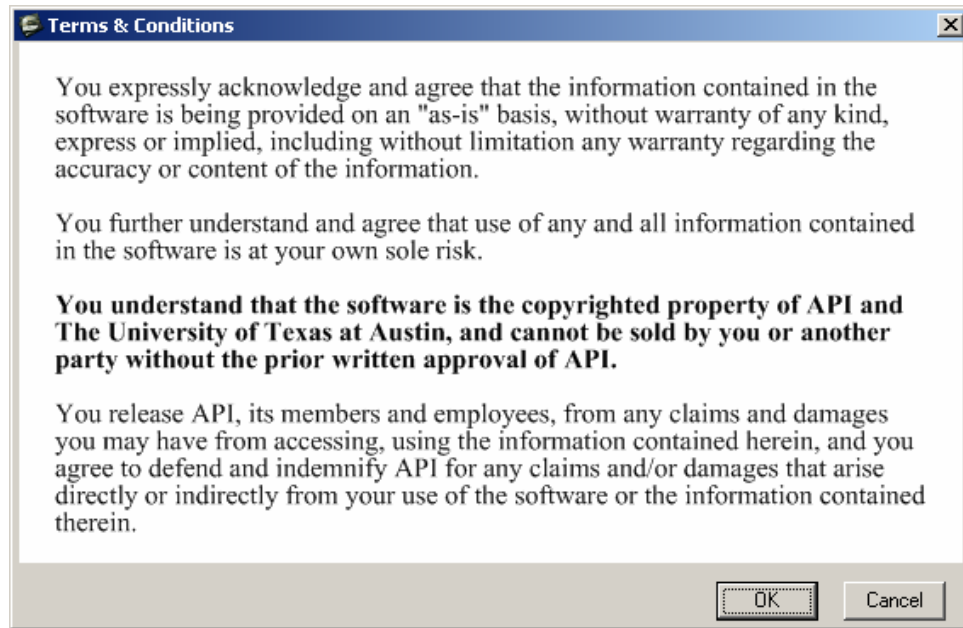


Figure 2.3—Terms and Conditions Window

Once the Terms and Conditions have been accepted (click on OK), the initiation message box shown in Figure 2.4 appears and provides the user with options on how to proceed. The user may open an existing simulation file, start a new simulation file, or exit the program. Select the appropriate item and click OK. If the user selection the Open option, then the standard Open File dialog appears (as shown in Figure 2.5), and one may navigate the file system and select the desired simulation file to open. Only files with the “*.txt” extension may be used as input files. No options are provided for opening input files with another extension. Thus input files are standard ASCII text files and can be read and used by other text processing software, allowing the experienced user to edit input files without running the application.

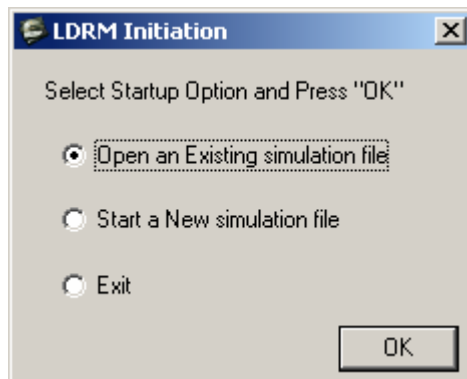


Figure 2.4—Initiation Message Box

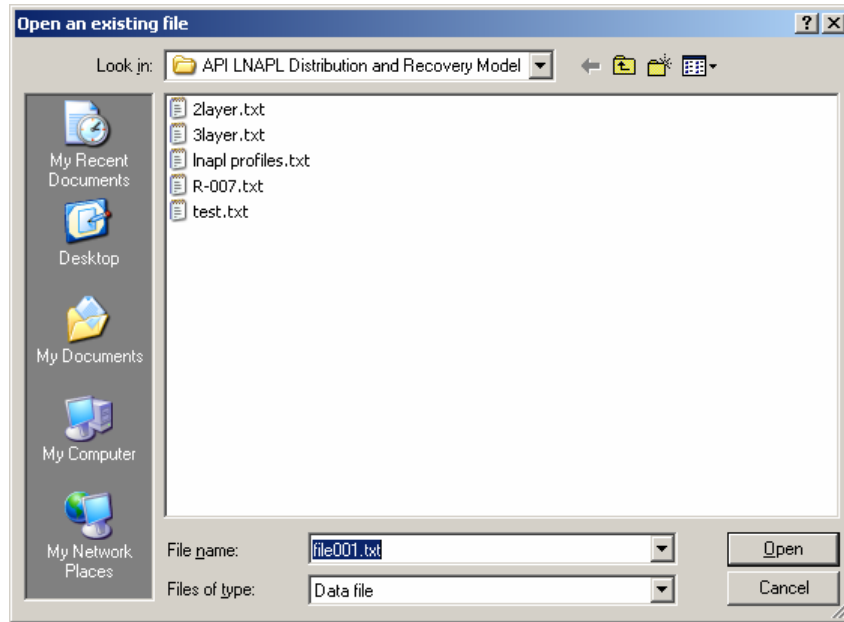


Figure 2.5—Standard Open File Dialog

If in the initiation message box (Figure 2.4) the user selects to start a new simulation file, then the Project Setup dialog appears, as shown in Figure 2.6. Basic choices for a given simulation can only be made through this dialog, and cannot be changed later (the user would have to start a new simulation). These choices include selection of units (English or Metric), number of layers (1, 2, or 3), and elevation representation (elevation above a selected datum or depth below ground surface, BGS). Other options that are selected through this dialog are whether to use a drawdown correction for LNAPL smearing and the LNAPL residual saturation representation. Both of these selections can be changed at a later time, and both are discussed in detail below (Smear Correction in Section 2.4.6; LNAPL Residual Saturation in Section 2.4.4). Click OK to continue.

