EARTH SCIENCES
SIMON FRASER UNIVERSITY

AN ASSESSMENT OF THE METHODOLOGIES USED FOR ANALYZING HYDRAULIC TEST DATA FROM BEDROCK WELLS IN BRITISH COLUMBIA

Final Report

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1.0 Introduction

1.1 Background

Hydraulic test data obtained from constant discharge testing, recovery testing and step discharge testing of water wells, are routinely used by the groundwater industry to estimate the hydraulic properties of aquifers. These properties describe both the hydraulic conductance of an aquifer (i.e., how rapidly water is transmitted) and how much water can be potentially stored in the voids and fractures that make up the rock matrix. Reliable estimates of an aquifer's hydraulic properties are used routinely to predict the long-term capacity of a community water supply well and of an aquifer.

In most cases, hydraulic test data are analyzed using one of several common analytical methods (e.g. Theis, Cooper-Jacob). However, each analytical method has its specific limitations, and should be used only when the assumptions inherent to the model are valid for the aquifer being characterized. Frequently, it is difficult to identify accurately the limiting conditions present at a site that may serve to partially or completely invalidate a particular analytical method. These include the presence of fractures, heterogeneities in the aquifer matrix, sources of constant head such as rivers and streams that are in hydraulic connection with the aquifer, unconfined conditions, and subsurface boundaries such as geological contacts. When present, these conditions contribute to "irregularities" in the aquifer that ultimately lead to departures from ideal conditions upon which the common analytical methods are based. When non-ideal conditions exist in the aquifer being investigated, the use of one of the standard analytical methods for aquifer test data analysis can lead to inaccurate estimates of the hydraulic properties. In turn, use of these hydraulic properties can provide a less than reliable estimate of the long-term yield of a well or an aquifer.

Often more suitable analytical methods can be used for analysis that better represent the hydrogeology of the site. For example, single fracture flow models may be used when there is geological or hydrogeological evidence of a major fracture near the well, double porosity models may be used when both fractures and a porous media are active in the transmission and storage of water in the aquifer, and unconfined models may be used to estimate the hydraulic properties of an aquifer that exhibits classical de-watering during pumping at mid- to late-times. Despite the obvious advantage of using suitable models for analyzing hydraulic test data in non-ideal aquifers, it is often difficult to identify irregularities in the pump test curves (drawdown versus time) that are attributable to irregularities in the aquifer. Departures from the ideal response (Theis response) are often subtle, thus making it difficult to identify which analytical method may be more appropriately utilized.

1.2 Objectives of Research

A research study was initiated by Dr. Diana Allen of the Earth Sciences Program and Simon Fraser University in Burnaby, British Columbia in collaboration with the Groundwater Section of the British Columbia Ministry of the Environment, Lands and Parks (BC MoELP) in Victoria to undertake a detailed examination of hydraulic test data collected in several bedrock aquifers in the Province. The purpose of the research was to identify what types of flow conditions are typically present in bedrock aquifers around the province to determine how these are manifest as subtle departures from ideal flow conditions as exhibited in the hydraulic test data.

There were several objectives for the research:

1. To develop a digital database for hydraulic test data collected in bedrock aquifers in the Province. The Groundwater Section maintains a water utility database of hydraulic test data collected by industry to “prove-up” well water supplies around the Province. This database exists primarily in the form of hardcopy final reports prepared by the various hydrogeological consultants. The digital database could be used not only for this research project but also for future studies.

2. To apply the derivative method for the analysis of hydraulic test data from the various aquifers. The derivative method can be used to identify departures from radial flow conditions at different times during testing. By examining the occurrence of non-radial flow in aquifer test data, more suitable analytical models can be selected for analyzing the data.

3. To analyze the hydraulic test data using several standard and non-standard analytical methods of analysis, and to determine the range of hydraulic parameters calculated using the different methods.

