API LNAPL Transmissivity Workbook: A Tool for Baildown Test Analysis

User Guide

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AMERICAN PETROLEUM INSTITUTE

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Regulatory and Scientific Affairs

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PREFACE

LNAPL transmissivity provides a useful measure of potential hydrocarbon liquid mobility within the subsurface environment. The magnitude of LNAPL transmissivity is being accepted as a metric for hydrocarbon recovery system performance and determination of technology-specific endpoints. Baildown tests are a simple method for estimating LNAPL transmissivity. This manuscript describes a spreadsheet tool that can be used to analyze results from baildown tests.

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LIST OF SYMBOLS

b_n	LNAPL thickness in well
b_{nR}	initial LNAPL thickness in well (same as at radius of influence)
b_{nW}	limiting effective LNAPL thickness in well (see Appendix F)
DZ_{12}	depth to top of perching layer
$F(\ )$	Cooper, Bredehoeft and Papadopulos slug test function
$G(\ )$	Jacob-Lohman free-flowing discharge function
h_n	LNAPL head
J	Kirkman J-ratio (see Appendix B)
L_e	initial LNAPL column height (contacting screen) in well
N	number of increments
Q_n	LNAPL discharge
Q_{ni}	LNAPL discharge at time t_i
R	radius of influence
r_c	radius of casing
r_e	effective well radius
$r_{e(i)}$	effective well radius at time t_i (varies with LNAPL column location in well)
r_w	well borehole radius
S	coefficient of storage
s_n	LNAPL drawdown
S_n	LNAPL storage parameter
s_{ni}	LNAPL drawdown at time t_i
S_y	LNAPL specific yield
T	transmissivity
t_i	time epoch
T_n	LNAPL transmissivity
V_n	LNAPL volume
$W(\ )$	Theis well function
z_{an}	elevation of air-LNAPL interface in well
z_{nw}	elevation of LNAPL-water interface in well
Δs_n	LNAPL drawdown correction
Δt_a	time adjustment factor
ρ_r	LNAPL-to-water density ratio

ACRONYMS

BOS	Bottom of Screen
B&R	(generalized) Bouwer and Rice method
CSM	Conceptual Site Model
C&J	Cooper and Jacob method
CB&P	Cooper, Bredehoeft and Papadopulos method
CV	Coefficient of Variation
DTP	Depth to Product
DTW	Depth to Water
ITRC	Interstate Technology Regulatory Council
LNAPL	Light Non-Aqueous Phase Liquid
SOP	Standard Operating Procedure
SSD	Sum-Square-Difference
TOS	Top of Screen

API LNAPL Transmissivity Workbook:
A Tool for Baildown Test Analysis—User Guide

1. Introduction

LNAPL transmissivity is a measure of lateral mobility of free-product hydrocarbon liquid within the groundwater environment. The magnitude of LNAPL transmissivity has been suggested as a possible endpoint criterion for LNAPL mass removal using LNAPL hydraulic recovery systems (ASTM E 2531-06 [Tbl X5.1], 2006; ITRC, 2009). Such hydraulic recovery systems include skimmer wells, single-pump wells, dual-pump wells, and trenches. Coupled with the LNAPL CSM, the magnitude of LNAPL transmissivity will assist in the selection of recovery system. As such, methods and their consistent application for estimating LNAPL transmissivity are significant. Perhaps the simplest methods for estimating LNAPL transmissivity are borehole slug test methods, or baildown tests, in which a volume of LNAPL is rapidly removed from a well and the rate of fluid-level recovery (water and LNAPL) is measured and analyzed. Several analytical methods are available to analyze the data from baildown tests to estimate LNAPL transmissivity and described herein. A more general discussion of LNAPL transmissivity measurement is provided by ASTM (2011).

Following a brief description of suggested well configuration, pre-test and test measurements and methods, application of the spreadsheet tool is discussed. Subsequent sections provide a more detailed discussion of significant parameters and basis for the various analysis procedures. A number of example applications are presented. Further details on the different methods are provided in the appendices. Noteworthy is the introduction of the J-ratio (*J*) described in Appendix A, which appears to render discussions over preference between Lundy and Zimmerman (1996) versus Huntley (2000) methods moot.

2. Well Configuration Data

The following well configuration data should be gathered for baildown test analysis:

1. Elevation of ground surface. This generally serves as the datum with elevations specified as depth below ground surface, bgs. Elevations presented with the geologic log are generally expressed as depth bgs. If data are not conveniently available (or necessary), enter 0 on the spreadsheet.
2. Elevation of top of casing (depths to fluid levels are usually measured from top of casing). If data are not conveniently available (or necessary), enter 0 on the spreadsheet.
3. Well casing radius, r_c (ft).
4. Well borehole radius, r_w (ft).
5. Depth of top of screen (ft bgs). The top of screen can be interpreted to be the top of screen or filter pack, depending on the well construction and gauged fluid levels, and it is

up to professional judgment to correctly select between these. If data are not conveniently available (or necessary), enter 0 on the spreadsheet.

6. Depth of bottom of screen (ft bgs). If data are not conveniently available (or necessary), enter 0 on the spreadsheet.

3. Pre-Test Data

Certain data should be gathered before performance of the baildown test, in order to establish and verify initial conditions. The depth to product (DTP) and depth to water (DTW) should be measured over a period equal to the expected test duration; if the test duration is unknown then use of historic hydrograph data and gauging 8 hours before the test would provide a basic level of understanding for equilibrium conditions. The DTP and DTW should then be measured immediately before start of the test to confirm that fluid levels are stable and in equilibrium. The best practice to confirm equilibrium fluid levels is to gauge the well until it fully recovers as discussed in ASTM E2856-11, Section 6.1.4.16 (2011). Additionally, when conditions allow, it is useful to remove LNAPL from the well during a period before the test (e.g. within one month) to confirm equilibrium contact between formation and well hydrocarbon liquid. This is necessary especially if standing LNAPL is observed or LNAPL has not been recovered from a well for a while. Baildown tests are analyzed by slug test methods modified for two fluids, and it is important that formation and well fluids are in equilibrium. If tidal fluctuations are present the DTP and DTW must be measured regularly for at least a week leading up to the test. In any case it is imperative that the LNAPL/water interface should be positioned across the well screen for confined LNAPL conditions, or the air/LNAPL interface for perched LNAPL conditions, if not both the interfaces.

4. Baildown Test Procedures and Data

In performance of a baildown test a volume of hydrocarbon liquid is rapidly removed from the well and the DTP and DTW are measured as a function of time during the fluid recovery period. Fluid recovery rates generally vary logarithmically, so measurements should be taken more frequently during the initial period following hydrocarbon removal, and the measurement frequency decreases during the later period of the test. The ASTM standard E2856-11 provides a thorough procedure for conducting baildown tests, however, a brief description of significant features are provided below:

- Initial hydrocarbon liquid removal should be rapid. Commercial peristaltic pumps (such as Spill Buddy ™) are preferred since the pump intake can be located to remove only hydrocarbon liquid during the baildown stage. If a bailer is used then additional precautions are necessary to minimize fluid disturbance during LNAPL removal. If removal of larger LNAPL volumes is required, then vacuum trucks can be used, recognizing that significant volumes of water may be removed in addition to LNAPL.

- Following the baildown stage of hydrocarbon liquid removal, the DTP and DTW are measured as a function of time. Measurements can be taken using interface probes (optical and electrical resistivity), and data are recorded as depth (feet) below top of casing.
- In general, the interface depth measurements are taken more frequently during the initial recovery period, and the frequency decreases as recovery proceeds. If recovery rates are too rapid for (near) simultaneous measurement of DTP and DTW, then a pressure transducer can be placed below the LNAPL-water interface and connected to a data-logger. In this case only the DTP need be measured, and such measurements combined with the data-logger record and LNAPL density can be used to calculate the DTW at desired time intervals.
- When possible, recovery monitoring should continue until essentially complete LNAPL recovery is achieved. In low LNAPL transmissivity locations, time requirements might be excessive and early termination will be necessary. Nearly full recovery is especially important for confined and perched LNAPL conditions, to help verify the site conceptual model for the test.
- A record of 20 to 30 measurements (each for DTP and DTW) is generally adequate for data analysis. When possible, these data should be evenly spread in terms of recovery volume. [For example, if the initial LNAPL thickness in a well is 4 ft and the LNAPL thickness after baildown is 0.5 ft, then measurements might be taken when the LNAPL thickness roughly has the following sequence of values: 0.50, 0.52, 0.54, … 3.90, .. ft.]

5. Post-Test Data

LNAPL transmissivity value from a baildown test is estimated based on measurement of LNAPL drawdown and recharge to the well as a function of time, along with a conceptual site model that can include geologic log and well configuration data to identify possible unconfined, confined, or perched LNAPL conditions. Estimation of formation discharge (well recharge) is based on changes in DTP and DTW values. Changes in fluid levels in the well compared with screen elevations determine the effective storage associated with the well. This storage can include only the casing volume or the casing volume plus some fraction of the pore space of the filter pack that has been drained of LNAPL during the baildown stage of the test. This latter case becomes more complicated, depending on the fluid levels versus the well screen interval, since only part of the LNAPL column in the well may be in contact with the screened interval of the well. These issues are discussed in more detail in Appendix B with regard to estimation of the effective well radius, r_e.

The post-test data that must be calculated include estimation of LNAPL drawdown (s_n) and well discharge (Q_n) as a function of time, and this in turn depends on the effective well radius value along with DTP and DTW measurements.

The LNAPL drawdown is measured based on the DTP, along with any correction that is applied to account for initial non-equilibrium between formation and wellbore LNAPL. Specifically, the drawdown corresponding to time t_i is calculated using

$$(5.1) \quad s_{ni} = DTP_i - DTP_0 - \Delta s_n$$

In Eq. (5.1) DTP_0 is the initial (pre-test) depth to product and Δs_n is a possible LNAPL drawdown correction as discussed below.

The LNAPL discharge from the formation to the well is calculated based on the effective well radius ($r_{e(i)}$) and changes in DTP and DTW over time. Once the effective well radius has been determined, the well discharge from time t_i to time $t_{\mathrm{i}+1}$ is calculated using the following equation:

$$(5.2) \quad Q_{ni} = \pi\, r_{e(i)}{}^2 \left(DTP_i - DTP_{i+1} + DTW_{i+1} - DTW_i\right) \Big/ \left(t_{i+1} - t_i\right)$$

This equation accounts for the increase in LNAPL storage volume over the time interval, and specifically identifies that the effective well radius might not be constant (such as a change from well casing storage to casing/screen plus filter pack storage).

6. Overview and General Discussion: Analysis of LNAPL Transmissivity Baildown Test Data

This section briefly summarizes methods for analysis of LNAPL transmissivity baildown test data. Additionally, use of time cutoff and time adjustment to eliminate early-time data influenced by filter pack drainage or other factors is discussed, and a default method for estimation of LNAPL storage coefficient is described. Finally, a flowchart that outlines the LNAPL transmissivity estimation process using this workbook is presented.

6.1. Methods for Estimating LNAPL Transmissivity

Among the variety of methods suggested in the literature for analysis of slug test data, three different methods are presented here for analysis of unconfined LNAPL transmissivity baildown tests. These three methods are designated through their original presentation in the literature as follows:

- B&R - Bouwer and Rice (1976)
- C&J - Cooper and Jacob (1946)
- CB&P - Cooper, Bredehoeft and Papadopulos (1967)

LNAPL baildown tests are inherently transient, meaning that fluid levels and flow rates change with time. Experience with transient aquifer tests suggests that at least two parameters are necessary to describe system performance. With a conventional pumping test one estimates the aquifer transmissivity and storage coefficient. For LNAPL baildown test analysis, both parameters are also necessary, though only the LNAPL transmissivity is of direct interest.

The Bouwer and Rice (B&R) method is conceptually the simplest. The method uses a linear model (Thiem equation) to relate LNAPL discharge to LNAPL drawdown, and is based on continuity of LNAPL volume within the well. LNAPL drawdown versus time data are used to determine the LNAPL transmissivity, based on an estimate of the well radius of influence provided through the empirical analysis presented by Bouwer and Rice (1976). Interesting questions remain in the literature between the applications of the B&R method for LNAPL baildown testing as presented by Lundy and Zimmerman (1996) and Huntley (2000). These approaches differ in terms of assumed fluid levels in the well during recovery. The Huntley method assumes that the water table elevation remains constant during the recovery period. The Lundy method, which proposes removal of a small slug of LNAPL from the well, assumes that the depth to water remains constant during the recovery period. This difference in assumptions results in the Huntley method including an additional factor $1/(1 - \rho_r)$ in the calculation of LNAPL transmissivity, where ρ_r is the LNAPL-water density ratio. For many LNAPL transmissivity baildown tests, neither assumption is observed. For the general case, Andrew Kirkman (personal communication) suggests introduction of the J-ratio parameter that is directly based on measured data to address this issue. The Kirkman J-ratio is described in Appendix A and the J-ratio method is used herein for both the B&R, and the CB&J methods. The magnitude of the J-ratio is determined by the user using Fig. 4 on the "Figures" worksheet. The B&R method is developed in Appendix C.

The Cooper and Jacob (C&J) method provides an estimate of the LNAPL transmissivity based on the LNAPL discharge to the well and LNAPL drawdown, as a function of time. The method also requires estimation of an LNAPL storage coefficient. Guidance on suggested magnitudes of the LNAPL storage coefficient is provided for the user. The C&J method is developed in Appendix D.

The Cooper, Bredehoeft and Papadopulos (CB&J) method provides an estimate of the LNAPL transmissivity based on measurements of LNAPL drawdown versus time. The method also requires an estimate of the LNAPL storage coefficient. The CB&P method does not directly use the LNAPL discharge to the well, and it does require an estimate of the effective initial LNAPL drawdown. The CB&P method is developed in Appendix E.

LNAPL can also be found under confined or perched conditions. Methods based on the Bouwer and Rice method of analysis are developed for confined and perched LNAPL in Appendices F and G, respectively.

Discussion

There is no *a priori* preferred method for analysis of LNAPL baildown test data. The B&R method is good for long well purging events, whereas relatively instantaneous events are used with the C&J and CB&P methods because they incorporate transient storage effects. The B&R method is independent of absolute time; rather, just the slope of the log-normalized drawdown versus change in linear time is important. However, if a straight line is not observed with B&R and it concaves upward (as a result of storage effects), then C&J or CB&P are more able to account for the effects attributed to storage. Absolute time is critical for both C&J and CB&P, and thus it is necessary to adjust the effective time origin when early-time data is eliminated because of filter pack drainage. With the B&R method, the well radius of influence is estimated using well configuration data based on analog simulation analysis described by Bouwer and Rice (1976) for flow of groundwater to a well in an unconfined aquifer. This relationship is assumed to hold for LNAPL. The C&J method is based on an approximate solution describing flow of groundwater to a well under conditions of constant discharge and variable drawdown, and constant drawdown and variable discharge. The relationship is also assumed to apply to flow of LNAPL to a well when both the LNAPL discharge and LNAPL drawdown vary with time. The CB&P method is based on an analytical solution for a slug test in a confined aquifer, and is assumed to apply for LNAPL under unconfined conditions. With the CB&P method, both the effective initial drawdown and LNAPL storage coefficient must be estimated along with the LNAPL transmissivity. Because the CB&P method does not directly consider data regarding LNAPL discharge to the well, it is possibly the most uncertain method of analysis. Nevertheless, when properly applied, the user can often estimate LNAPL transmissivity value with coefficient of variation (ratio of the standard deviation to mean value) of 20 % or less when considering analyses using all three methods.