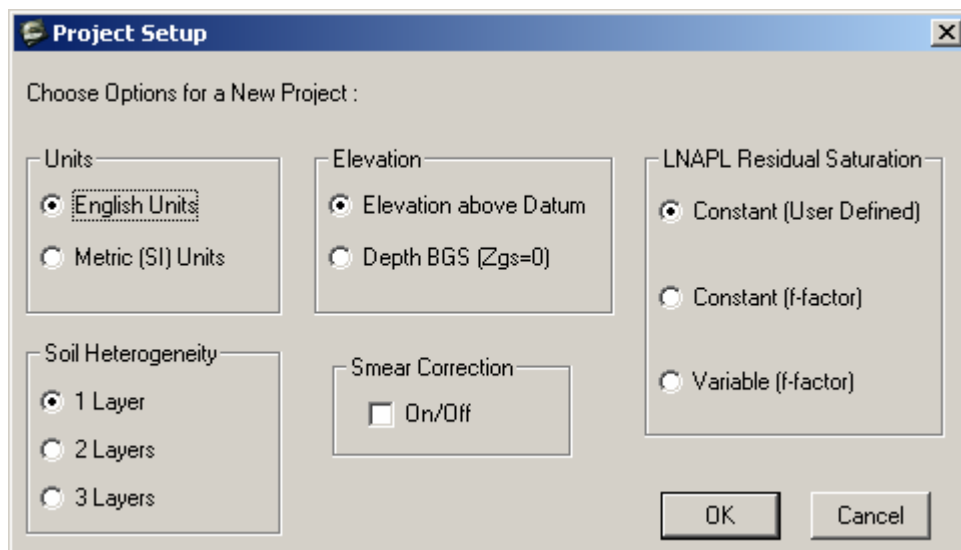


Figure 2.6—Project Setup Dialog that Appears Only When “New” Simulation is Selected

2.3 DATA INPUT WINDOW

Once a selection has been made to Open an existing simulation or start a new simulation, the Data Input window appears, such as shown in Figure 2.7. The appearance of this window differs depending on the selected options, in particular Soil Heterogeneity (number of layers) and Elevation representation. Figure 2.7 corresponds to English units, 1 layer, and Elevation above Datum (options shown in Figure 2.6). The Data Input windows for 2 layer and 3 layer simulations are shown in Figures 2.20 and 2.38 below. The basic data requirements should be straightforward, based on the background information presented in Volume 1. A couple of items are of note:

- If a vertical gradient is specified, then it applies only for the uppermost layer. There is no capability for specifying a vertical gradient in a lower layer.
- The Burdine (default) or Mualem relative permeability model may be selected for any layer, and a combination of models may be specified for a multiple-layer soil profile.
- Required Residual LNAPL Saturation and Residual LNAPL f-factor data requirements will vary with selected representation model, and these entry boxes may appear with “Constant” or “Variable” for other options.

Data Input

Thickness, Elevations, Vertical gradient

Maximum Monitoring Well LNAPL Thickness [ft] = 5.000

Ground Surface Elevation [ft] = 25.000

Water table Elevation [ft] = 22.000

Water Vertical gradient (+ for upward) = 0.000

Fluid Characteristics

LNAPL density [gm/cc] = 0.800

LNAPL viscosity [cp] = 2.000

Air/Water surface tension [dyne/cm] = 65.000

Air/LNAPL surface tension [dyne/cm] = 25.000

LNAPL/Water surface tension [dyne/cm] = 15.000

Soil Characteristics

Porosity = 0.400

Hydraulic Conductivity [ft/d] = 5.000

Van Genuchten "N" = 3.500

Van Genuchten "a" [ft-1] = 2.000

Irreducible water saturation = 0.250

Residual LNAPL saturation = 0.100

Residual LNAPL f-factor = 0.300

Relative Permeability Model (Burdine is default)

Use Mualem Model for Layer ☐ Layer 1

OK Cancel

Figure 2.7—Data Input Window for a 1 Layer Model

2.4 MENU ITEMS

Access to most model options is achieved through use of the main menu and selection of menu items. The File menu (Figure 2.8) contains standard items for control of files, including creation

of a New simulation file, Open an existing simulation file, file Save, and Exit the application. The user is prompted to save an existing file if Exit is selected.

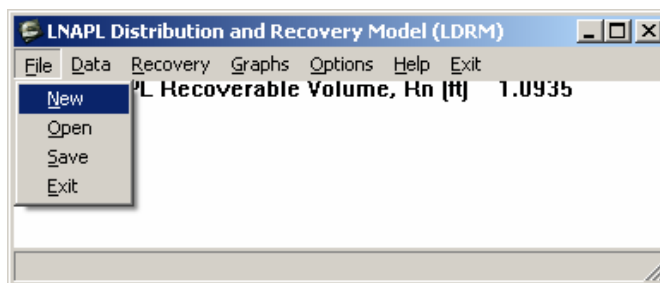


Figure 2.8—Standard File Menu Items

The Data menu contains three items, as shown in Figure 2.9. The first of these is to call the Edit the basic input data for the simulation, and the standard Data Input window (Figure 2.7) is opened. One may change input parameters during a simulation. The second menu item allows the user to Add field data to the graphs that are generated by the application. Such input field data is also added to the output data file. The detailed procedure for adding field data is presented in Section 2.4.1. The third item allows the user to Remove all field data from output graphs and from the output file.