4. To assess the applicability of each model for the various types of flow conditions evident in the data, and to determine if the standard methodologies currently used by industry for evaluating hydraulic test data are valid for diverse types of bedrock aquifer environments, and if they are not, to suggest alternative methods of analysis.

5. To determine the implication of the presence of non-radial flow conditions at the sites to the calculation of long term yield, and to make recommendations based on the results for conducting tests and evaluating hydraulic test data in fractured bedrock aquifers.

1.3 Scope of Work

Prior to initiation of the research project, Mike Wei, a senior hydrogeologist in the Groundwater Section, compiled the hydraulic test data that have been submitted to the Ministry. An Excel spreadsheet, *wudbase.xls*, was developed to synthesize the information and provide a simple means of identifying which data sets might be appropriate for this study, and perhaps future studies. The spreadsheet contained such information as the type of aquifer (unconsolidated confined, unconsolidated unconfined, or bedrock), the types of tests conducted at each site (step or constant discharge and their respective flow rates), the duration of the tests, and whether observation wells were available. Well test records for this study consisted only of those obtained in bedrock aquifers. Suitable well tests were selected on the basis of completeness of data and constant pumping rates.

In order to meet with the objectives established for the research project, Dr. Allen and her research assistant, Lyndon Tiu, undertook the following tasks.

1. Visiting the Groundwater Section office in Victoria in order to collect reports for those sites where suitable hydraulic test data were available. A total of 16 reports were selected for analysis.

2. Reviewing the documents to summarize the well test information contained therein.

3. Developing a multi-page spreadsheet (Microsoft Excel 7.0) that could be used as a template to enter data from well tests and perform analyses based on several analytical methods (derivative method, Theis, Cooper-Jacob, etc.).

4. Developing a spreadsheet that would contain type curve data for various analytical methods used in the study.

5. Analyzing and interpreting the hydraulic test data using the derivative method, the standard radial flow models and other non-standard methods that were deemed suitable at each site on the basis of the hydraulic responses measured.

6. Preparing the final report.

1.4 Outline of Report

This report consists of several main sections. Section 2.0 describes the database, providing details concerning file organization, and the design of the Excel spreadsheet used for analyzing the data. Section 3.0 describes the considerations for hydraulic testing and data analysis in bedrock aquifers, the theory for each analytical method, and the results obtained using each method. Section 3.0 is supplemented by appendices that provide the raw data for the type curves used (Annexes), and the relevant equations for each analytical method. Section 4.0 offers a discussion of the results with specific sub-sections on the use of the derivative method, the application of various flow models in different geological regimes, and estimation of transmissivity values in bedrock aquifers. Section 5.0 offers some generalized conclusions and recommendations for conducting tests and evaluating hydraulic test data in bedrock aquifers.

1.5 Acknowledgements

I would like to acknowledge the contribution of several individuals to this research. I am very grateful to Lyndon Tiu who was my primary research assistant for this project. Lyndon worked diligently to sort, enter and analyze all of the hydraulic test data for this project. This was a task of tremendous magnitude and Lyndon did an exceptional job. I would also like to thank Mike Wei, without whose support and encouragement, this project would not have been possible. I would also like to thank Daron Abbey, an M.Sc. student at Simon Fraser University under my supervision, who is conducting a field-based study of similar nature to the current study. Daron not only provided assistance to Lyndon during this project, but he also offered his comments on the strategies employed for analyzing the data.

Finally, I would like to acknowledge the support of the British Columbia Ministry of the Environment, Lands and Parks for its financial assistance for this project.

2.0 The Database

2.1 Data Collection/Verification

The British Columbia Ministry of Environment, Lands and Parks maintains a Water Utility database of hydraulic test data from public and private wells in BC. From this database, Dr. Allen of Earth Sciences Program at Simon Fraser University, acquired 16 files that contained data from wells in fractured bedrock aquifers. Data in these files were collected in the field by Hydrogeology / Engineering consultants and submitted to the Ministry as part of the requirements for the development of water supply wells in residential subdivisions. During the compilation stage of this project, 13 of the 16 files were found to contain usable hydraulic test data for a total of 28 water supply wells. Some of the usable files contained single well tests, while some contained multiple well tests of the same wells. Some files contained test data from different unrelated wells. Most wells were tested alone (without observation wells) and only once, and some wells were tested more than once. Wells in a file that were tested separately (i.e., independently) from other wells or multiple test data for a single well are treated as sub-files in a main file (see Section 2.2).