6.2. Time Cutoff and Time Adjustment

Early-time data from baildown testing may be significantly impacted by filter-pack drainage or other effects that do not reflect LNAPL flow from the formation to the well during recovery. Such data may be eliminated by specifying a cutoff time. Data from times earlier than the cutoff time are not considered in estimation of LNAPL transmissivity. The cut-off time may be used with the B&R, C&J, and CB&P methods. The B&R method does not depend on the time origin, so no further adjustments are necessary. However, both the C&J and CB&P methods include an LNAPL storage coefficient as a parameter, which represents a capacitance factor, and time origin is significant to the theoretical model. For the C&J method a time adjustment of the apparent time origin may be applied. One may think of the Time Adjustment as accounting for the delay in LNAPL flow from the formation to the well associated with the duration of significant filter-pack drainage. Limited experience suggests that the Time Adjustment and Time_{cut} may be related through the following: Time Adjustment = (0.6 or 2/3) * Time_{cut}. The effects of Time_{cut} and Time Adjustment are shown in Figure 6.1. In this figure, it is desired to eliminate data earlier than 25 minutes because of effects from filter-pack drainage (Time_{cut} = 25 minutes); for a discussion of how this 25-minute Time_{cut} was selected, see discussion leading to Fig. 7.4 below. A Time Adjustment = 15 minutes is applied for analysis of LNAPL transmissivity using the C&J method, meaning that the apparent time origin for data later than 15 minutes is shifted as shown. For the CB&P method, one simply uses the estimated drawdown at the Time_{cut} as the initial drawdown value.

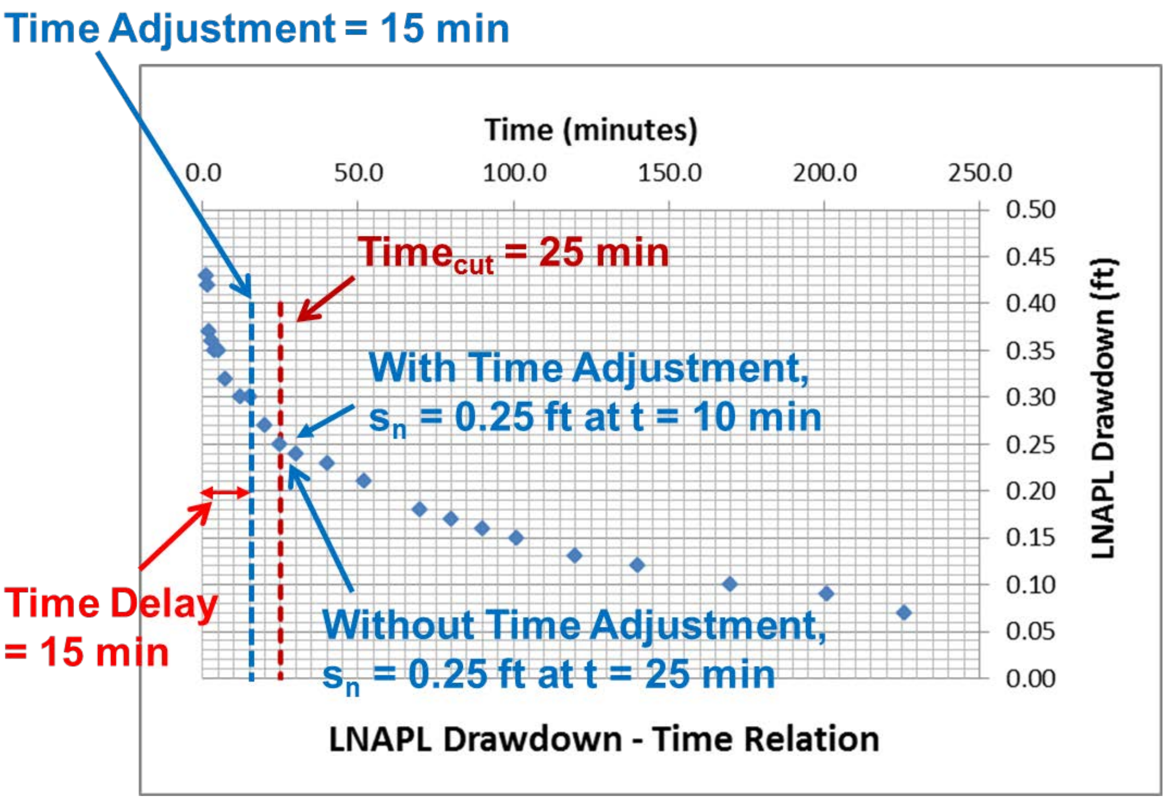


Figure 6.1. **Application of $Time_{cut}$ and Time Adjustment to eliminate early-time data influenced by filter-pack drainage or other effects**

6.3. Analysis of LNAPL Storage Coefficient

The storage parameter S_n is used in the C&J and CB&P methods. The maximum value should equal a reasonable drainable porosity value for the formation. An upper bound estimate would be 0.15 for coarse sands, 0.06 for fine sands, 0.004 to 0.025 for silts. Clays would be on the low end of silts or lower unless LNAPL exists in secondary porosity. These values assume that the recoverable fraction of LNAPL is up to 50% saturation for coarse sands and 5% for silts and clays. These values will be lower (i.e., a factor of 10 to 50) for wells with minimal LNAPL recovery. Results are relatively insensitive to this parameter if realistic values are used. The table below provides general guidance on appropriate values.

Table 6.1: Recommended Relationship between LNAPL Transmissivity and LNAPL Storage Coefficient (from ASTM, 2011)

LNAPL Transmissivity (ft^2/d)	LNAPLStorage (vol/vol)
50	0.175
20	0.122
10	0.070
5	0.053
1	0.035
0.1	0.008

A "Default" option is available for estimating the LNAPL storage coefficient for the C&J and CB&P methods. An approximate model is fit to the data in Table 6.1, as shown in Figure 6.2.

(6.3.1) $$S_n = 0.025\sqrt{T_n}$$

In Eq. (6.3.1) the units of T_n are ft^2/d. The default option is selected by entering the letter d in the S_n entry cell. With the default option selected, the LNAPL storage coefficient is estimated implicitly as part of determining the LNAPL transmissivity.

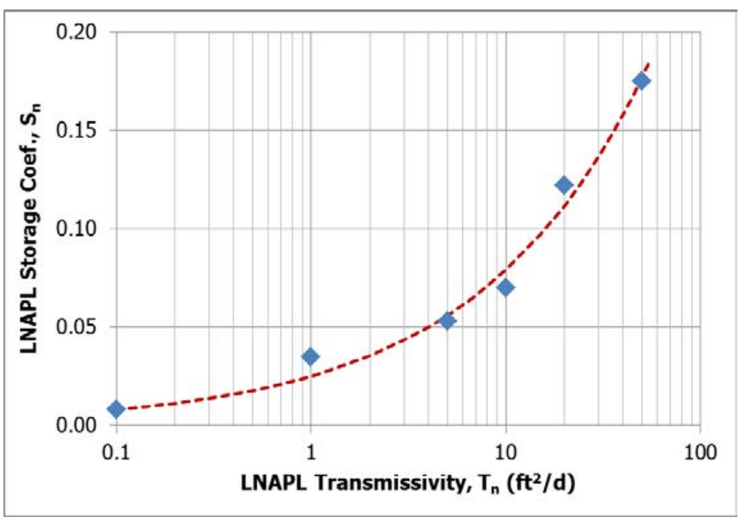


Figure 6.2. LNAPL storage coefficient vs. LNAPL transmissivity

6.4. General overview of LNAPL transmissivity estimation process

The process for estimating LNAPL transmissivity from LNAPL baildown test data using the API LNAPL Transmissivity Workbook is outlined in the flowchart shown in Figure 6.3. Further details are provided in ASTM (2011).

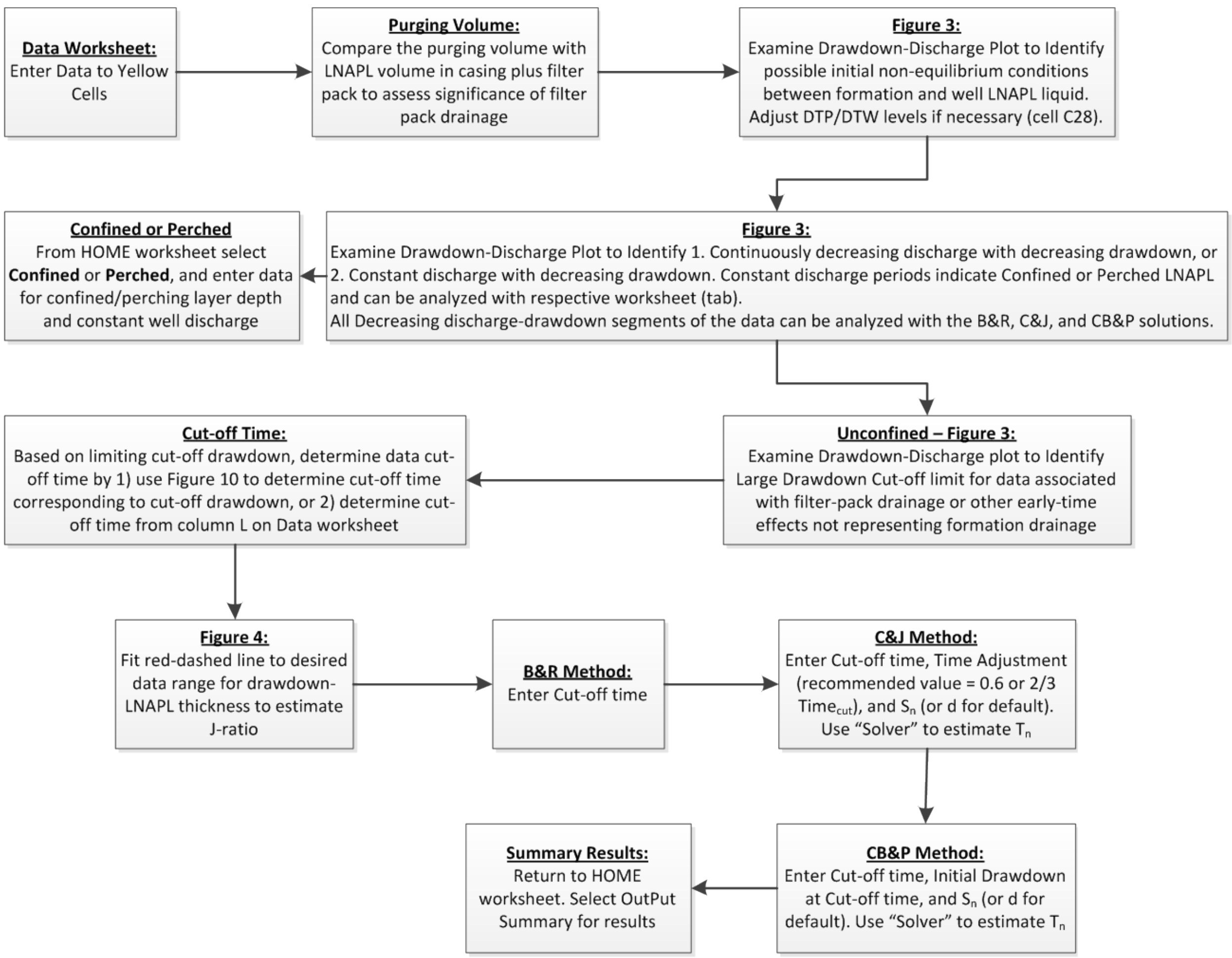


Figure 6.3. Flowchart outlining steps in LNAPL baildown test analysis

7. LNAPL Transmissivity Workbook

The *API LNAPL Transmissivity Workbook* tool is a Microsoft Excel ™ spreadsheet that may be used to estimate LNAPL transmissivity values from baildown test data under unconfined, confined and perched conditions. For unconfined conditions, three methods are used to calculate LNAPL transmissivity, and the results are averaged. The Kirkman J-ratio is required for two of these methods, and the magnitude of the J-ratio is determined by the User with Fig. 4 on the “Figures” worksheet. For both confined and perched LNAPL conditions, only a single estimate of LNAPL transmissivity is made based on the constant LNAPL discharge rate during part of the recovery period of the test.

The application tool has ten different worksheets that are designated as follows:

- HOME - Control and output worksheet
- Data - Entry of well configuration and fluid level data
- Figures - Basic figures showing data
- B&R - Bouwer and Rice method worksheet
- C&J - Cooper and Jacob method worksheet
- CB&P - Cooper, Bredehoeft and Papadopulos method worksheet
- B&R Type Curve - Set of type curves provided as aid to field work
- Confined - Confined LNAPL worksheet
- Perched - Perched LNAPL worksheet
- Flowchart - Flowchart outlining steps in LNAPL baildown test analysis

As discussed below, not all worksheets are visible at any time, though the first three worksheets and the last worksheet are always available.

7.1 “HOME” Worksheet

An example “HOME” worksheet is shown in Figure 7.1. This is the primary worksheet that outlines the steps in data analysis as follows:

1. Reset Output Summary
2. Enter Data & View Figures
3. Choose Well Conditions
4. LNAPL Transmissivity Summary

Step 1 hides the method-specific worksheets. The “Data”, “Figures”, and “Flowchart” worksheets remain visible and accessible. No existing data are cleared when the RESET button is selected. Step 2 requires entry of data on the “Data” worksheet and review of data on the “Figures” worksheet. Step 2 provides preliminary information to guide in selecting LNAPL condition (unconfined, confined, or perched) for analysis. If unconfined conditions are observed, then the J-ratio MUST be determined using Fig. 4 on the “Figures” worksheet. Based on Step 2 assessment, Step 3 is selection of LNAPL condition which makes visible either the worksheets appropriate for unconfined conditions, or individually, the worksheets for confined or perched conditions. Step 4, selection of the OUTPUT SUMMARY button copies results from the method-specific worksheets to summary output.