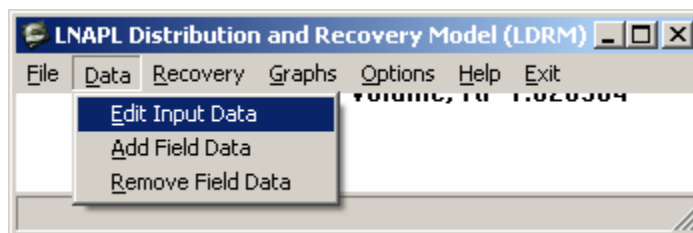


Figure 2.9—Data Menu Items

The Recovery menu (Figure 2.10) allows the user to select the LNAPL recovery technology and its characteristics for use during the simulation. Wells includes single and dual pump wells, vacuum-enhanced wells, and skimmer wells. If the well water discharge and vacuum are specified as 0, then the model assumes that a skimmer well is being used. A trench may also be specified. The model input for wells or a trench are discussed in Section 2.4.2.

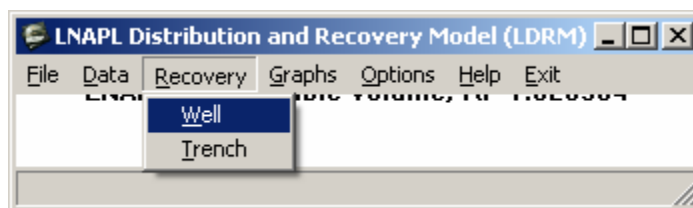


Figure 2.10—Recovery Menu Items

The Graphs menu (shown in Figure 2.11) has the available graphs listed as items. A total of 7 different graphs are available. However, graphs providing output on LNAPL recovery are active only after the recovery option (Recovery menu item) has been selected and executed. The menu shown in Figure 2.11 has the Saturation Profiles, Specific Volume, and LNAPL Distribution

graphs active. The Thickness, Drawdown, Rate and Volume graphs become active once the recovery has been calculated. The specific graph output is described in detail in Section 2.4.3.

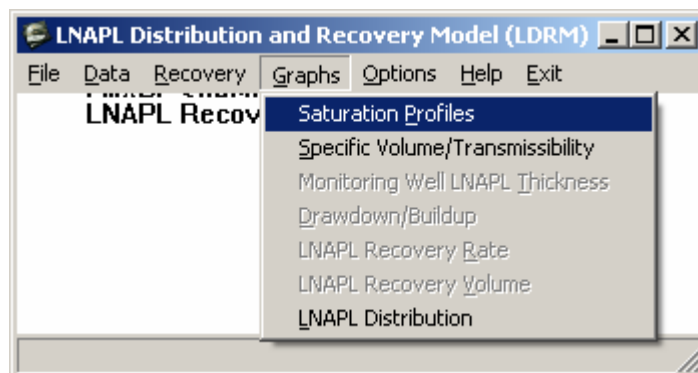


Figure 2.11—Graphs Menu Items

The Options menu (shown in Figure 2.12) provides access to two options that control calculation of important model features. The first option allows the user to change between different models for specifying the residual LNAPL saturation. These different models are explained in detail in Section 2.4.4. The second option, Pick Break Points: *bn1*, *bn2* (Alt-b), allows the user to specify the piecewise linear segment breakpoint values of LNAPL thickness for the LNAPL specific storage and transmissibility functions.

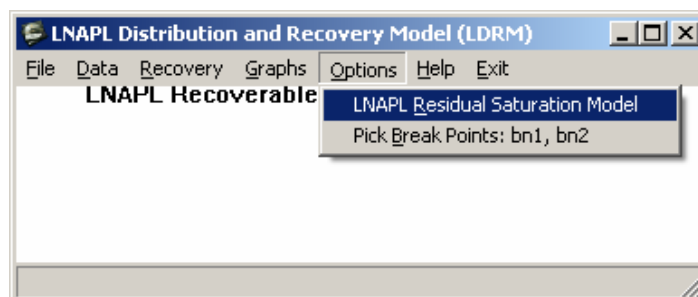


Figure 2.12—Options Menu Items

The Help menu (shown in Figure 2.13) provides limited help and model information for the user. The Soil Parameters item refers to API documents and programs that are useful in selection of model parameters relating to soil characteristics. The Rel. Perm. Models item is a warning that for a specific soil, the van Genuchten soil characteristic parameters α and N will differ with selection of the Burdine or Mualem relative permeability models. The other two items provide information on model development and acknowledgements for model support.

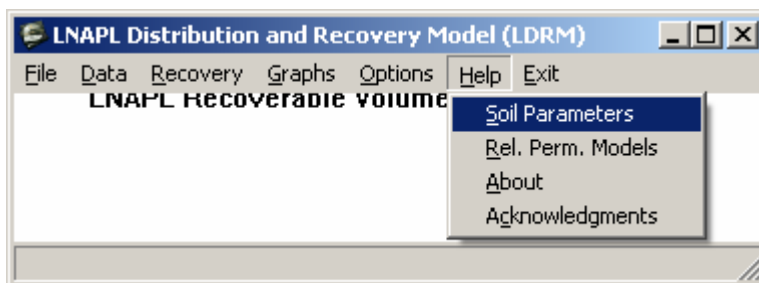


Figure 2.13—Help Menu Items

The Exit menu provides direct access to model termination with a message box that inquires whether the user wishes to save current work.

2.4.1 Add Field Data

The following field data values may be entered and displayed on the graphical output from model simulations:

- LNAPL saturation (S_n),
- LNAPL monitoring well thickness (b_n),
- LNAPL cumulative recovery volume (V_n), and
- LNAPL recovery rate (Q_n).