2.2 Database File Organization

Information contained in these files were entered into a PC based spreadsheet database (.xls format; Microsoft Excel 7.0 spreadsheet) and are organized into a total of 16 discrete directories (Fig. 2.1). The original names of these files are confidential and the files are given new names in the form of numeric codes (001, 002 …..). The key to these file name codes can be found in 'Appendix 3.0' (*Note; Not available in all versions of this report*).

The name of the root (main) directory of the report is "WellsBC". In this root directory are two directories, namely "Documents Main" and "Pump Test Database Main" (Fig. 2.1). "Documents Main" contains all of the tables and graphs generated for this report, including the final report. The database files, which contain the actual hydraulic test data (i.e. 001, 002 ….), are located in the "Pump Test Database Main" directory (Fig. 2.2). These files are organized into either Pumping or Recovery data (Fig. 2.3). Hydraulic data for pumping wells and any observation wells are contained in these sub-directories (Fig. 2.4, 2.5).

Certain files may contain sub-files and some contain multiple test data for the same set of wells.

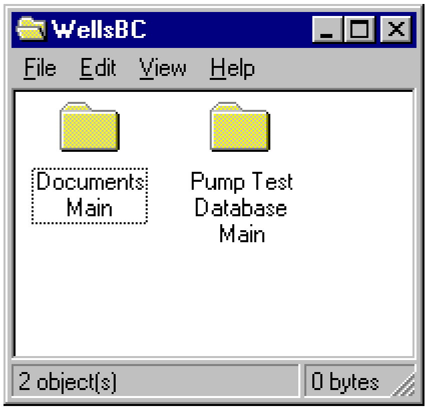


Figure 2.1: Contents of the WellsBC Directory.

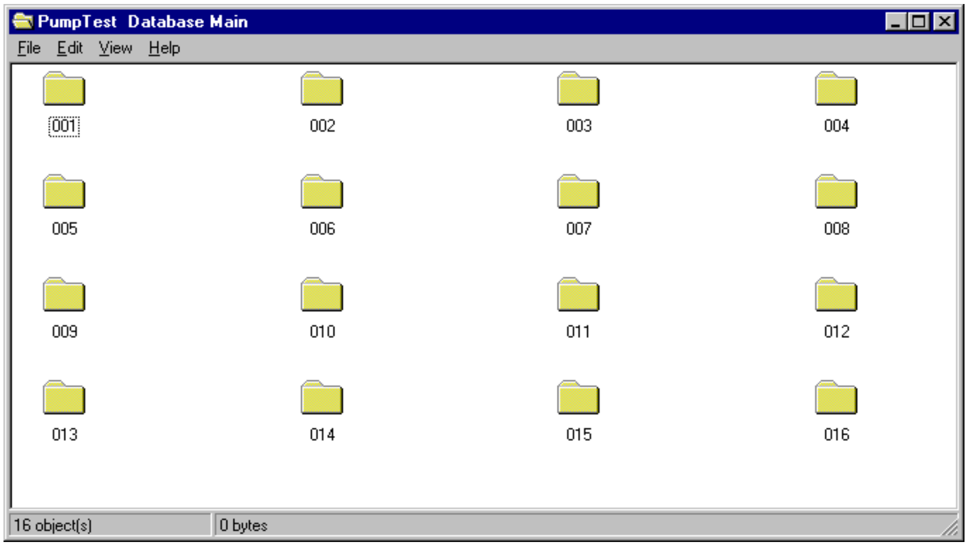


Figure 2.2: Database file directories contained in directory "Pump Test Database main".