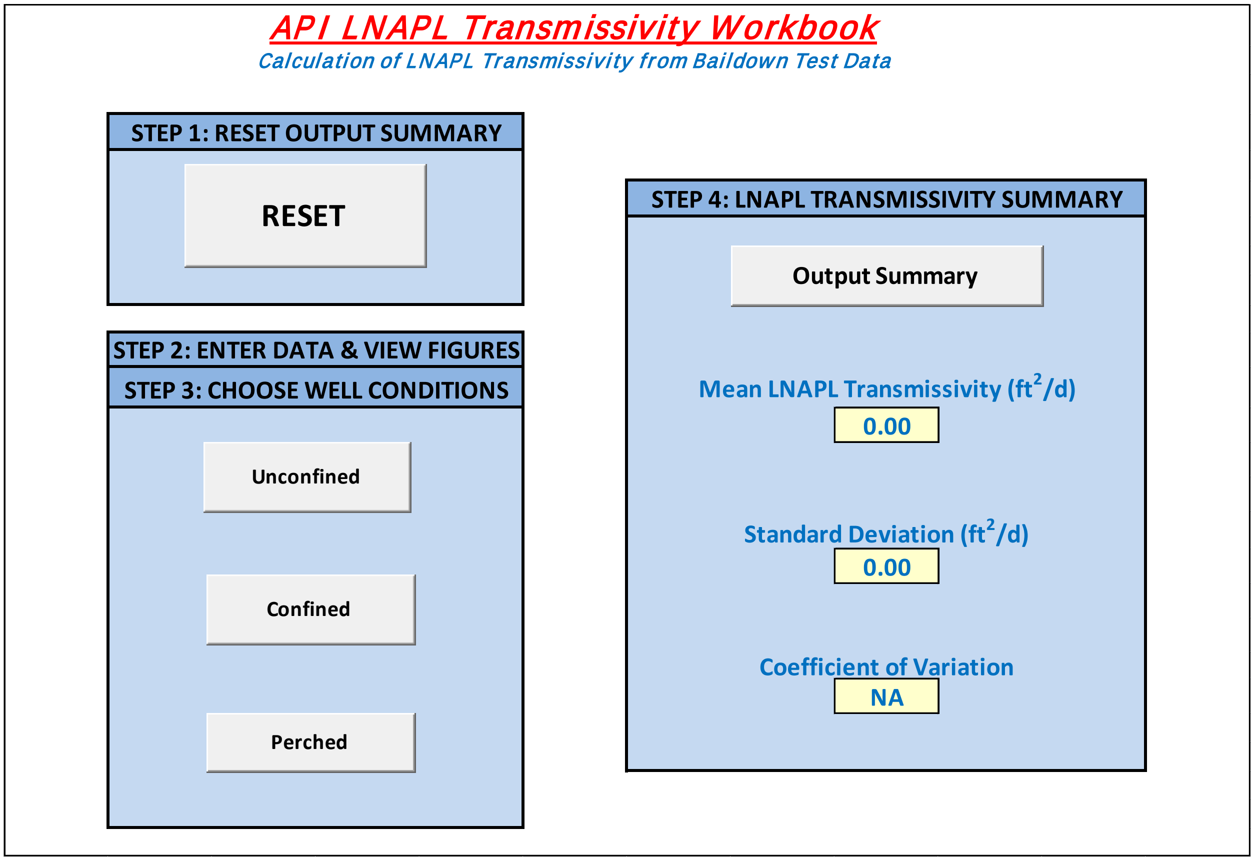


Figure 7.1. “HOME” worksheet

7.2 “Data” Worksheet

An example “Data” worksheet page is shown in Figure 7.2. The cells for data entry are shown in light yellow color and user must input the data in the units indicated. Other cells are locked to help protect against inadvertent modification to the worksheet. This worksheet includes the well configuration data listed in Section 3, along with records of depth to product (DTP) and depth to water (DTW) as a function of time, as measured from the top of casing. The initial values of DTP and DTW are also entered. The LNAPL Specific Yield, S_y, on this worksheet refers to the filter pack. A default value 0.175 is recommended, though the value can be modified by the user. The default value is based on an assumed filter-pack porosity of 0.35, and an assumed specific yield of 50 % of the void space. The LNAPL Density Ratio, ρ_r, is estimated from field data on product type. The LNAPL Baildown Volume is entered for comparison purposes only; it is not used elsewhere in the workbook. The “Drawdown Adjustment” value is read from the data entry for Fig. 3 on the “Figures” worksheet. Calculations performed on this worksheet include adjustment of fluid levels to give depth bgs, estimation of the water table depth based on DTP and DTW along with LNAPL-water density ratio, LNAPL drawdown using Eq. (5.1) and LNAPL discharge using Eq. (5.2), and the effective well radius as outlined in Appendix B. If both the ground surface elevation and top of casing elevation are entered as zero, then no adjustment is made to DTP and DTW fluid levels. For unconfined conditions with the LNAPL column within the screened interval of the well, these data are not necessary.

Well Designation:	YYY	Beckett and Lyverse (2002)		
Date:	date			
Ground Surface Elev (ft msl)	0.0	Enter These Data		**Drawdown**
Top of Casing Elev (ft msl)	0.0			**Adjustment**
Well Casing Radius, r_c (ft):	0.170	r_{e1}		**(ft)**
Well Radius, r_w (ft):	0.500			0.08
LNAPL Specific Yield, S_y:	0.175			
LNAPL Density Ratio, ρ_r:	0.780			
Top of Screen (ft bgs):	0.0			
Bottom of Screen (ft bgs):	0.0			
LNAPL Baildown Vol. (gal.):				
Effective Radius, r_{e3} (ft):	0.260	Calculated Parameters		
Effective Radius, r_{e2} (ft):	0.245			
Initial Casing LNAPL Vol. (gal.):	2.10			
Initial Filter LNAPL Vol. (gal.):	2.81			

	Enter Data Here					Water Table Depth (ft)	LNAPL Drawdown s_n (ft)	Average Time (min)	LNAPL Discharge Q_n (ft^3/d)	s_n (ft)	b_n (ft)	r_e (ft)
	Time (min)	DTP (ft btoc)	DTW (ft btoc)	DTP (ft bgs)	DTW (ft bgs)							
Initial Fluid Levels:	0	22.29	25.38	22.29	25.38	22.97					3.09	
Enter Test Data:	1.0	22.80	23.30	22.80	23.30	22.91	0.43				0.50	
	1.5	22.79	23.38	22.79	23.38	22.92	0.42	1.3	55.041	0.43	0.59	0.260
	2.0	22.74	23.41	22.74	23.41	22.89	0.37	1.8	48.925	0.40	0.67	0.260
	3.0	22.73	23.50	22.73	23.50	22.90	0.36	2.5	30.578	0.37	0.77	0.260
	4.0	22.72	23.54	22.72	23.54	22.90	0.35	3.5	15.289	0.36	0.82	0.260
	5.0	22.72	23.59	22.72	23.59	22.91	0.35	4.5	15.289	0.35	0.87	0.260
	7.5	22.69	23.66	22.69	23.66	22.90	0.32	6.3	12.231	0.34	0.97	0.260
	12.0	22.67	23.89	22.67	23.89	22.94	0.30	9.8	16.988	0.31	1.22	0.260
	15.0	22.67	23.90	22.67	23.90	22.94	0.30	13.5	1.019	0.30	1.23	0.260
	20.0	22.64	23.98	22.64	23.98	22.93	0.27	17.5	6.727	0.29	1.34	0.260
	25.0	22.62	24.04	22.62	24.04	22.93	0.25	22.5	4.893	0.26	1.42	0.260
	30.0	22.61	24.07	22.61	24.07	22.93	0.24	27.5	2.446	0.25	1.46	0.260
	40.0	22.6	24.15	22.60	24.15	22.94	0.23	35.0	2.752	0.24	1.55	0.260
	52.0	22.58	24.22	22.58	24.22	22.94	0.21	46.0	2.293	0.22	1.64	0.260
	70.0	22.55	24.31	22.55	24.31	22.94	0.18	61.0	2.039	0.20	1.76	0.260
	80.0	22.54	24.36	22.54	24.36	22.94	0.17	75.0	1.835	0.18	1.82	0.260
	90.0	22.53	24.39	22.53	24.39	22.94	0.16	85.0	1.223	0.17	1.86	0.260
	101.0	22.52	24.44	22.52	24.44	22.94	0.15	95.5	1.668	0.16	1.92	0.260
	120.0	22.5	24.50	22.50	24.50	22.94	0.13	110.5	1.288	0.14	2.00	0.260
	140.0	22.49	24.57	22.49	24.57	22.95	0.12	130.0	1.223	0.13	2.08	0.260
	170.0	22.47	24.65	22.47	24.65	22.95	0.10	155.0	1.019	0.11	2.18	0.260
	201.0	22.46	24.74	22.46	24.74	22.96	0.09	185.5	0.986	0.10	2.28	0.260
	226.0	22.44	24.79	22.44	24.79	22.96	0.07	213.5	0.856	0.08	2.35	0.260

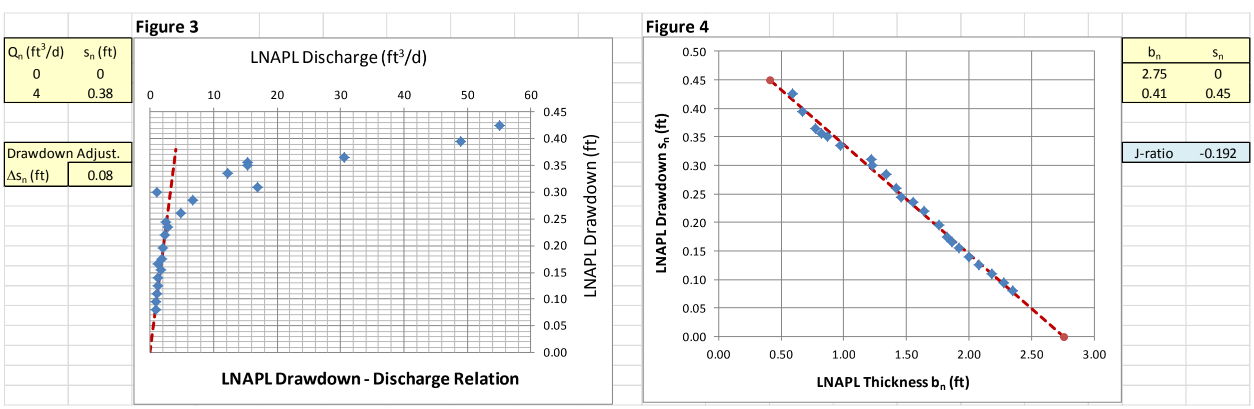
Figure 7.2. “Data” entry worksheet

7.3 “Figures” Worksheet

This worksheet contains ten miscellaneous figures showing the input and the output data. As discussed below, the most important diagnostic tools include the plot of LNAPL drawdown versus discharge, and the plot of LNAPL drawdown versus LNAPL thickness (J-Ratio). The figures (objects) are not protected to allow edits (i.e., axis scales, etc.). The figures are numbered one through ten and are described as follows:

- Fig 1: Depth to Fluid Interface vs. Time (arithmetic time scale). This figure also shows the initial DTP and DTW. Depending on the screen interval data entered on the “Data” worksheet, the screened interval of the LNAPL column is also shown. The entire screen length is not shown. Instead, only the screened interval extending one foot above and/or below the initial LNAPL well thickness is shown. Fig. 1 is useful for evaluating how the potentiometric surface varied over the test duration. Looking for trends of water-table fluctuation will help identify any significant deviations from the assumed constant background conditions.

- Fig 2: Depth to Fluid Interface vs. Time (logarithmic time scale). This figure also shows the initial DTP and DTW. Depending on the screen interval data entered on the "Data" worksheet, the screened interval of the LNAPL column is also shown. The entire screen length is not shown. Instead, only the screened interval extending one foot above and/or below the initial LNAPL well thickness is shown. Similar to Fig. 1, however the early portion of the test can be better viewed for longer term tests.
- Fig 3: LNAPL Drawdown vs. LNAPL Discharge. This is an important diagnostic tool used to determine Drawdown Adjustment that is copied to the "Data" worksheet and other worksheets to account for initial non-equilibrium between formation and well fluids. The LNAPL Drawdown-LNAPL Discharge data should extrapolate to the origin (zero value) for small values. To aid analysis, a linear model is added with data entry in the yellow-fill box adjacent to the figure, as shown in Figure 7.3(a). LNAPL drawdown-discharge should exhibit a direct relationship. Deviations from this indicate the baildown test may be significantly affected by outside factors (e.g., nearby changes in pumping) or confined or perched conditions (where constant discharge is observed).
- Fig 4: LNAPL Drawdown vs. LNAPL Thickness. This is an <u>essential</u> diagnostic tool that is used to estimate the J-ratio magnitude, as described in Appendix A, and used with the "B&R" worksheet and "CB&P" worksheet. A linear model is provided with data entry in the yellow-fill box adjacent to the figure, and with estimated J-ratio value shown in the blue-fill box adjacent, as shown in Figure 7.3(b).



(a) (b)

Figure 7.3. Fig. 3 and Fig. 4 from the "Figures" worksheet showing data entry boxes for estimation of drawdown adjustment and J-ratio

- Fig. 5: Depth to Product (DTP) vs. LNAPL Discharge. This figure may be helpful as a diagnostic tool to identify soil stratigraphic influences.
- Fig 6: Depth to Water (DTW) vs. LNAPL Discharge. This figure may be helpful as a diagnostic tool to identify soil stratigraphic influences.
- Fig 7: LNAPL Thickness vs. Time. This figure may be useful for evaluating if the fluid levels reach equilibrium at the end of the test.
- Fig 8: LNAPL Discharge vs. Time. This figure represents an alternative method for evaluating if the baildown test has completed and the well reaches equilibrium conditions.
- Fig 9: LNAPL Well Inflow Volume vs. Time. Fig. 9 is analogous to Fig. 7 except provided in terms of the total well volume. In addition for being useful to evaluate test completion, this figure is useful for design of future baildown tests in terms of volume to remove from the well and filter pack.
- Fig 10: LNAPL Drawdown vs. Time. Linear model tool is also added with data entry in the yellow-fill box adjacent to the figure. In combination with Fig. 3, this figure is useful in identifying cut-off time for early-time data.

7.4 "B&R" Worksheet

The "B&R", or Bouwer and Rice worksheet calculates the LNAPL transmissivity and standard deviation based on the Bouwer and Rice (Bouwer and Rice, 1976; Bouwer, 1989) method using the method of linear least squares. As shown in Eq. (C.3), according to this method, the logarithm of the drawdown varies as a linear function of time. A straight line is automatically fit to the log-drawdown vs. time data and the slope of this line is used to determine the LNAPL transmissivity. The variance of the slope of the line is used to estimate the LNAPL transmissivity standard deviation. The ratio of the radius of influence to the effective radius is calculated using the polynomial approximation presented by Butler (2000). The user may eliminate early time data from the analysis by entering a non-zero value for the cutoff time (yellow cell). An example worksheet is shown in Figure 7.5. The only active cell on this worksheet is the cut-off time, and the LNAPL transmissivity value is automatically calculated. The lower figure on the worksheet shows the fit of the model data to the B&R Type Curve (see discussion below).