Field data is entered through use of a spreadsheet. The spreadsheet is automatically formatted for input. Field data is copied from another spreadsheet or text (ASCII) file. Upon saving and closing the spreadsheet, the entered data is copied to the simulation model and will be displayed when a figure is opened. All data is saved on the output file from a simulation.

To add field data select the Data → Add Field Data (Alt-d → Alt-a) item from the menu. The options message box shown in Figure 2.14 will be displayed. Select the data-type for entry and click OK. Two things then happen. First, the dialog shown in Figure 2.15 is displayed. Do not click OK on this dialog until after the data has been entered and saved. The second thing that happens is that a spreadsheet file *field_data.csv* is created in the folder from which the application was launched (not the data folder if this is different), as shown in Figure 2.16. Open this spreadsheet and enter the data (which may be copied and pasted from another data spreadsheet). Once the data are entered, as shown in Figure 2.17, save *field_data.csv*, click Yes on the “features” message box, close *field_data.csv*, and click No on the “save” message box. One may now click OK on the dialog shown in Figure 2.15, and the data is copied to the simulation application file.

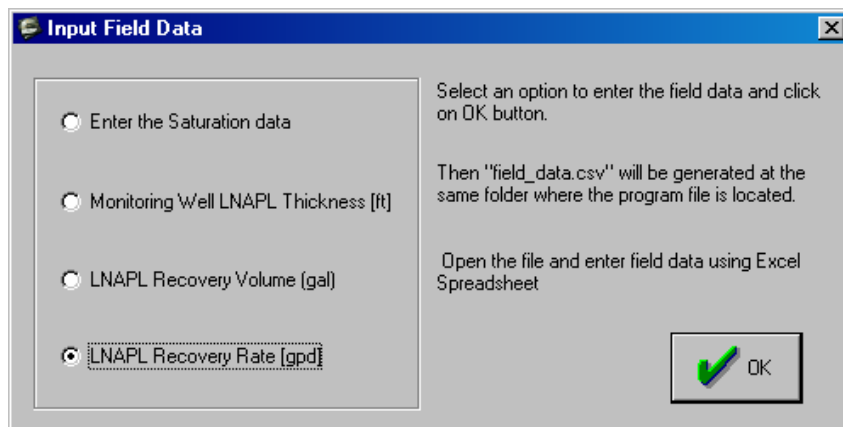


Figure 2.14—Input Field Data Options Message Window

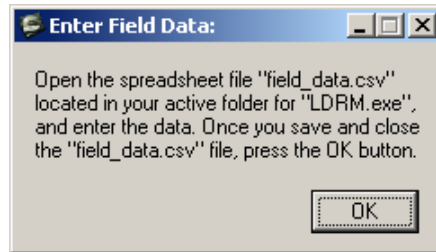


Figure 2.15—Data Transfer Control Message Box

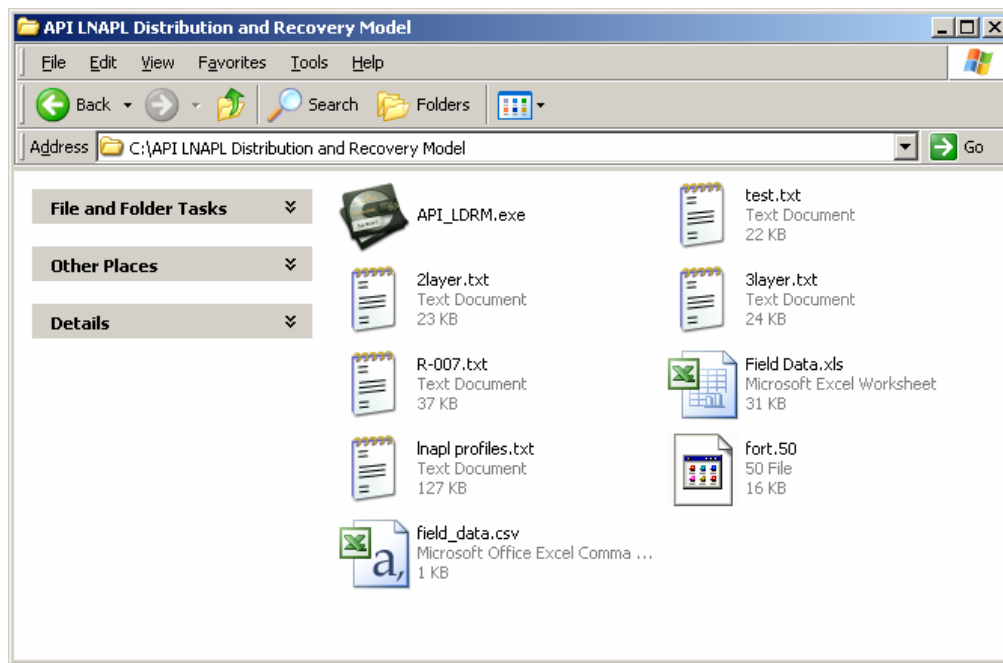


Figure 2.16—Application Folder with “field_data.csv” Spreadsheet

	A	B	C	D	E
1	Field-Measured LNAPL Recovery Rate				
2					
3	Time[yr]	Qn[gpd]			
4	0.000	57.8			
5	0.019	61.0			
6	0.036	75.1			
7	0.068	83.7			
8	0.090	101.9			
9	0.112	101.8			
10	0.132	100.6			
11	0.134	100.0			

Figure 2.17—"field_data.csv" Spreadsheet with Data

2.4.2 LNAPL Recovery

Once the basic input data (Section 2.3) has been entered, the user may select a recovery technology using the menu Recovery (Alt-r) item. Two options are available, as shown in Figure 2.10. If the user selects the Well (Alt-w) item, then the *Well Recovery Systems* data entry window shown in Figure 2.18 is displayed. The following parameters may be entered.