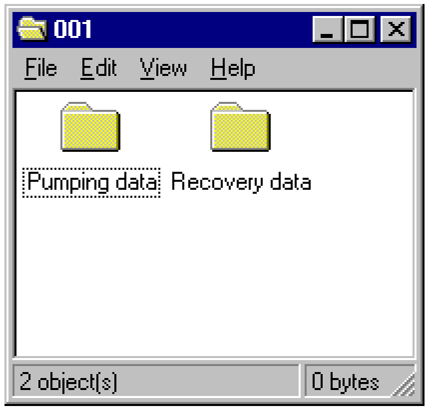


Figure 2.3: Sub-directories within each Data Directory.

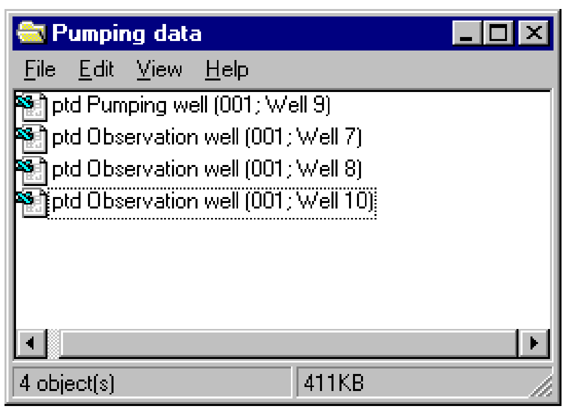


Figure 2.4: MS Excel spreadsheet files containing the hydraulic test data for pumping tests.

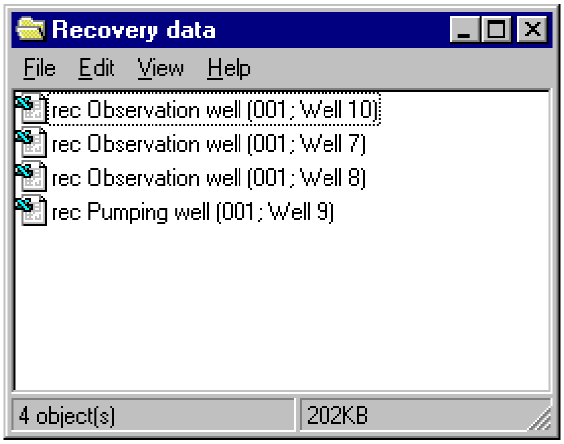


Figure 2.5: MS Excel spreadsheet files containing the hydraulic test data for recovery tests.

The format of a spreadsheet file name is written so as to clearly identify four attributes:

1) the type of test conducted. The first three characters "ptd" stand for pump test data (Fig. 2.4). The characters "rec" stand for recovery data (Fig. 2.5),
2) the type of well for which the data were acquired (i.e., Pumping well or Observation well),
3) the file name code (e.g., 001),
4) and its original name assigned by the consultant (e.g., Well 9).

2.3 Spreadsheet Construction

Spreadsheets were developed for each of the constant discharge test data (pump test data) and the recovery data. These spreadsheets are described separately below.

2.3.1 Pumping Data Spreadsheet

The pumping data spreadsheets contain the constant discharge test data for the pumping well and the available monitoring wells (separate spreadsheets for each). Each MS Excel spreadsheet file represents one hydraulic test on one well and contains pertinent information such as the date of test, well construction, equipment used, observations noted by the consultants in addition to the time and drawdown data (Fig. 2.6).

Each spreadsheet consists of several pages, with labelled tabs at the bottom of the page corresponding to actual data, graphs, the derivative calculations, calculation for the hydraulic parameters and summary tables. One can navigate through the different spreadsheet pages by simply clicking on a tab. Arrows at the left-hand side of the labelled tabs at the bottom of the page, can be used to scroll though all sheets, including those that are hidden (only a few can be seen at a time).