For the example shown in Figure 7.5 the cut-off time is set at 25 minutes. This cut-off time is based on eliminating early-time data associated with large filter pack drainage to the well. The drawdown-discharge curve for this example (Fig. 3 on the "Figures" worksheet) is shown in Figure 8.1 (c) and Figure 8.1 (d) (expanded scale after drawdown correction). In particular, Figure 8.1 (d) shows that the linear relationship between drawdown and discharge is reached once the LNAPL drawdown is about 0.25 ft. The LNAPL drawdown vs. time curve (Fig. 10 from the "Figures" worksheet) is shown in Figure 7.4, which gives the corresponding cut-off time 25 minutes for an LNAPL drawdown of 0.25 ft.

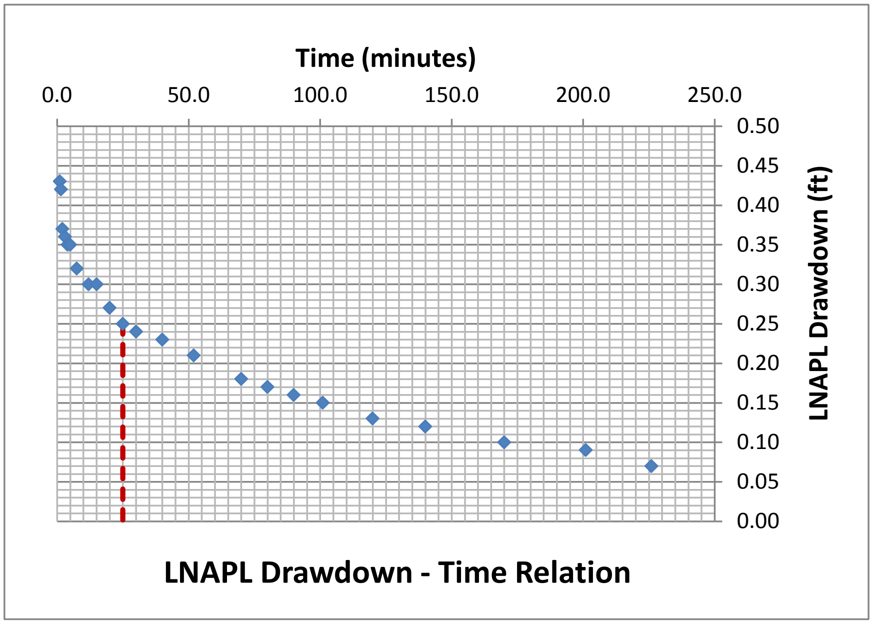


Figure 7.4. LNAPL Drawdown vs. Time Curve (Fig. 10 from "Figures" Worksheet)

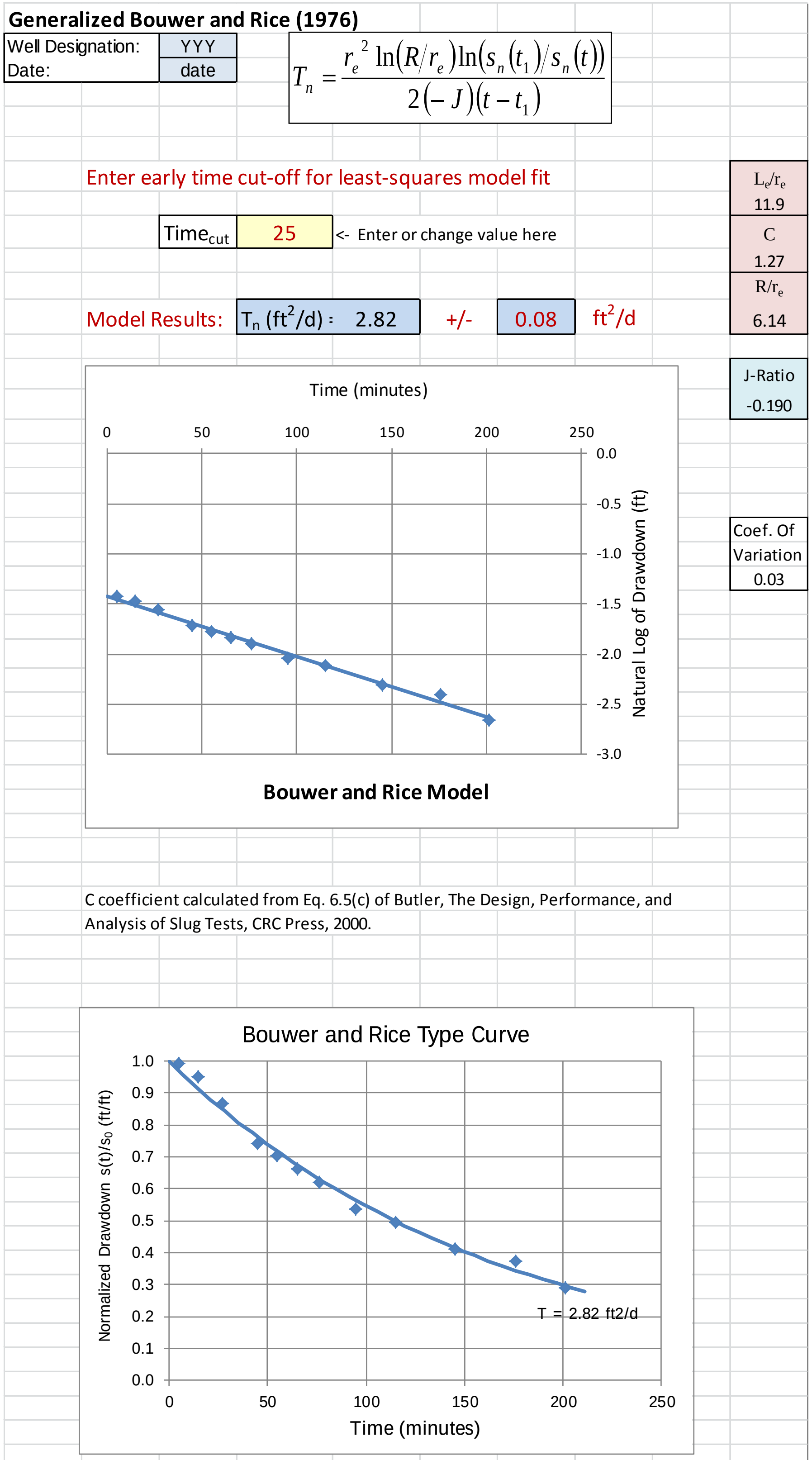


Figure 7.5. **“B&R” worksheet**

7.5 “C&J” Worksheet

The Cooper and Jacob (C&J) worksheet is used to calculate the LNAPL transmissivity value based on the Cooper and Jacob (1946) equation. [As described in Appendix D, the Theis equation is actually used in calculations, though the more commonly used Cooper and Jacob designation has been retained here.] The method used is modified from that presented as method three of Huntley (2000). The method is outline in Appendix D. Unlike the B&R method, both the C&J method and the CB&P method use a storage parameter (S_n) in addition to LNAPL transmissivity (T_n) to fit the model and data. Use of the storage parameter implies that the time origin is critical to data analysis for both methods. Yet, it is recognized that early-time data can be impacted by filter-pack drainage and not reflect natural LNAPL flow from the formation to the well. Thus the user may specify a cut-off time to eliminate early-time data from the analysis. To provide consistency with the model basis, the user may also adjust the time origin to a fraction of the cut-off time. There is little guidance towards an appropriate fraction, though the range 50 % to 80 % appears reasonable. Recommended values are 0.6 or 2/3, whichever is more convenient. Both the cut-off time and time adjustment values are specified by the user (light yellow cells). For further discussion, see Section 6.2. In some cases, repeating the test with alternative field methods that reduce the removal time or reduce the filter pack recharge may help reduce the need for the time adjustment.

The estimate of LNAPL transmissivity is found by minimizing the root-mean-square error between model prediction and data by varying the storage coefficient and LNAPL transmissivity. An example worksheet is shown in Figure 7.6. The Adjusted Time is set to 6 minutes, which is 60 % of the cut-off time. The Excel “Solver” function is used to find the root-mean-square error, which is the square root of the sum square difference (SSD) provided by Eq. (D.6). Instead of using “Solver” to find both S_n and T_n, it is recommended that the user select a trial value of S_n and use “Solver” to find T_n. Alternatively, the letter d may be entered as the Trial S_n value to select the default option described in Section 6.3.

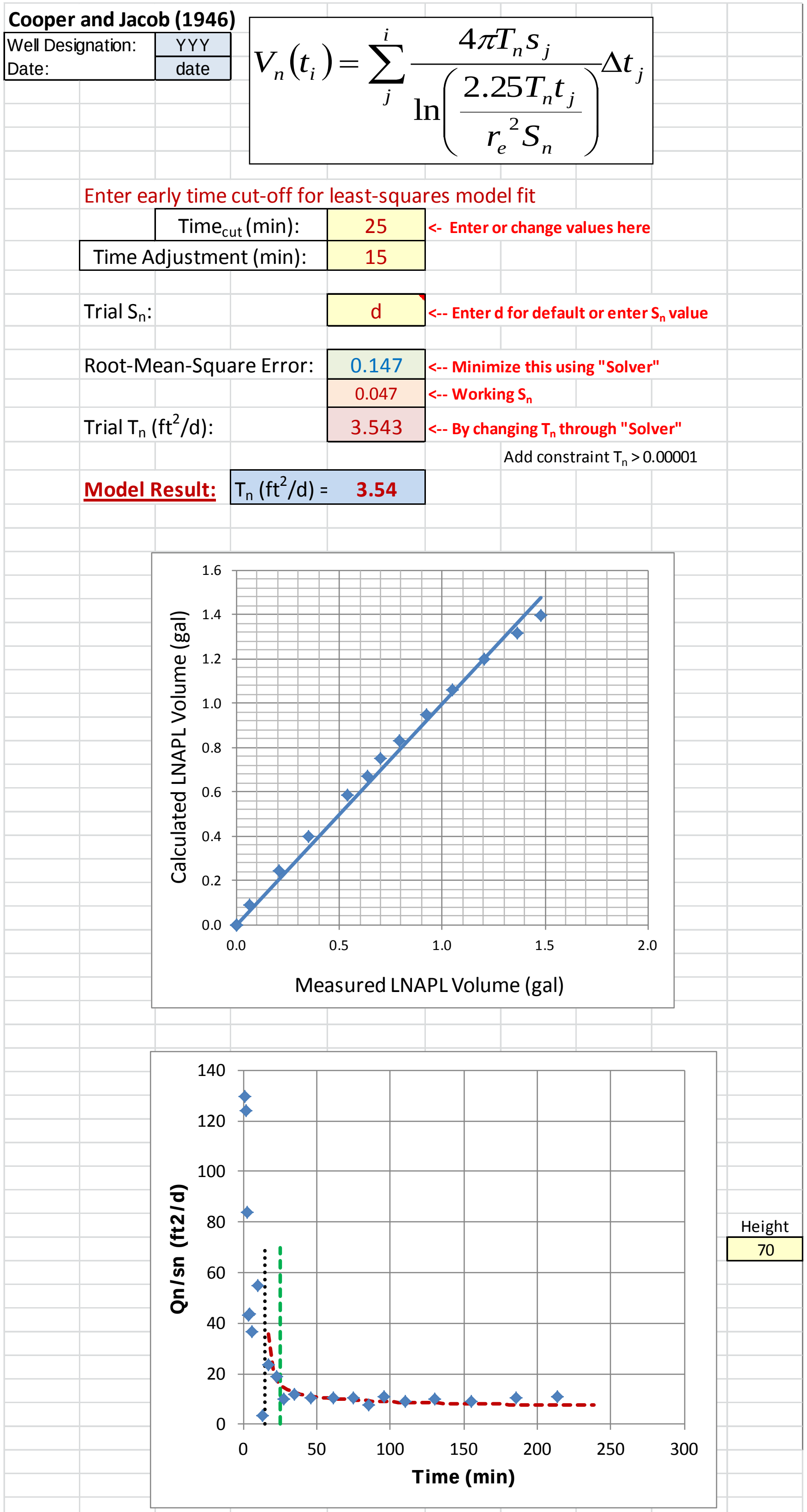


Figure 7.6. “C&J” worksheet

7.6 “CB&P” Worksheet

The Cooper, Bredehoeft and Papadopulos (CB&P) worksheet is used to calculate the LNAPL transmissivity value based on the Cooper, Bredehoeft and Papadopulos (1967) slug test model. Application of this model for an LNAPL baildown test is described in Appendix E, and an example worksheet is shown in Figure 7.7. For application of this method, there are three unknown parameters: initial LNAPL drawdown $s_n(0)$, LNAPL transmissivity T_n, and LNAPL storage coefficient S_n. Trial estimates of these quantities are entered on the worksheet, and the Excel “Solver” function is used to minimize the root-mean-square error given by the square-root of Eq. (E.7). An estimate of the initial drawdown is provided by the extrapolated drawdown at the cut-off time. Alternatively, the initial drawdown is selected so that the drawdown ratio s_n/s_{n0} extrapolates to 1 at time = 0 (which includes the cut-off time adjustment). The algorithm used to evaluate the model equations is derived from Charbeneau (2000).