Recovery time (T) – time duration for simulated recovery

Radius of Pumping Well (L) – production or suction well effective radius

Radius of Recovery (L) – radius of capture (see discussion in Section 4.1 of Volume 1) of groundwater-enhanced or skimmer well

Radius of Influence (L) – radial distance with significant water-table drawdown associated with groundwater production

Water production rate (L^3/T) – groundwater pumping discharge from single- or dual-pump well

Water saturated thickness (L) – effective aquifer thickness of active flow towards the groundwater pumping well. This may be approximated by the well screened interval below the water table

Suction Pressure (fraction of atmospheric pressure) – well-suction applied for vacuum-enhanced recovery. Entered as a positive number

Screen length (L) – length of the well screened interval above the water table

Air Radius of Capture (L) – effective radial distance of influence for air flow

Well Recovery Systems	
Water Enhanced system	
Water production rate [gpm] =	9.700
Water Saturated thickness [ft] =	30.000
Air Enhanced system	
(-)Suction Pressure [atm] =	0.000
Screen Length [ft] =	0.000
Air Radius of Capture [ft] =	0.000
OK Cancel	

Recovery time [yr] =	1.000
Radius of Pumping Well [ft] =	0.500
Radius of Recovery [ft] =	85.000
Radius of Influence [ft] =	200.000

Figure 2.18—Well Recovery Systems Data Entry Window

Discussion:

1. If both the *Water production rate* and the *Suction Pressure* are zero (0.0) then a skimmer well is assumed. Further, if the downward hydraulic gradient within the upper soil layer exceeds the critical value for LNAPL displacement (see Volume 1, Section 3.2.2), then only residual LNAPL is assumed to exist in the upper layer and the model for recovery of LNAPL beneath fine-grain zones using skimmer wells (see Volume 1, Section 3.3.6) is assumed.
2. When a recovery well has both groundwater production and vacuum enhancement, then the *Radius of Recovery* and *Air Radius of Capture* can differ, and the water table drawdown/buildup is calculated using superposition.
3. The default Air Radius of Capture is calculated using equation (3.49) from Volume 1, though the user can enter a different value that will be used in calculations.

If the user selects the Trench (Alt-t) item from the Recovery menu, then the *Interceptor Trenches* data entry window shown in Figure 2.19 is displayed. The following parameters may be entered.

Recovery time (T) – time duration for simulated recovery

Q_w (L^3/T) – groundwater production rate that is used to enhance the natural hydraulic gradient

J_w (-) – natural hydraulic gradient towards the trench

Trench length (L) – length of the trench or width of the LNAPL plume transverse to the hydraulic gradient, whichever is smallest

Lens width (L) – longitudinal extent of the LNAPL plume in the flow direction

Screen depth (L) – effective depth of the trench beneath the water table. This is used in conjunction with the *Trench length* and Q_w to determine the additional hydraulic gradient causing LNAPL migration to the trench (see equation 3.61 from Volume 1)

The screenshot shows the 'Interceptor Trenches' data entry window. It includes input fields for Recovery time [yr] (10.000), Q_w [gpm] (0.100), and J_w (0.001). Below these are dimensions: Trench length [ft] (75.000), Lens width [ft] (100.000), and Screen depth [ft] (5.000). A diagram on the right illustrates a trench (vertical line) intercepting a hydrocarbon lens (shaded area). Flow vectors Q_n (red), J_w (blue), and Q_w (blue) are shown. Dimensions L (lens width), L_T (trench length), and W_T (screen depth) are labeled. The window has 'OK' and 'Cancel' buttons at the bottom.

Figure 2.19—Interceptor Trench Data Entry Window

2.4.3 Graphs Output

As shown in Figure 2.11, seven different graphs may be displayed to summarize simulation model output. All data that are used to generate these graphs are written to the output file, so that graphical generation can be easily re-produced using alternative software. The first two and last graph are available once the basic input data has been entered (*Data Input* window, Section 2.3). The remaining four graphs require that a recovery technology be selected (menu Recovery item, Section 2.4.2). The content of these graphs is described as follows.

The first graph, *Saturation Profiles* (Alt-p), shows the vertical distribution of LNAPL saturation (red), LNAPL residual saturation (red-dashed), water saturation (blue), and LNAPL relative permeability (grey). An example profile corresponding to the *Data Input* window of Figure 2.20 is shown in Figure 2.21. This represents a two-layer heterogeneous system with a low permeability unit overlying a unit of higher permeability. The ground surface is located at an elevation of 25 feet above the datum, while the water table is at an elevation of 22 feet. The vertical facies transition occurs at an elevation of 20 feet (5 feet BGS). The heavy black line drawn along the right border of the figure shows the 5-foot LNAPL thickness in the well (extending from an elevation of 18 feet to 23 feet). The residual LNAPL saturation values are calculated using the residual f-factor (see equation 2.2, Volume 1) and results in different constant LNAPL residual saturation values for each layer. The maximum LNAPL saturation occurs immediately below the facies interface. The largest LNAPL saturation in the upper unit occurs at the elevation of the air-LNAPL interface in the well (elevation 23 feet). Because of capillary forces, the LNAPL saturation remains above residual even at the ground surface. The

LNAPL relative permeability is calculated using the LNAPL and water saturation, with the Mualem model for the upper layer and the Burdine model for the lower layer.