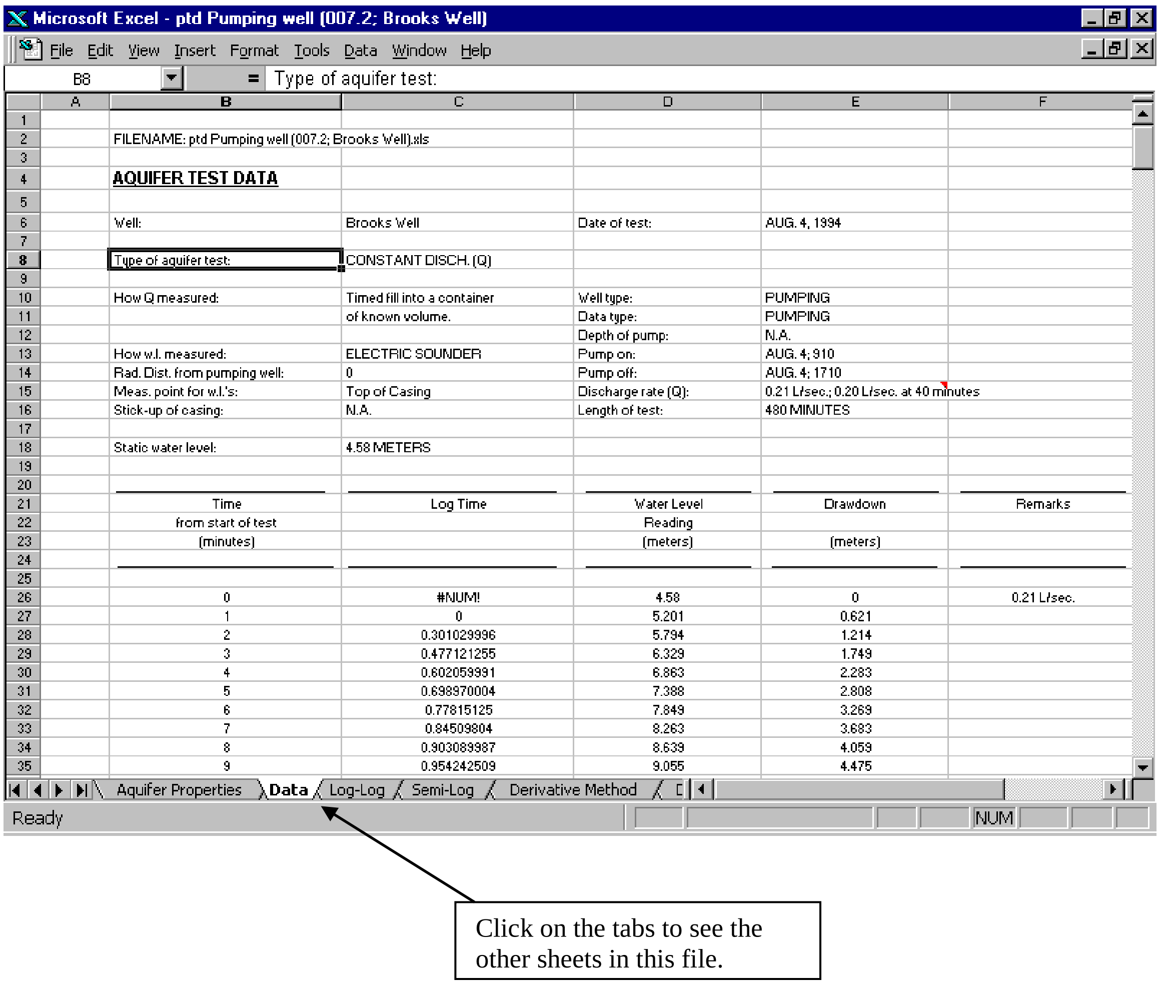


Figure 2.6: Data sheet containing pertinent well and hydraulic test information.

Graphs were plotted to show drawdown versus time in both log-log and semi-log formats (Fig. 2.7). Summary tables showing the relevant calculations and the hydraulic parameter were also generated (under Aquifer Properties Tab) (Figure 2.8).