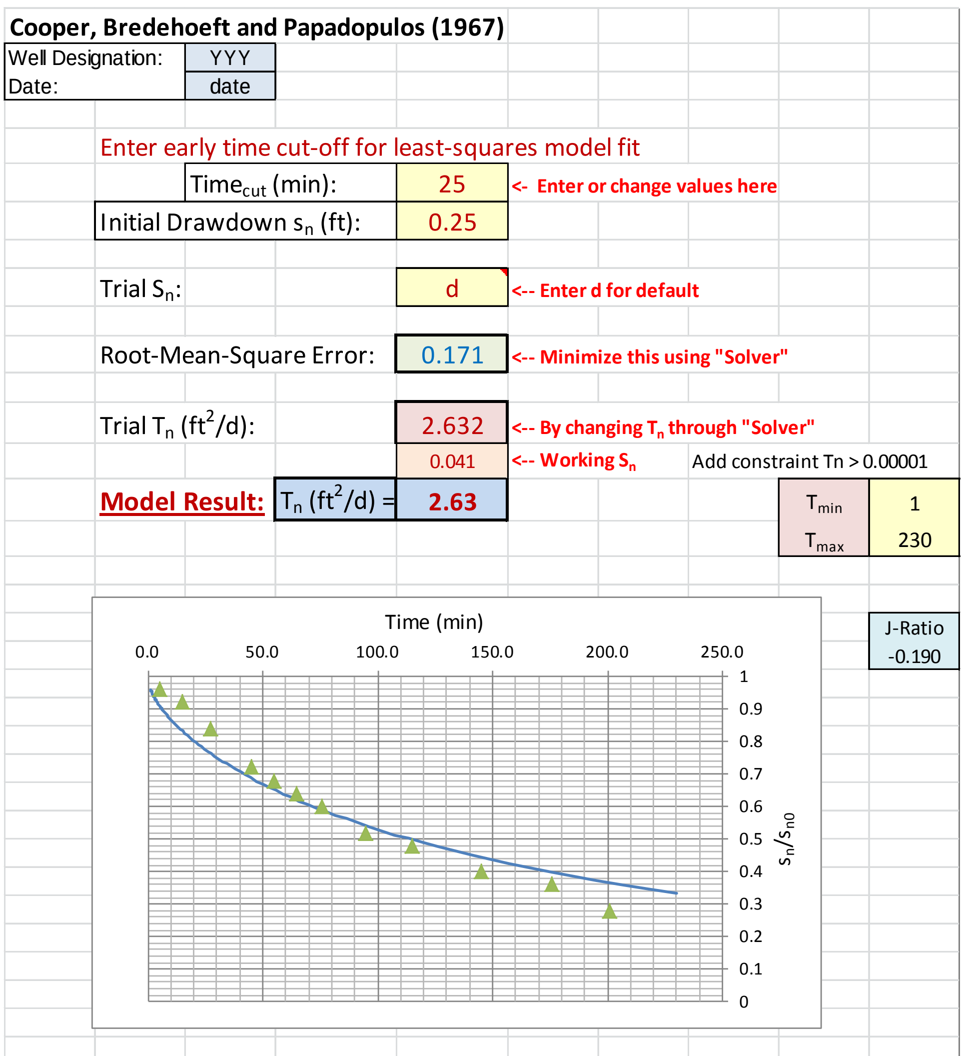


Figure 7.7. “CB&P” worksheet

7.7 "B&R Type Curve" Worksheet

This worksheet presents a type curve based on the Bouwer and Rice method along with a supporting data sheet. The type curve was developed to support rapid field evaluation of LNAPL baildown tests when the user is primarily interested in 'order-of-magnitude' estimates of LNAPL transmissivity and possible early termination of a field test of a particular well. The type curve is a normalized plot of the Bouwer and Rice solution present at the top of the B&R worksheet, where the type curve shows normalized drawdown as a function of time for selected values of LNAPL transmissivity. The use of the type curve requires that the well-specific construction and specific yield data be entered into the "Data" worksheet in order to generate the correct type curves. A J-ratio of (ρ_r – 1) is recommended unless well-specific behavior is available. The user may change the range of LNAPL transmissivity curves shown on the curve and associated maximum times (which may correspond to the test time) (light yellow cells). The lower part of the worksheet provides a data sheet that may be copied for field use. The type curve application was suggested by Andrew Kirkman. Figure 7.8 shows an example worksheet.

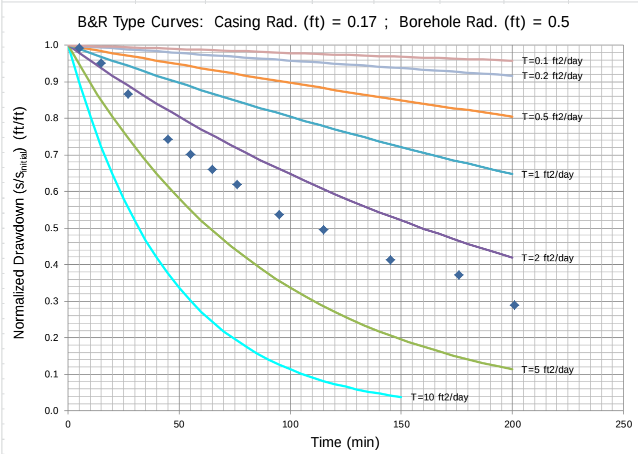
Bouwer and Rice Short Term LNAPL Mobility Test Type Curves

B&R Type Curves: Casing Rad. (ft) = 0.17 ; Borehole Rad. (ft) = 0.5

Enter these values

Type Curve ID	Type Curve Name	Notes	Max Time (min)	Transmissivity (ft^2/day)
1	T=10 ft2/day		150	10
2	T=5 ft2/day		200	5
3	T=2 ft2/day		200	2
4	T=1 ft2/day		200	1
5	T=0.5 ft2/day		200	0.5
6	T=0.2 ft2/day		200	0.2
7	T=0.1 ft2/day		200	0.1

J-Ratio	
-0.192	<-- If uncertain use
	-0.22



Field Data

Record Data in Fields Below						Calculate and Plot Fields Below		
Well ID		Well Dia. (ft)	Total Depth (ft)					
Notes	Date	Time	Elapsed Time (min)	Depth To Product (TOC)	Depth to Water (TOC)	Product Thickness (ft)	Drawdown (s) DTP-DTP(initial) (ft)	Normalized Drawdown ($s/s_{initial}$)
Initial Measurement								
Stopped Bailing/Start Gauging			0					
Well Starts recovering								

Figure 7.8. "B&R Type Curve" worksheet

7.8 “Confined” Worksheet

The “Confined” worksheet is used to estimate LNAPL transmissivity under confined LNAPL conditions. This worksheet is visible and available when the CONFINED button is selected under Step 3 Conditions on the “Selection and Results” worksheet. The basic equations are presented in Appendix F, and an example worksheet is shown in Figure 7.9. The depth to base of confining bed is entered to determine the effective limiting thickness of LNAPL in the well b_{nW} (see Eq. F.2). The constant discharge from the steady discharge portion of the test is then entered and used to calculate the LNAPL transmissivity. The radius of influence term for the skimmer well equation is determined from the Bouwer and Rice (B&R) worksheet.

Confined LNAPL Model:

$$T_n = \frac{Q_n \ln\left(R/r_w\right)}{2\pi\left(1-\rho_r\right)\left(b_{nR}-b_{nW}\right)}$$

Well Designation:	HMW-44C
Date:	12-Aug-09

Depth to base of confining bed (ft bgs) [from boring log	29.35
Constant LNAPL discharge to well (ft^3/d):	8
Depth to top of screen (ft bgs):	27.2
Corrected water table elevation (ft bgs):	28.0
Limiting effective LNAPL thickness in well, b_{nW} (ft):	1.7
Limiting effective LNAPL drawdown, s_{nW} (ft):	0.09
Initial LNAPL thickness, b_{nR} (ft):	2.1
Radius of influence ratio (from Bouwer and Rice), R/r_w:	6.5
LNAPL Transmissivity, T_n (ft^2/d):	**25.67**

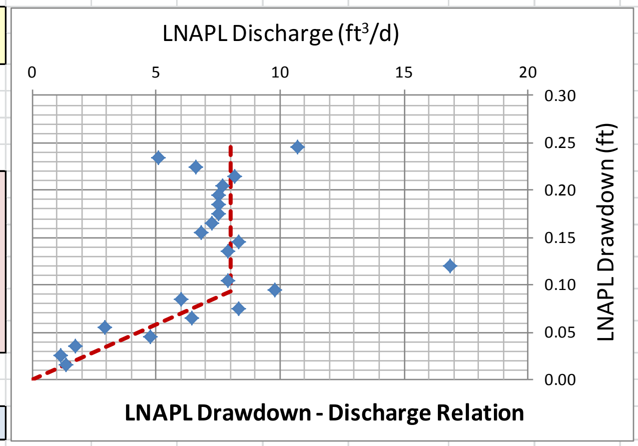


Figure 7.9. “Confined” worksheet

7.9 “Perched” Worksheet

The “Perched” worksheet is used to estimate LNAPL transmissivity under perched LNAPL conditions. The basic equations are presented in Appendix G. The depth (bgs) to the top of the perching layer, DZ_{12}, is entered to determine the effective limiting drawdown of LNAPL in the well based on the initial depth to product DTP_0. The constant discharge from the steady discharge portion of the test is then entered and used to calculate the LNAPL transmissivity. The radius of influence term for the skimmer well equation is determined from the Bouwer and Rice (B&R) worksheet. The worksheet mirrors the “Confined” worksheet and is not repeated here.

8. Examples and Important Diagnostic Tools

An important diagnostic tool is a plot of the well drawdown versus well discharge. The general shape of this relationship can be used to identify conditions with significant borehole recharge from the filter pack, screen for perched or confined LNAPL conditions, and help identify whether formation LNAPL was initially in equilibrium with well-bore LNAPL (and whether drawdown adjustment might be necessary). Some example curves are discussed below.

Figure 8.1 shows a number of drawdown-discharge curves. Figure 8.1(a) shows an example for unconfined LNAPL where significant borehole recharge from the filter pack is not an issue. While the initial calculated data (point with large Q_n, large s_n) is not consistent with other data on this figure, it is based on measurements taken at 0.5 and 1 minute into the test and could be associated with measurement uncertainty. Figure 8.1(b) gives an example where borehole recharge from the filter pack is significant. The initial data show large discharge which is primarily associated with filter pack drainage. Once the drawdown falls below 0.35 feet, consistent linear drawdown-discharge behavior is observed.

Figures 8.1(c) and (d) show the same data set. First, Figure 8.1(c) shows that significant borehole recharge does occur. Also, significantly, the linear part of the curve does not approach zero drawdown at zero discharge. Instead, it appears that the extrapolated limit has zero discharge with s_n = 0.08 ft. Such behavior suggests that the formation and wellbore LNAPL fluids were not initially in equilibrium, and that a drawdown correction of Δs_n = 0.08 ft should be applied to the data before LNAPL transmissivity analysis. Figure 8.1(d) shows an expanded view of this data <u>after</u> the correction has been applied. Such a correction does affect the resulting LNAPL transmissivity value that is calculated. With the correction Δs_n = 0.08 ft, the average LNAPL transmissivity T_n = 2.99 ft^2/d with CV = 0.16. For the same data and analysis without the 0.08 ft correction, the drawdowns are larger and the estimated LNAPL transmissivity is smaller with an average value T_n = 1.89 ft^2/d and coefficient of variation = 0.19.

Figure 8.1(e) shows behavior that suggests confined (or perched) LNAPL conditions. In this case it represents confined conditions with the water table initially located at an elevation above the confined LNAPL and with resulting exaggerated LNAPL thickness in the well. Immediately following LNAPL removal from the well, there is no LNAPL within the wellbore to “push” back against LNAPL inflow from the formation, and LNAPL discharge from the formation occurs at a constant rate while the LNAPL drawdown is declining. Once the LNAPL column within the wellbore increases in thickness to contact the mobile formation LNAPL, the inflow rate is retarded and decreases at a linear rate along with the LNAPL drawdown. One may analyze LNAPL transmissivity from the constant inflow rate along with limiting LNAPL drawdown value (about 0.1 ft in this example), or one can use standard (unconfined) equations on the data from the linear drawdown-discharge part of the curve. Figure 8.1(f) shows large initial LNAPL inflow, which in this case is likely associated with aggressive purging in addition to filter pack drainage (this corresponds to Figure B.1(c)).

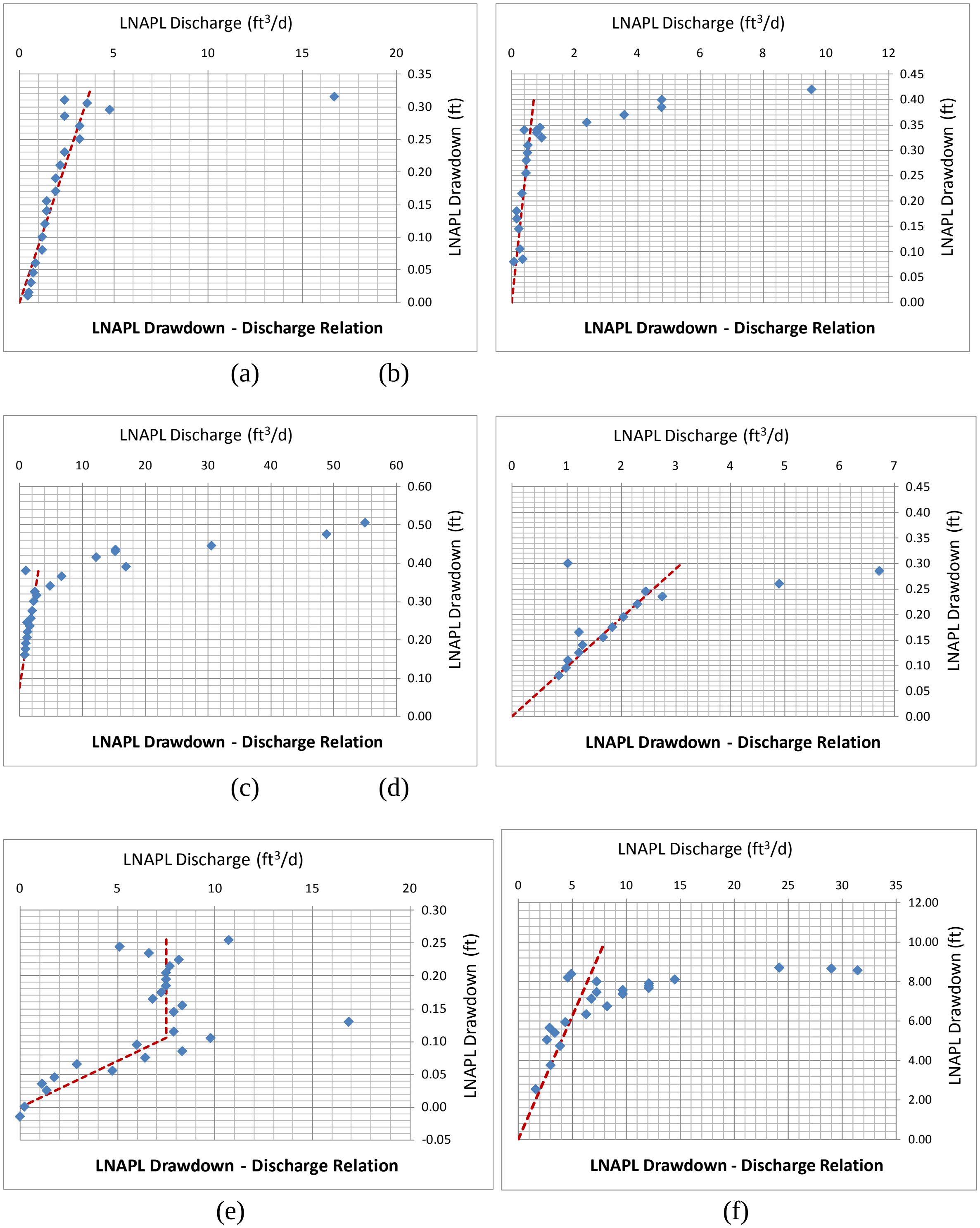


Figure 8.1. Example LNAPL drawdown-discharge curves

A couple of examples are considered in a little more detail. The first example, Figure 8.2, shows results from a baildown test with initial LNAPL thickness approximately 1.5 ft. During fluid removal from the wellbore both LNAPL and water were removed, and there is significant fluid recovery during approximately the first 6 minutes of the test, after which the calculated water table elevation remains stable. While there is significant scatter in the early-time data (larger drawdown values), the latter-time data shows a nearly linear relationship between discharge and drawdown. It also appears that the drawdown intercept with the $Q_n = 0$ axis has a residual value of about $s_n = 0.02$ ft (0.24 inch). While this magnitude correction appears small, it does represent nearly 20 % of the drawdown being analyzed during the test analysis. A drawdown correction of magnitude 0.018 ft is applied (larger corrections would result in negative drawdown and require further individual data adjustment or use of an alternative model for analysis). A cut-off of 10 minutes is assumed, and the data gives $J = -0.179$. The calculated LNAPL transmissivity is $T_n = 10.45$ ft^2/d, and the coefficient of variation (ratio of standard deviation to mean transmissivity value based on the three methods of data analysis that are discussed below) is $CV = 0.13$. [If drawdown correction is not applied the model provides a LNAPL transmissivity estimate $T_n = 5.34$ ft^2/d with CV = 0.28.]