Data Input

Thickness, Elevations, Vertical gradient

Maximum Monitoring Well LNAPL Thickness [ft] = 5.000

Ground Surface Elevation [ft] = 25.000

Water table Elevation [ft] = 22.000

Elevation of Soil Faces Interface [ft] = 20.000

Water Vertical gradient (+ for upward) = -0.050

Fluid Characteristics

LNAPL density [gm/cc] = 0.800

LNAPL viscosity [cp] = 2.000

Air/Water surface tension [dyne/cm] = 65.000

Air/LNAPL surface tension [dyne/cm] = 25.000

LNAPL/Water interfacial tension [dyne/cm] = 15.000

Relative Permeability Model (Burdine is default)

Use Mualem Model for Layer ☒ Layer 1 ☐ Layer 2

Soil 1

Porosity = 0.400

Hydraulic conductivity [ft/d] = 0.200

Van Genuchten "N" = 1.300

Van Genuchten "a" [ft⁻¹] = 0.600

Irreducible water saturation = 0.500

Residual LNAPL saturation = 0.070

Residual LNAPL f-factor = 0.400

Soil 2

Porosity = 0.380

Hydraulic conductivity [ft/d] = 5.000

Van Genuchten "N" = 3.500

Van Genuchten "a" [ft⁻¹] = 2.000

Irreducible water saturation = 0.150

Residual LNAPL saturation = 0.185

Residual LNAPL f-factor = 0.250

OK Cancel

Figure 2.20—Data Input Window for Two-Layer Soil

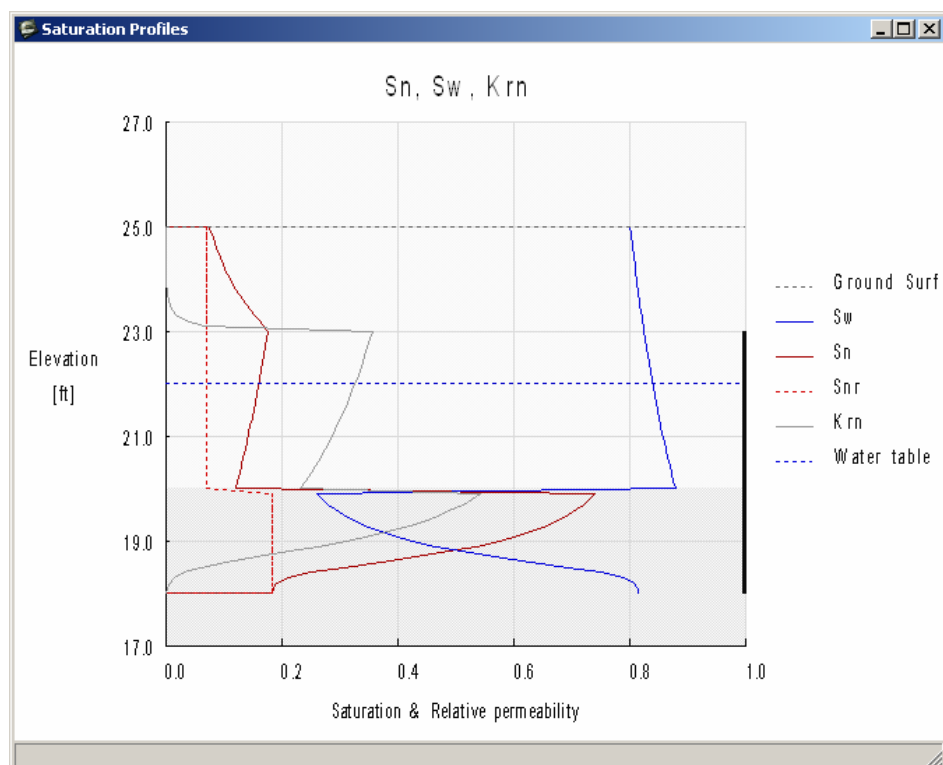


Figure 2.21—Saturation Profiles Graph Output

The second graph, *Specific Volume/Transmissibility* (Alt-s), is shown in Figure 2.22. The three curves present the specific volume functions $D_n(b_n)$ and $R_n(b_n)$ and the LNAPL transmissibility function $T_n(b_n)$. The solid red, blue and grey curves are developed as follows. For twenty evenly distributed values of b_n ranging from zero to the maximum value specified on the Data Input window, the functions are evaluated using equations (2.40), (2.41), and (3.31) from Volume 1. For each b_n value, the corresponding z_{nw} and z_{max} values are calculated using equations (2.20) and (2.38). Using the sets of (b_n, R_n) and (b_n, T_n) values, a difference algorithm is used to select two values (b_{n1} and b_{n2}) to use at the breakpoints for the piecewise linear approximation models specified by equations (4.3) and (4.4). These values are used to plot the piecewise linear approximations (dashed segments) to $R_n(b_n)$ and $T_n(b_n)$ shown in Figure 2.22. As discussed in Section 2.4.5, the user may select alternative breakpoint values to use in the recovery model calculations.