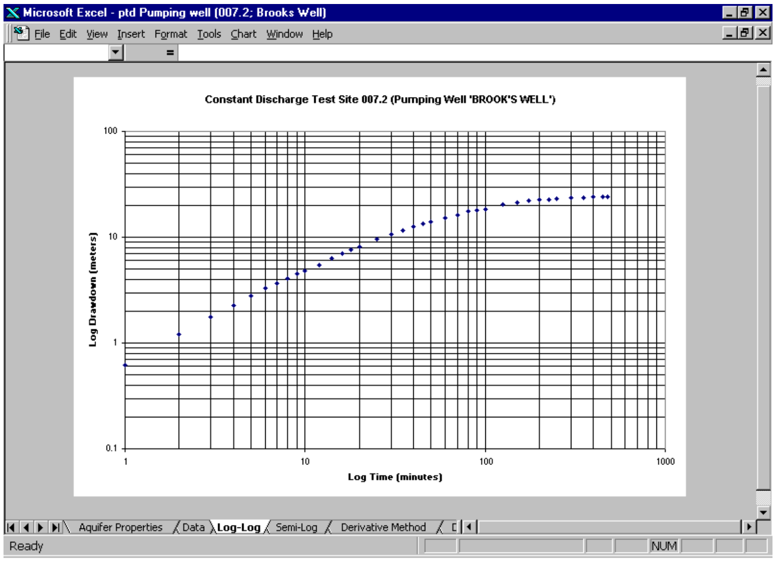


Figure 2.7a: Graph of hydraulic test data. Drawdown vs. time in log-log format.

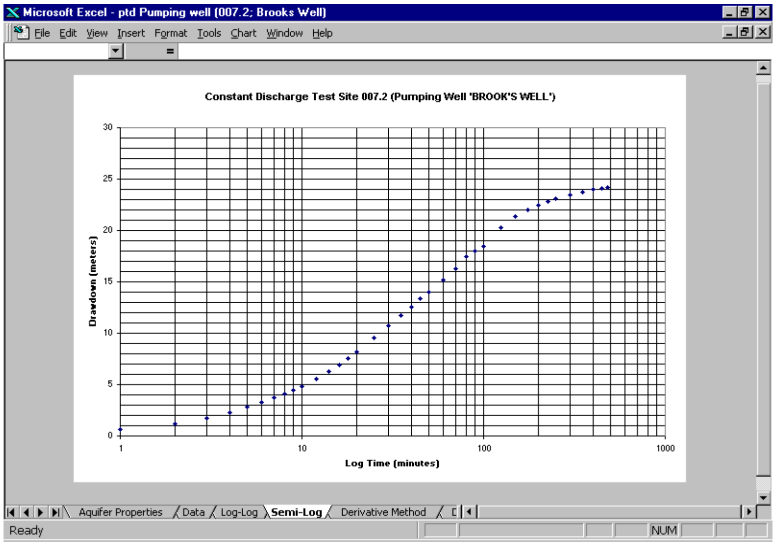


Figure 2.7b: Graph of hydraulic test data. Drawdown vs. time in semi-log format.

A special analysis program (DERIV) was also incorporated into the database (see 'Section 3.3 for a discussion of the theory for the application of the derivative and 'Appendix 2.0' for a description of the set-up of the spreadsheet).