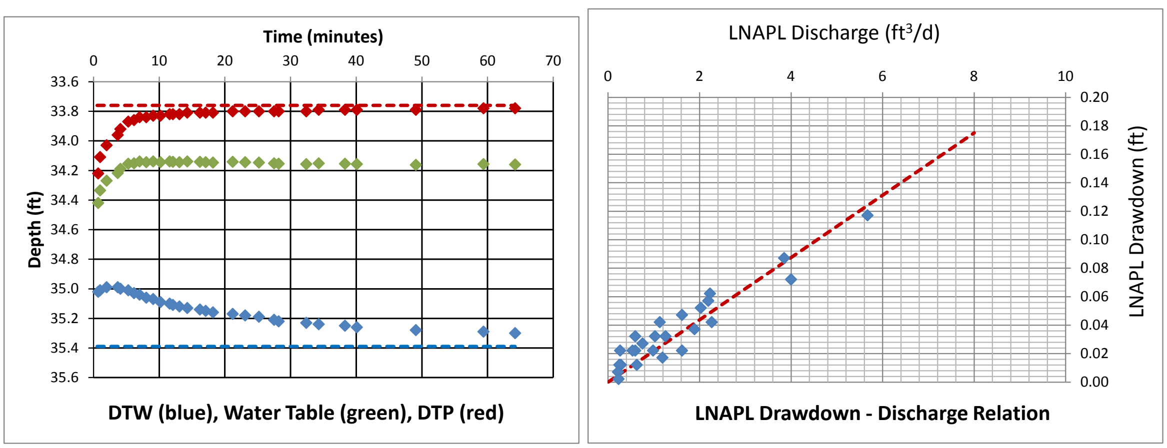


Figure 8.2. Example E1: T_n = 10.4 ft^2/d; CV = 0.13

The second example shown in Figure 8.3 represents a test where purging resulted in significant removal of both LNAPL and groundwater. The bottom of screen is located at a depth 27 ft, and this is the initial elevation for fluid interfaces in the well. Figure 8.3(b) shows the LNAPL drawdown-discharge graph. The expected linear relationship between LNAPL drawdown and discharge is not observed until the drawdown reaches approximately 4.2 ft. Figure 8.3(c) shows that the J-ratio is $J = -1.18$. This is consistent with a rising water table and LNAPL-water interface elevation throughout the test. Figure 8.3(d) is the graph of LNAPL drawdown versus time (Fig. 10 on the “Figures” worksheet). The LNAPL drawdown is 4.2 ft at a time of 24 minutes. A cut-off time of 25 minutes is assumed, with an Adjustment Time Δt_a = 15 minutes for the C&J and CB&P methods. Results from the three analysis methods give $T_n = 3.08$ ft^2/d with $CV = 0.07$.

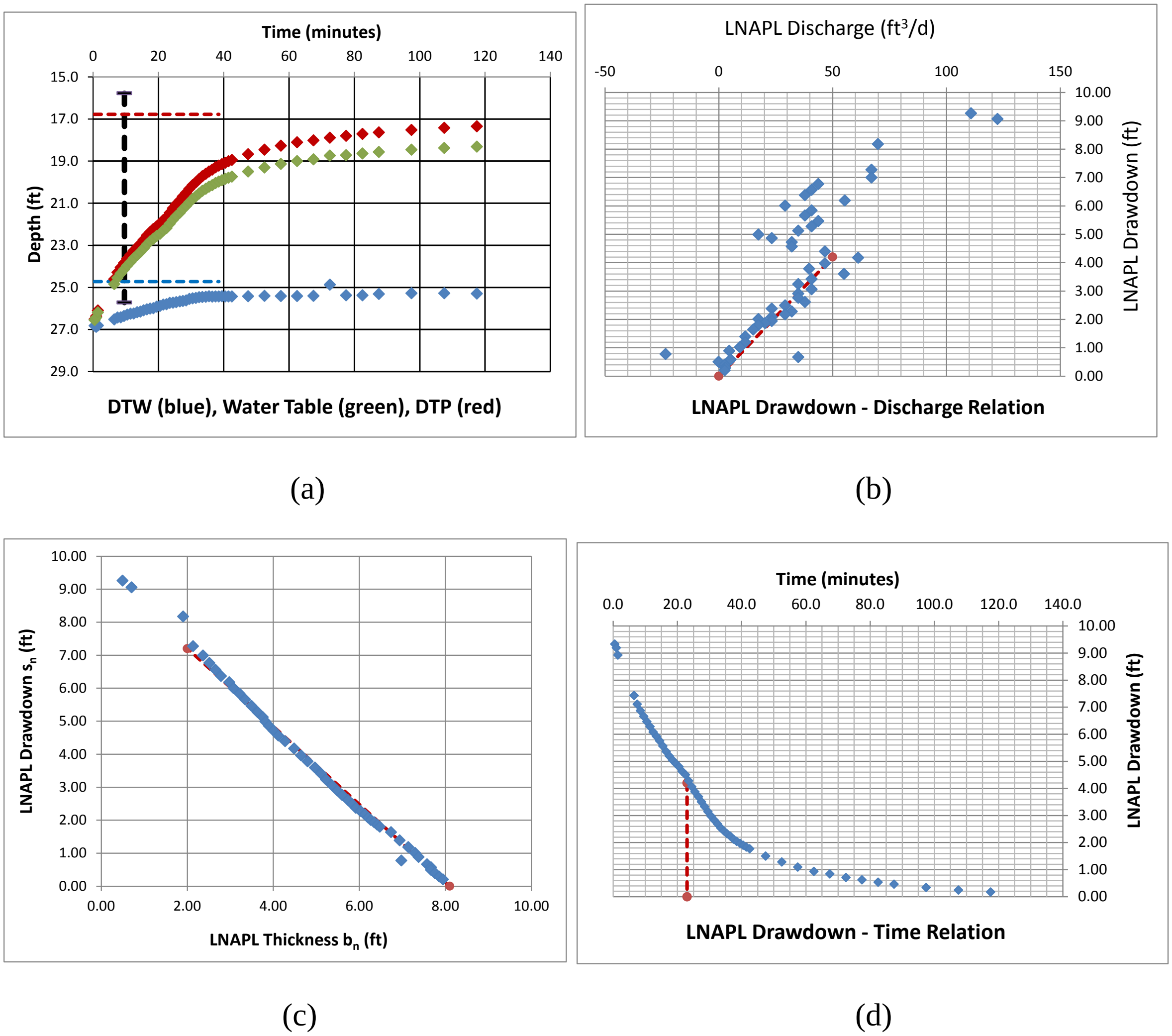


Figure 8.3. **Example E2: T_n = 3.08 ft^2/d; CV = 0.07**

A third example shown in Figure 8.4 corresponds to the confined LNAPL test shown in Figure 7.9. The LNAPL transmissivity value calculated in Figure 7.9 is based on a single data corresponding to the drawdown and discharge at the end of the "constant discharge" segment. The following example shows that consistent results can be achieved if only the late-time data is used. The drawdown-discharge curve of Figure 8.4(b) shows that the linear relationship is observed starting at a drawdown of about 0.1 ft. Figure 8.4(c) shows that J = -0.257, which is close to the values that would be used with the Huntley method of analysis (for this well, ρ_r = 0.764). Figure 8.4(d) shows that a drawdown of 0.1 ft is observed at a time 12 minutes, which serves as the cut-off for the three methods of analysis. A time adjustment Δt_a = 8 minutes is used for the C&J method. Results from the three methods give T_n = 23.56 ft^2/d with CV = 0.14. This LNAPL transmissivity estimate compares favorably with the estimate T_n = 25.67 ft^2/d from Figure 7.9.

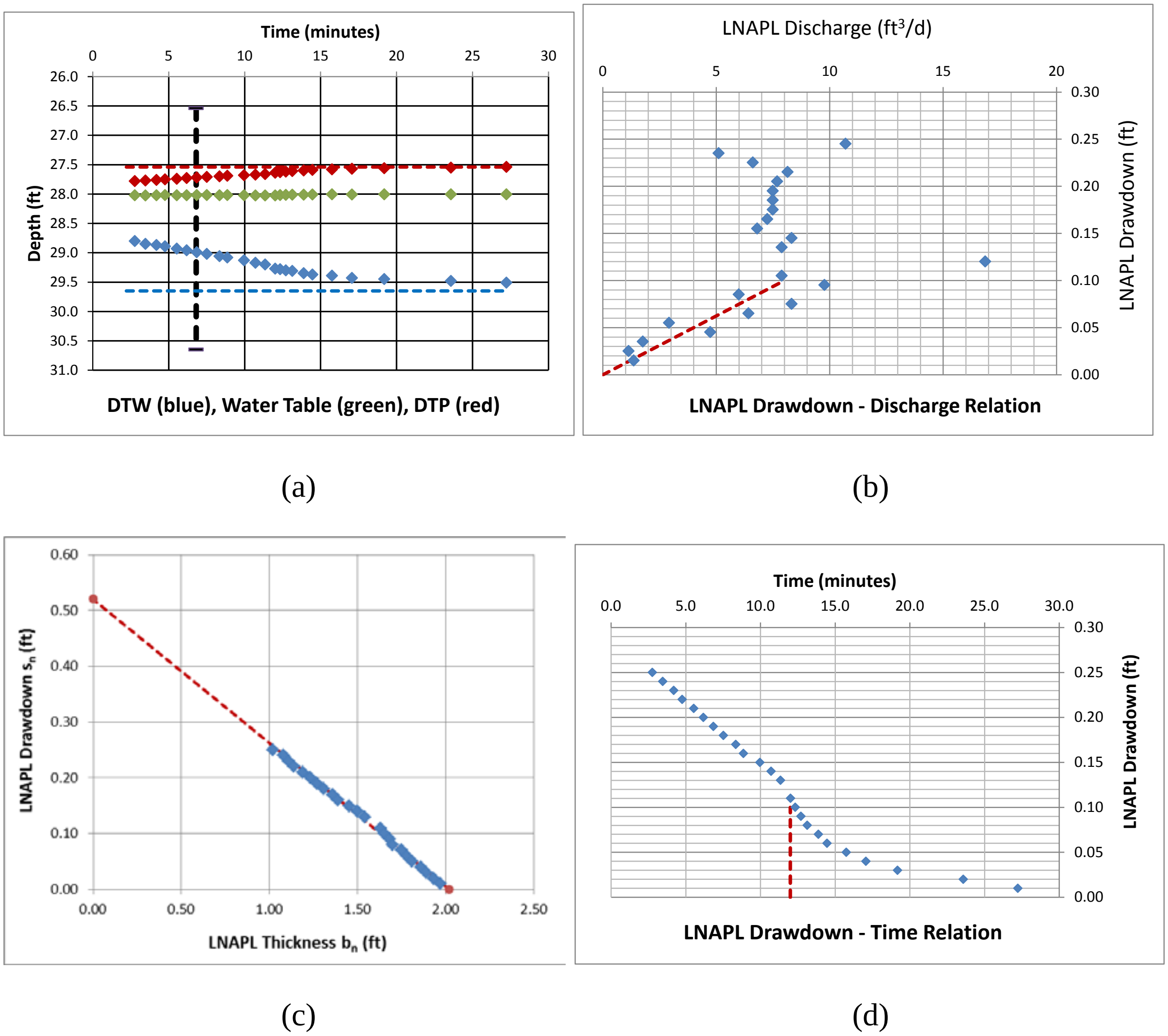


Figure 8.4. Example E3: T_n = 23.56 ft^2/d; CV = 0.14

8. Bibliography

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Appendix A: Kirkman J-Ratio

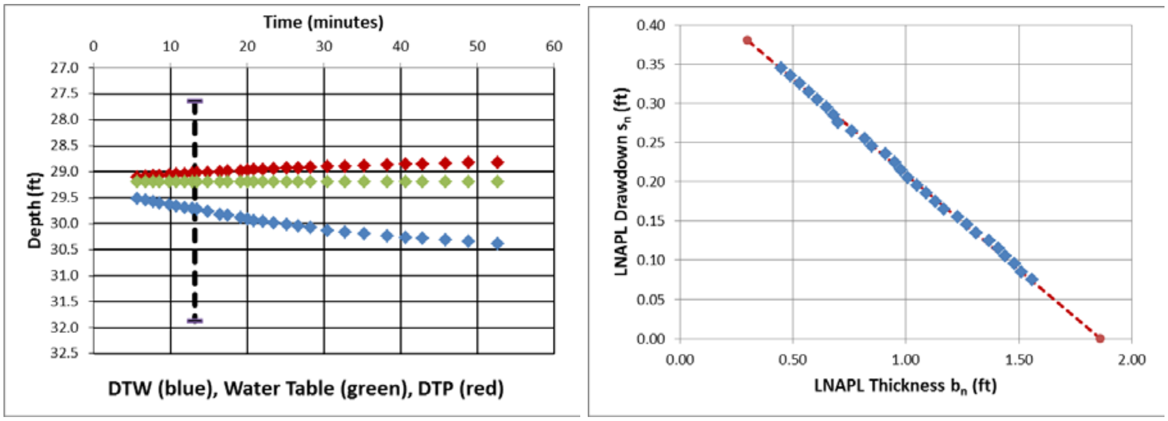
The LNAPL discharge from the formation to the well is also related to changes in LNAPL drawdown. This relationship is critical to the generalized Bouwer and Rice method and Cooper, Bredehoeft and Papadopulos method discussed herein. With the effective well radius (see Appendix B), the relationship is written

(A.1) $$Q_n = \pi r_e^{\,2} \frac{db_n}{dt} = \frac{\pi r_e^{\,2}}{J} \frac{ds_n}{dt}$$