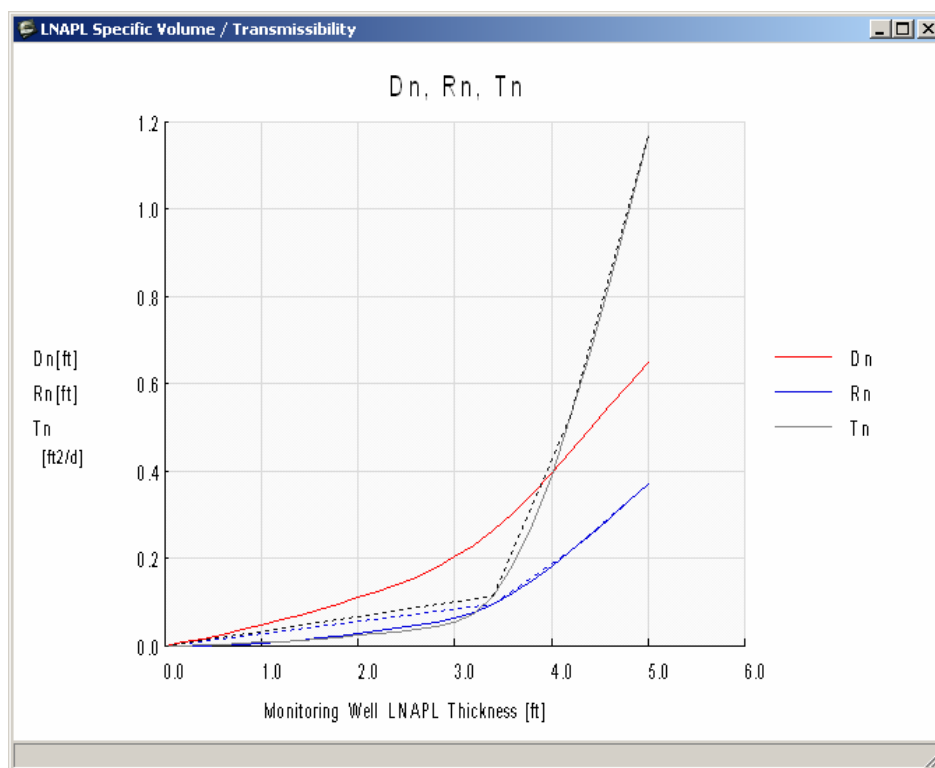


Figure 2.22—Specific Volume/Transmissibility Graph Output

The third graph, *Monitoring Well LNAPL Thickness* (Alt-t), is shown in Figure 2.23. This graph is available only after the recovery model has been run. This graph shows how the free product thickness (b_n) varies with time during the recovery time interval. For the example shown in Figure 2.23, the LNAPL thickness decreases from 5 feet to about 3.7 feet over a time period of two years.

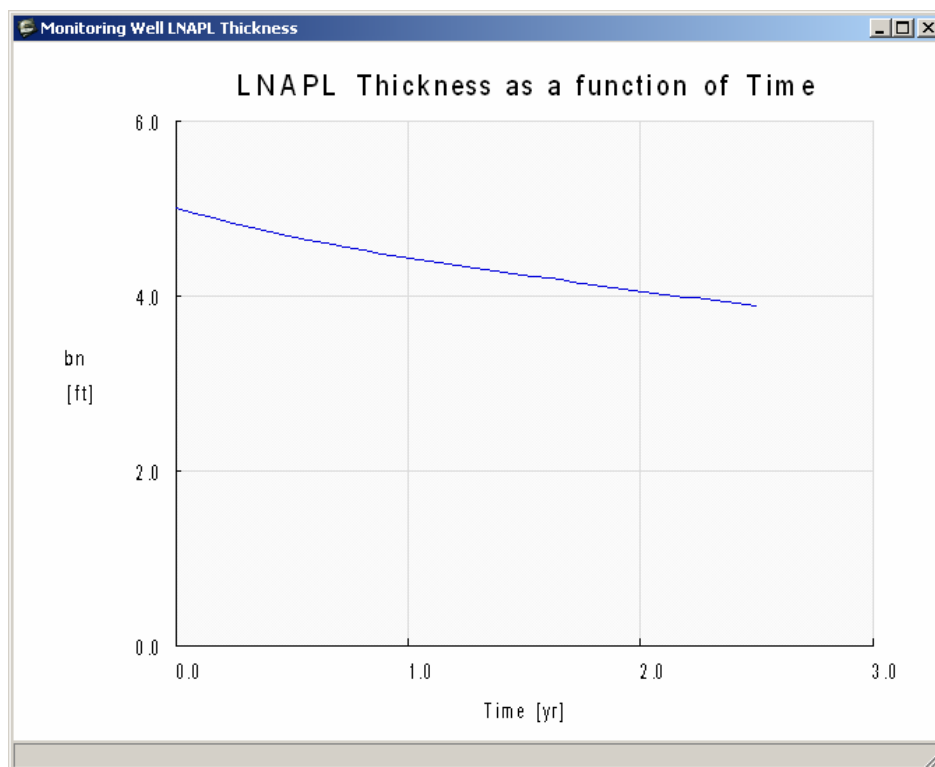


Figure 2.23—Free Product Thickness Graph Output

The fourth graph, *Drawdown/Buildup* (Alt-d), is shown in Figure 2.24. This graph is available only after the recovery model has been run, and only for groundwater or vacuum-enhanced wells. This graph shows the water table drawdown (due to groundwater pumping) and rise or buildup of the water table (due to an applied vacuum). Drawdown and buildup of the water table are added to calculate the net water table change, which is also plotted. Finally, the average drawdown/buildup within the radius of capture of the recovery well is shown. Drawdown and buildup are calculated using the Thiem equation (equation 3.34 and 3.52, respectively, from Volume 1). The average is a radial-distance weighted average. The example shown in Figure 2.24 corresponds to a radius of capture equal 60 feet (radius of influence equal 250 feet) and air radius of capture equal 20 feet. The groundwater production rate is 1 gallon per minute and the air-enhanced system suction pressure is 0.05 atmospheres. The average drawdown within the radius of capture is 0.88 feet for this example.