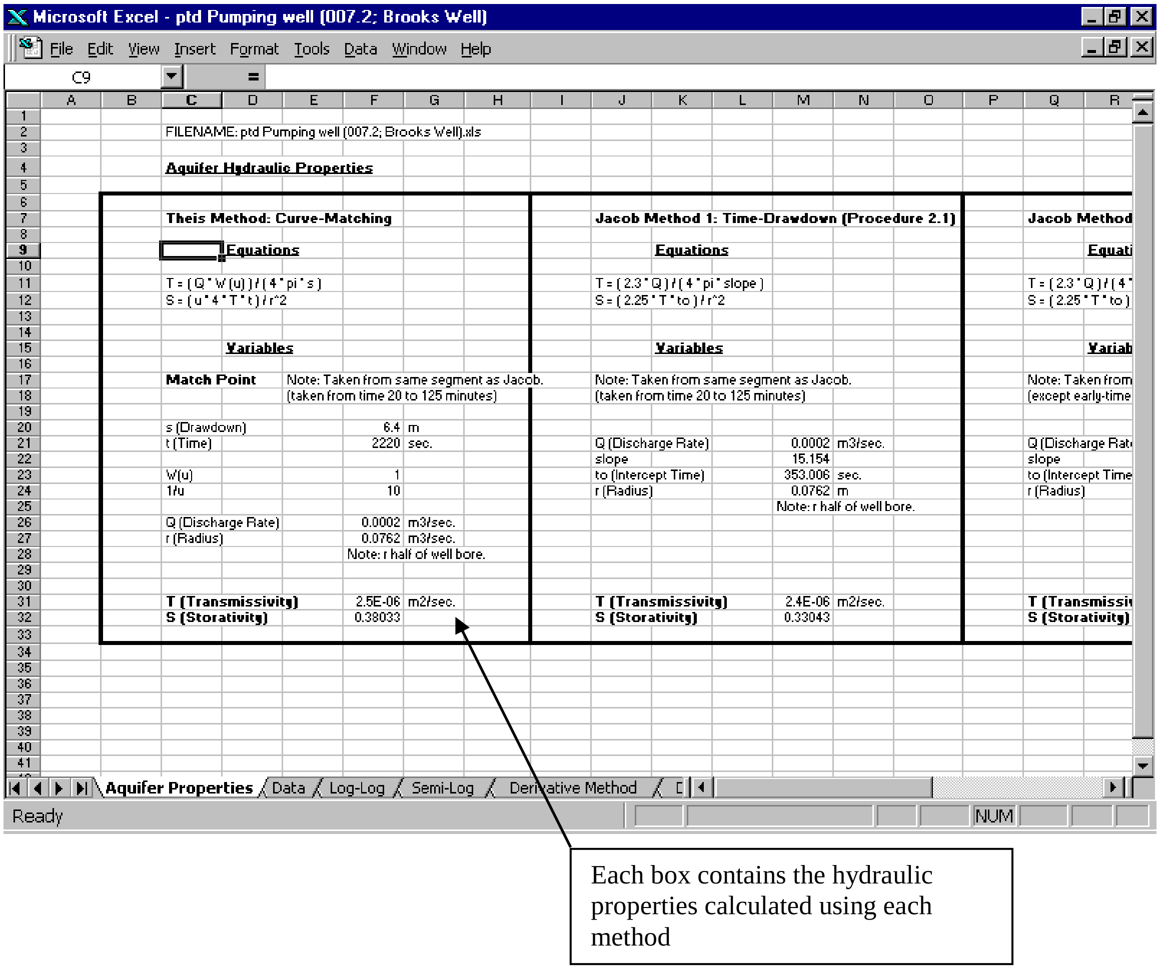


Figure 2.8: Aquifer properties calculations and the T and S values.

2.3.2 Recovery Data Spreadsheet

The recovery data spreadsheets contain the available recovery data for each well monitored. The assembly of the recovery spreadsheet is very similar to that for the constant discharge test data, therefore, no further discussion is provided here.

3.0 Analysis of Hydraulic Test Data

3.1 Considerations for Aquifer Testing

A well test is a single test conducted at a pumping well that is undertaken to assess the well's hydraulic capacity (i.e., its well yield). Well test data (for step tests, constant discharge tests and recovery tests) provide estimates of the hydraulic properties of the aquifer in the immediate vicinity of the well tested. An aquifer testing program generally consists of pumping one or more wells individually and measuring the response in one or more observation wells nearby. Typically, the recovery of water levels are monitored following pump shut off in order to provide an additional data set from which to evaluate the aquifer's hydraulic properties.