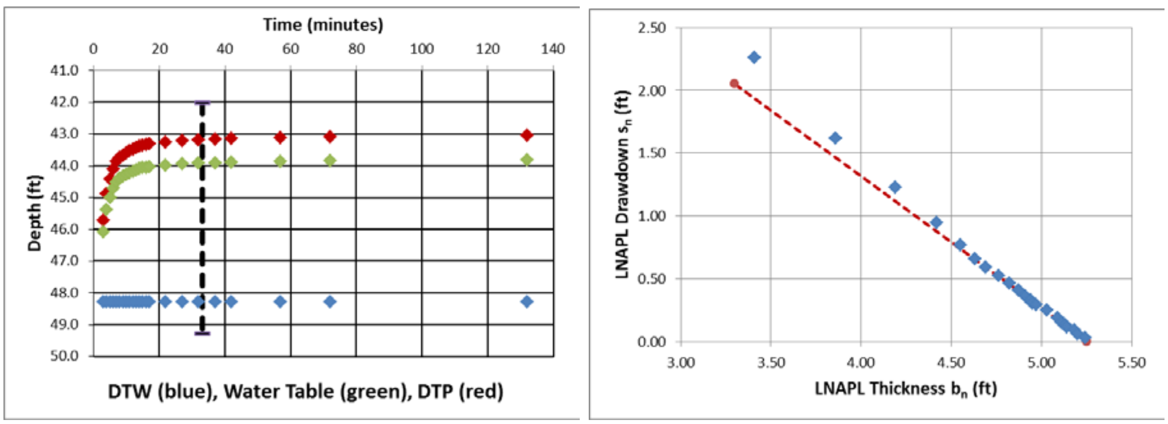
Equation (A.1) states that the LNAPL discharge is equal to the rate of LNAPL accumulation within the well. Andrew Kirkman (personal communication) has suggested that this rate can be generally related to the change in LNAPL drawdown through introduction of a J-ratio parameter. The J-ratio is the slope of the linear relationship between LNAPL drawdown and LNAPL well thickness:

(A.2) $$J = \frac{\Delta s_n}{\Delta b_n}$$

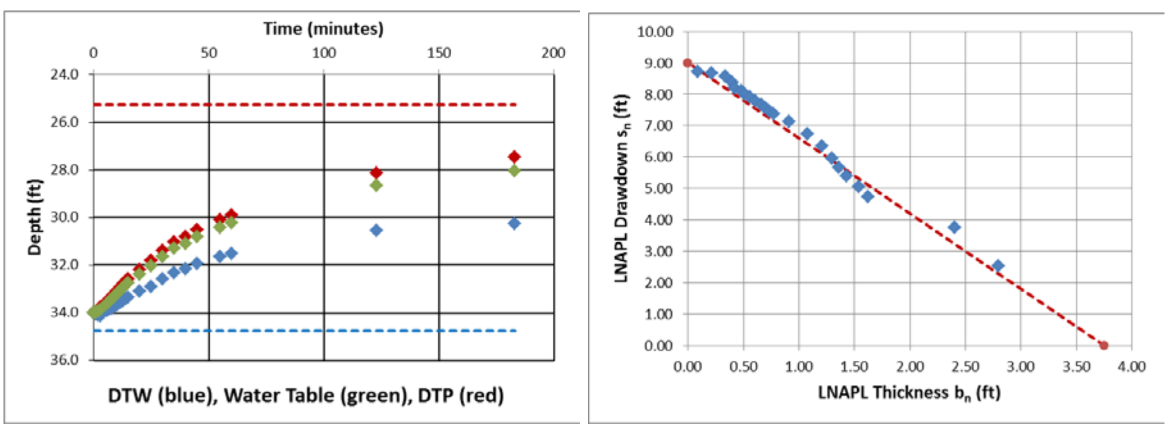
The magnitude of the J-ratio varies with the nature of LNAPL recharge to the well. If, during a baildown test, LNAPL is removed from the well using a peristaltic pump with no removal of water and the water recovers quickly (i.e., water transmissivity is much greater than LNAPL transmissivity through the well screen), then the water table elevation should remain constant and J = - (1 – ρ_r). If both LNAPL and water are removed during a baildown test, and if the LNAPL transmissivity greatly exceeds the water transmissivity for recharge to the well, then the elevation of the LNAPL-water interface can remain constant and J = -1. Values outside of this range are also observed. Three examples are shown in Figure A.1. In case (a) the water table elevation remains constant, and the value J = -0.244 is close to J = –(1 – ρ_r) [for this well, ρ_r = 0.764]. For case (b), the LNAPL-water interface elevation remains constant and J = -1.051. For case (c) the interface elevations increase throughout the recovery period and J = -2.400.



(a)



(b)



(c)

Figure A.1. Variation of J-ratio with nature of recharge to the well. (a) J = -0.244; (b) J = -1.051; (c) J = -2.400

Appendix B: Effective Well Radius

During a baildown test the fluid levels in a well are monitored, and it is necessary to relate the LNAPL volume flux, dV_n, into the well to the increase in LNAPL thickness, db_n, or equivalently to the increase in LNAPL head, dh_n, or decrease in LNAPL drawdown, $-ds_n$. By definition of the J-ratio (see Eq. A.2), $ds_n = J\, db_n$. Clearly,

(B.1) $$dh_n = dz_{an} = -\, ds_n = -\, J\, db_n$$

(B.2) $$db_n = dz_{an} - dz_{nw} \rightarrow dz_{nw} = dz_{an} - db_n = -\,(J + 1)\, db_n$$

In general during a baildown test, after removal of LNAPL from the well, the air-LNAPL interface elevation increases ($dz_{an} > 0$). However, depending on test conditions, the elevation of the LNAPL-water interface can increase, decrease, or remain constant. This is accounted for through the magnitude of the J-ratio. If the J-ratio magnitude is less than -1, then the elevation of the LNAPL-water interface increases ($dz_{nw} > 0$). Otherwise, if the magnitude of the J-ratio is greater than -1, then the elevation of the LNAPL-water interface decreases ($dz_{nw} < 0$). Finally, if $J = -1$, then the elevation of the LNAPL-water interface remains constant ($dz_{nw} = 0$).

The increase in LNAPL volume within the well (well casing plus filter pack) depends on the location of the LNAPL column within the well. Three cases are shown in Figure B.1. In the first case both z_{an} and z_{nw} are located within the casing. In the second case z_{an} is located within the casing while z_{nw} is located within the screen section of the well with filter pack. Finally, in the third case both z_{an} and z_{nw} are located within the screened section with filter pack. The elevation of top of screen (TOS) and bottom of screen (BOS) are also shown.

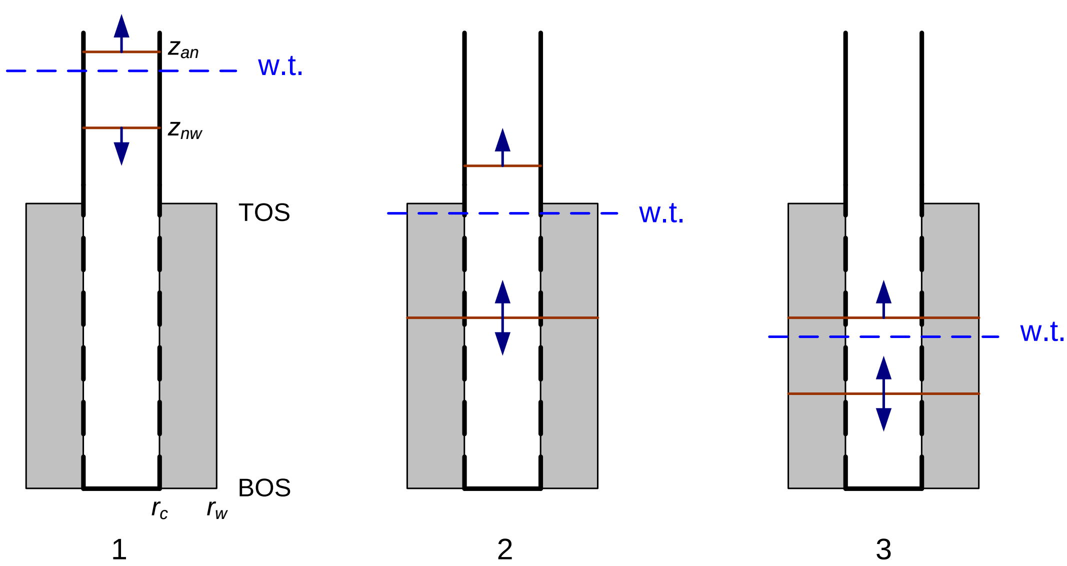


Figure B.1. Three cases showing configuration of LNAPL column in a well

To simplify analysis, it is useful to handle the three cases shown in Figure B.1 with a consistent notation by introducing the effective well radius, r_e. Then for all three cases one has

(B.3) $$dV_n = \pi r_e^{\,2} \, db_n$$

For Case 1 one clearly has

(B.4) $$r_{e1} = r_c$$

Similarly, for Case 3 one has

(B.5) $$r_{e3} = \sqrt{r_c^{\,2} + S_y \left(r_w^{\,2} - r_c^{\,2} \right)}$$

Case 2 is a little more subtle. One has

$$dV_n = \pi r_{e1}^{\,2} \left(dz_{an} \right) + \pi r_{e3}^{\,2} \left(- dz_{nw} \right)$$

Using Eqs. (B.1) and (B.2) this may be written

$$dV_n = \pi r_{e1}^{\,2} \left(-J \, db_n \right) + \pi r_{e3}^{\,2} \left(\left(J + 1 \right) \, db_n \right)$$

Comparing this result with Eq. (B.3) gives

(B.6) $$r_e = \sqrt{-J \, r_{e1}^{\,2} + \left(J + 1 \right) r_{e3}^{\,2}}$$

Appendix C: Generalized Bouwer and Rice Method

The Bouwer and Rice (1976) method for slug test analysis is based on combining a simple representation for flow to the well from the Thiem equation (steady state radial flow to a well) and continuity of fluids within the well. The flow equation takes the form

$$Q_n = \frac{2\pi T_n s_n}{\ln(R/r_w)} \tag{C.1}$$

Importantly, in Eq. (C.1) it is assumed that the effective radius of influence R is constant, so that there is a linear relation between the discharge Q_n into the well and the LNAPL drawdown s_n. The continuity equation for fluids in the well is problematic only in terms of determining an appropriate effective well radius r_e, as discussed above. With the effective well radius determined and with use of the Kirkman J-ratio, the continuity equation takes the form

$$Q_n = \pi r_e^{\,2} \frac{db_n}{dt} = \frac{\pi r_e^{\,2}}{J} \frac{ds_n}{dt} \tag{C.2}$$

Combining Eqs. (C.1) and (C.2) and integrating gives the generalized Bouwer and Rice formula for determining the LNAPL transmissivity

$$\frac{ds_n}{s_n} = \frac{2\,J\,T_n}{r_e^{\,2}\ln(R/r_w)}dt \quad \rightarrow \quad T_n = \frac{r_e^{\,2}\ln(R/r_w)\ln\left(s_n(0)/s_n(t)\right)}{2(-J)t} \tag{C.3}$$

Appendix D: Cooper and Jacob/Jacob and Lohman Method

Jacob and Lohman (1952) investigated the non-steady flow to a free-flowing well with constant drawdown in an extensive confined aquifer. The model assumes that the well drawdown s_w is constant (= difference between the static head measured during shut-in of the well and the outflow opening of the well). The discharge to the well is given by the following expression

(D.1) $$Q = 2\pi T s_w G(u_w)$$

The function G( ) is the Jacob-Lohman free-flowing discharge function and

(D.2) $$u_w = \frac{r_e^{\,2} S}{4Tt}$$

For all but extremely small values of t, Jacob and Lohman state that the function G( ) can be approximated by G ( ) = 2/W( ), where W( ) is the Theis well function. If, in addition, $u_w < 0.01$, the Theis well function may be approximated as follows:

(D.3) $$W(u_w) \cong \ln\left(\frac{0.561}{u_w}\right)$$

Thus Eq. (D.1) becomes

(D.4) $$Q = \frac{4\pi T s_w}{\ln\left(2.25Tt/r_e^{\,2}S\right)}$$

Equation (D.4) is the Cooper and Jacob (1946) approximation for the Theis well function for transient flow to a well in a confined aquifer with constant discharge and variable drawdown. Thus we find that Eq. (D.4) approximately applies both for constant drawdown and variable discharge, and for constant discharge and variable drawdown. During a baildown test both the LNAPL drawdown and discharge vary with time. With the C&J method, it is assumed that this relationship holds throughout the recovery period following baildown.

In application for baildown test analysis, Eq. (D.4) can be integrated between times t_i and t_{i+1} to give the volume inflow to the well as follows:

(D.5) $$V(t_i, t_{i+1}) = \int_{t_i}^{t_{i+1}} Q_n \, dt = \int_{t_i}^{t_{i+1}} \frac{4\pi T_n s_n}{\ln\left(2.25T_n t/r_e^{\,2}S_n\right)} dt$$

The volume inflow to the well is separately measured (see Eq. 5.2). The calculated inflow volume from the right of Eq. (D.5) depends on the drawdown, which is also separately measured (see Eq. 5.1) and the parameters T_n and S_n. By comparing the measured and calculated cumulative inflow volumes for each time increment, the parameters T_n (and S_n) can be estimated using the method of least squares. The sum-square-difference (SSD) is calculated using

(D.6) $$SSD = \sum_{J=1}^{N}\left[\sum_{i=1}^{J} Q_{ni}\Delta t_i - \sum_{i=1}^{J}\frac{4\pi T_n s_i}{\ln\left(2.25T_n\left(t_{i+1/2}-\Delta t_a\right)/r_e^{\,2}S_n\right)}\Delta t_i\right]^2$$

In Eq. (D.6), N = number of time increments during the baildown test, $\Delta t_i = t_{i+1} - t_i$, $t_{i+1/2} = (t_i + t_{i+1})/2$, and Δt_a = time adjustment factor that may be applied (see discussion in Section 6.2). The LNAPL transmissivity is estimated by minimizing the SSD in Eq. (D.6).

Fitting of data and estimation of LNAPL transmissivity is based on comparing the measured volume inflow to the well versus the calculated inflow using the Cooper and Jacob equation. It is of some interest to see how the data compares directly with the Cooper and Jacob equation. For this purpose, the ratio Q_n/s_n is plotted as a function of time, as shown in Figure D.1. The red-dashed curve shown in this figure is calculated using the following:

(D.7) $$\frac{Q_n}{s_n} = \frac{4\pi T_n}{\ln(2.25T_n\left(t-\Delta t_a\right)/r_e^{\,2}S_n)}$$

In Figure D.1, the vertical dotted and dashed lines show the Time Adjustment Δt_a and cut-off time, respectively. This figure is produced in the lower part of the C&J worksheet.