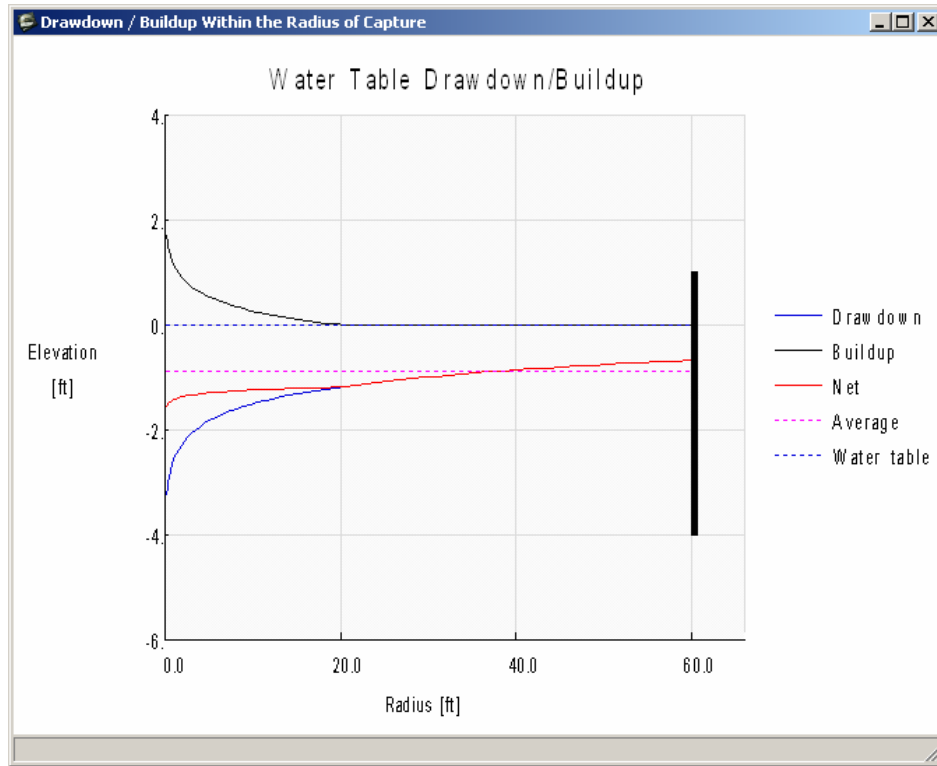


Figure 2.24—Drawdown/Buildup Graph Output

The fifth graph, *LNAPL Recovery Rate* (Alt-r), is shown in Figure 2.25. This graph is available only after the recovery model has been run. The LNAPL recovery rate, Q_n , is shown as a function of time during the recovery time period. For the example shown in this figure the recovery rate decreases from about 60 gallons per day (gpd) to about 10 gpd after two years. This corresponds directly to the nearly six-fold decrease in LNAPL transmissibility as the LNAPL thickness decreases from 5 to 3.7 feet (see Figures 2.22 and 2.23).

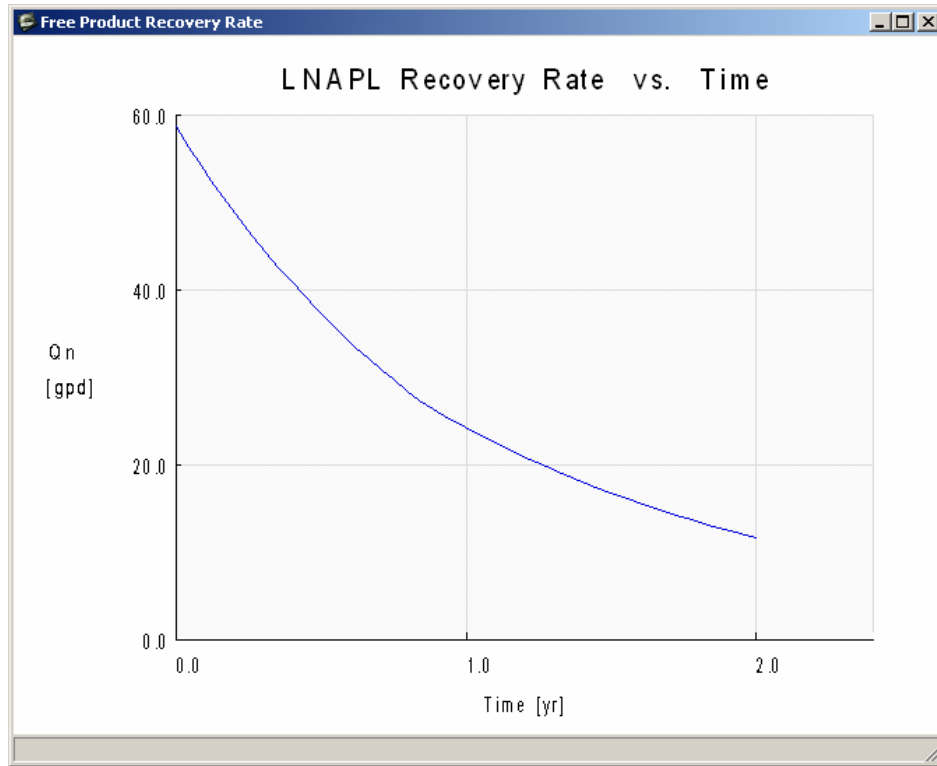


Figure 2.25—LNAPL Recovery Rate Graph Output

The sixth graph, *LNAPL Recovery Volume* (Alt-v), is shown in Figure 2.26. This graph is available only after the recovery model has been run. The cumulative LNAPL recovery volume, V_n , is shown as a function of time during the recovery period. In the example shown in this figure the recovery volume increases to approximately 20,000 gallons over two years. Also shown on this figure (blue dashed line) is the total LNAPL volume ($A_c D_n(b_{nmax})$) within the area of capture A_c . The maximum recoverable LNAPL volume within the capture area is $A_c R_n(b_{nmax})$.