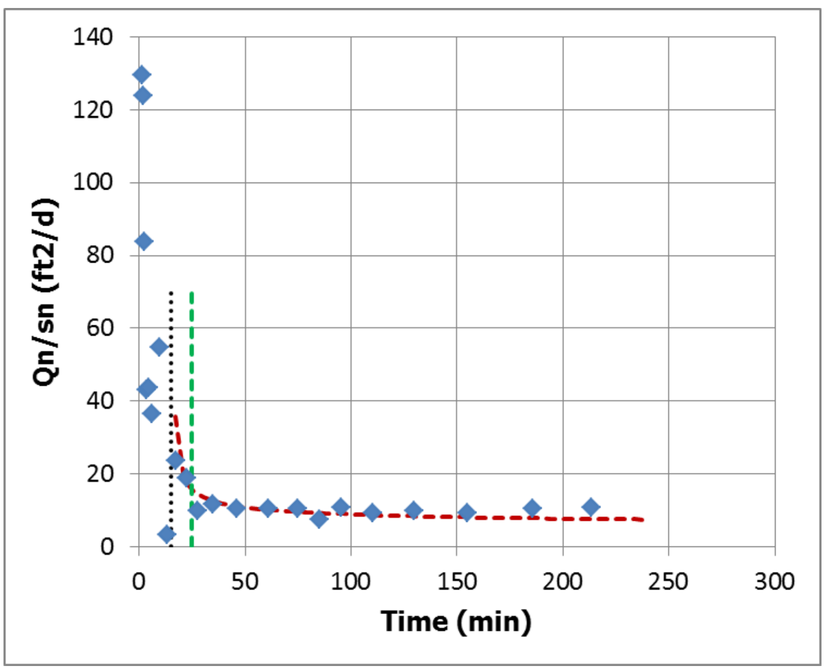


Figure D.1. Comparison of Cooper&Jacob equation with baildown test data. Red-dashed curve = C&J equation; green-dashed line (vertical) = cutoff time; black-dotted line (vertical) = time adjustment

Appendix E: Cooper, Bredehoeft and Papadopulos Method

A third model that can be used to estimate LNAPL transmissivity is based on the work of Cooper, Bredehoeft and Papadopulos (1967). The model assumes that a slug of fluid is added to the casing of a well in a confined aquifer, and the change in fluid levels is monitored. The configuration is shown in Figure E.1. The initial height of the water column above equilibrium, H_0, is related to the volume of water, V_w, added through

(E.1) $$H_0 = \frac{V_w}{\pi r_c^2}$$

The boundary conditions at the well are specified as

(E.2) $$h\left(r_s^+, t\right) = H(t)$$

(E.3) $$2\pi r_s T \frac{\partial h\left(r_s^+, t\right)}{\partial r} = \pi r_c^2 \frac{dH(t)}{dt}$$

The first of these equations states that the formation head just outside of the well screen is equal to the water column head above equilibrium within the well. The second of these equations equates the water volume flux into the formation to the change in water volume storage within the well casing. The following solution is presented by Cooper et al. (1967):

(E.4) $$\frac{H(t)}{H_0} = F\left(\frac{r_s^2 S}{r_c^2}, \frac{Tt}{r_c^2}\right)$$

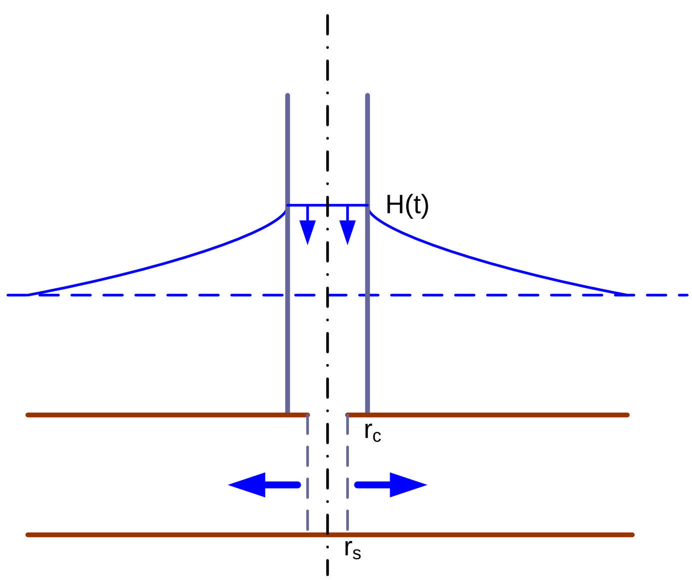


Figure E.1. Configuration for the Cooper et al. (1967) slug test

When applied to LNAPL in a well, the form of Eq. (E.4) and the boundary conditions specified by Eqs. (E.2) and (E.3) must be modified. Cooper et al. (1967) use the casing radius r_c in calculation of changes in well-bore storage. The screen radius r_s is used to designate the (radial) location where the LNAPL head (or drawdown) in the well-bore is equal to that in the formation. In analysis of LNAPL bail-down tests the effective radius r_e plays the same role as r_c. The presence of the filter pack in a bail-down test makes identification of an equivalent radius to r_s less obvious. A simple assumption is that r_e plays an equivalent role to r_s as well. Furthermore, the solution is written in term of the LNAPL drawdown, s_n. With Eq. (A.1), the boundary condition Eq. (E.3) can be written

(E.5) $$Q_n = -2\pi r_e T_n \frac{\partial s_n}{\partial r} = \pi\, r_e^{\,2} \frac{db_n}{dt} = \frac{\pi\, r_e^{\,2}}{J} \frac{ds_n}{dt}$$

These changes imply that Eq. (E.4) must be modified to

(E.6) $$\frac{s_n(t)}{s_n(0)} = F\left(S_n, \frac{(-J) T_n\, t}{r_e^{\,2}} \right)$$

Using the LNAPL drawdown (s_{ni}) versus time (t_i) data, a measure of how well the model fits the data is provided by the sum-square error specified by

(E.7) $$\sum_{i=1}^{N} \left[\frac{s_{ni}(t_i)}{s_n(0)} - F\left(S_n, \frac{(-J) T_n\, t_i}{r_e^{\,2}} \right) \right]^2$$

In Eq. (E.7), the summation is over all data included in the analysis.

Appendix F: Confined LNAPL

Figure F.1 (a) shows LNAPL confined beneath a fine-grain soil layer. The initial LNAPL thickness in an observation well, b_{nR}, depends on the water table elevation, z_{aw}, the LNAPL/water density ratio, ρ_r, and the initial elevation of the confined LNAPL-water interface in the formation and well, z_{nw}. During a baildown test the LNAPL discharge from the formation to the well is expected to initially be large, associated with rapid drainage of the filter pack and immediate well vicinity, and then the discharge should reach a constant magnitude that is determined by the radial LNAPL head difference experienced by the confined LNAPL. This head difference is equal to $(1 - \rho_r)(b_{nR} - b_{nW})$, and remains constant until the LNAPL column thickness in the well $b_n = b_{nW}$. For $b_n > b_{nW}$, the LNAPL head difference equals $(1 - \rho_r)(b_{nR} - b_n)$, and this magnitude decreases to zero ($b_n \rightarrow b_{nR}$) with further LNAPL inflow to the well. For this analysis it is assumed that the water table elevation remains constant and $J = -(1 - \rho_r)$. This is reasonable because for LNAPL under confined conditions, it is expected that the water transmissivity of the well will be much greater than the LNAPL transmissivity.

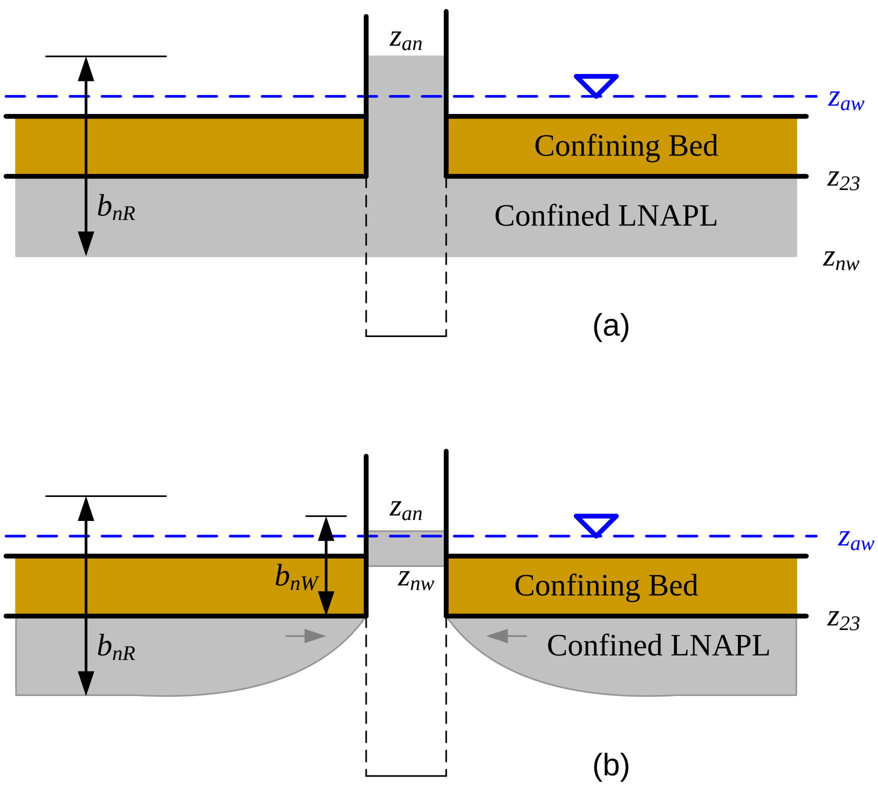


Figure F.1 Confined LNAPL conditions

The constant LNAPL discharge magnitude Q_n for the period with $b_n < b_{nW}$ can be used to estimate the LNAPL transmissivity:

(F.1) $$T_n = \frac{Q_n \ln(R/r_w)}{2\pi(1-\rho_r)(b_{nR} - b_{nW})}$$

With the configuration shown in Figure F.1, the limiting effective well thickness is

(F.2) $$b_{nW} = \frac{z_{aw} - z_{23}}{\rho_r}$$

The corresponding LNAPL drawdown is

(F.3) $$s_{nW} = (1-\rho_r)\left(b_{nR} - \left(\frac{z_{aw} - z_{23}}{\rho_r}\right)\right)$$

Figure F.1 (b) shows the well and LNAPL configuration under conditions with $b_n < b_{nW}$, and suggests that the effective LNAPL thickness at the well is equal to b_{nW}. Actually, under these cut-off conditions for the LNAPL column in the well, there will be a seepage face extending downward from the facies contact at elevation z_{23}. The thickness of the seepage face is unknown, but it may be anticipated that the limiting effective LNAPL thickness at the well might be greater than calculated using Eq. (F.2). Correspondingly, the effective elevation z_{23} as determined from the plot of z_{nw} (DTW) vs. LNAPL discharge (Fig. 6 on the "Figures" worksheet) might have a lower elevation from that estimated using a geologic log.

Appendix G: Perched LNAPL

Figure G.1 shows LNAPL perched upon a low-permeability unit. Analysis of perched LNAPL is essentially the same as that for confined LNAPL. The initial depth to product is DTP_0 and the depth to the top of the perching layer is DZ_{12} (the top of the perching layer is at elevation z_{12}). During a baildown test the LNAPL discharge from the formation to the well is expected to initially be large, associated with rapid drainage of the filter pack and immediate well vicinity, and then the discharge should reach a constant magnitude that is determined by the radial LNAPL head difference experienced by the perched LNAPL. This head difference is equal to $DZ_{12} - DTP_0$, and remains constant until the LNAPL column thickness in the well, b_n, increases in magnitude because of LNAPL inflow from the formation, until $z_{an} = z_{12}$. For $z_{an} > z_{12}$, the LNAPL head difference equals $DTP - DTP_0$, and this magnitude decreases to zero ($DTP \rightarrow DTP_0$) with further LNAPL inflow to the well.

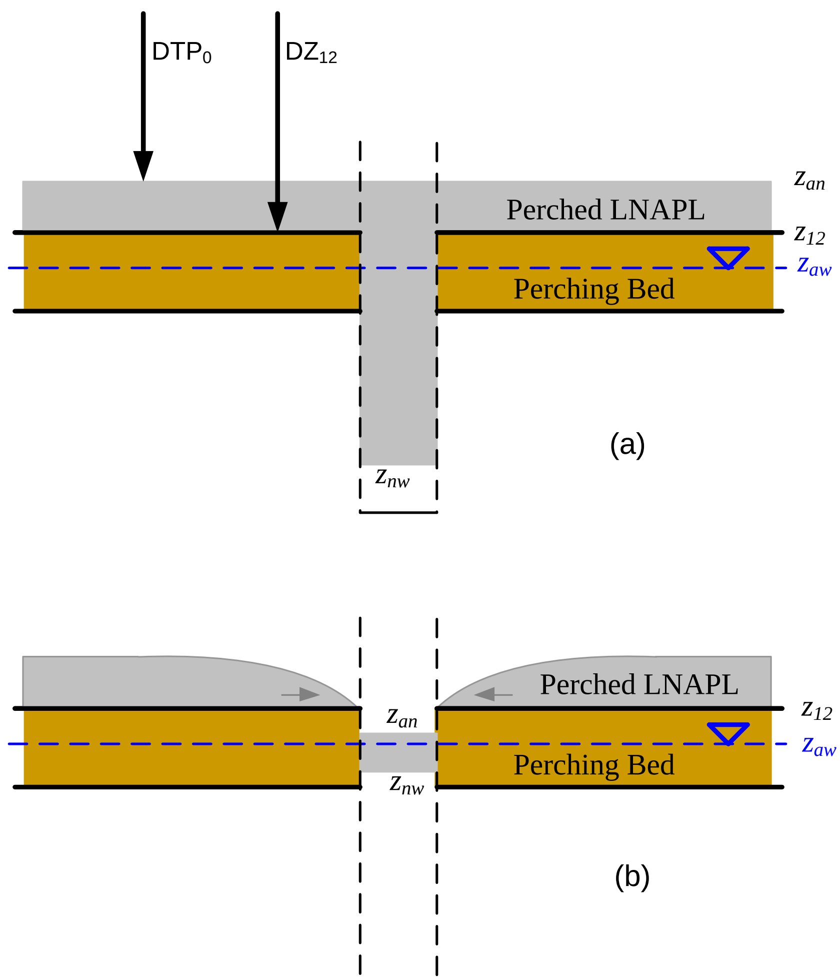


Figure G.1. Perched LNAPL conditions

The constant LNAPL discharge magnitude Q_n for the period with $DTP > DZ_{12}$ can be used to estimate the LNAPL transmissivity:

(G.1) $$T_n = \frac{Q_n \ln\left(R/r_w\right)}{2\pi\left(DZ_{12} - DTP_0\right)}$$

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