When conducting an aquifer test, it is preferable to have a well-distributed set of monitoring wells or piezometers and several multilevel monitoring points, to examine both the lateral and vertical heterogeneity within the aquifer. If the aquifer is known to be heterogeneous or anisotropic, wells or piezometers used as monitoring points should ideally be located at varying distances away from the pumping well and completed at different depths, and should be distributed to achieve a good spatial representation of the aquifer. Specific aquifer testing programs can be carried out to best extract information from the aquifer. In fact, there are particular configurations for monitoring wells that have been suggested for aquifer testing programs in situations where the aquifer is known to have anisotropy or hydrogeological barriers (reported in Kruseman and de Ridder, 1990). However, hydrogeologists often do not have control over the placement of wells to take advantage of these suggestions.

Typically, few or no observation wells are available when water supplies are being assessed, thus, limiting the range for hydraulic sampling. When observation wells are available they are rarely in convenient locations (i.e., they are too far away from the pumping well, are of a different depth, or are inaccessible because they are in use by residential land owners). Nevertheless, there are instances when the lack of a well-distributed array of observation wells may not necessarily be critical to the evaluation of the aquifer. Some of these include:

- Situations in which the aquifer is known to be ideal. That is, it is homogeneous and isotropic, of infinite aerial extent (in terms of pumping influence) and of uniform thickness.
- Situations where data are available from former aquifer or well tests conducted in the vicinity of the site.

When conducting well or aquifer tests in bedrock aquifers, invariably the flow is controlled completely or in part by fractures, and the response that is measured both in the pumping well and in the observation wells is complex. For this reason, it is desirable to access all of the available monitoring wells in the vicinity of the well being pumped. Use of as many observation wells as possible will provide critical information on the hydrogeologic structure of the aquifer, both in the vicinity of the pumping well and further afield.

A further complication is that in the absence of at least one observation well, an estimate of the storativity of the aquifer cannot be determined. Storativity estimates obtained from pumping well data are essentially nothing more than fitting parameters that can reproduce the pumping data if the radius of the well is considered.

The database available for this research project consisted of a variety of aquifer test data obtained from several different bedrock aquifer sites in the province. Many of the sites that were examined have hydraulic test data for both the pumping well and one or more observation wells, making the data invaluable for a research study of this type. It was hoped that by examining the data obtained for sites that offered somewhat ideal testing conditions (i.e., more than one well), that it might be possible to identify some of the hydrogeologic features of the aquifer that contribute to the responses in both the pumping and observation wells monitored.

3.2 Analytical Methods of Analysis

In general, every hydrogeologic model employed for data analysis is patterned after some prototype geologic model. These models are routinely used for calculating the transmissivity and storativity for the aquifer. One such model is the typical confined aquifer of large aerial extent, which is assumed to be isotropic and homogeneous, overlain by a confining layer over which there is a water table. If the confining layer is impermeable and has a specific storage, S_s, of zero, then all of the water removed from the aquifer will come from storage in the aquifer, and the drawdown, observed at any point in the aquifer, will vary with time. The drawdown versus time response, when plotted on semi-log paper (time on the log scale), is a straight line except at very early time. This straight line relation reflects the constant rate of drawdown (as a function of the logarithm of time) exhibited during radial flow. Theis (1935) and, later Cooper and Jacob (1946) developed procedures, based on simple analytical models, for analyzing the hydraulic responses of wells to pumping under radial flow conditions (ideal case). These are discussed in Section 3.4 and in Appendix 1.0.

A slightly more complex environment, fashioned after the basic model, is one in which the confining layer has a non-zero permeability but still contains an incompressible fluid and an incompressible matrix (*i.e.*, $S_s = 0$). Under these conditions it may be possible to invoke the transfer of water across the confining layer. The drawdown-time plot will reflect this additional water source and will show a downward deflection (log-log graph appears to level off) at some point in time. This is referred to as the leaky response (Hantush and Jacob, 1955). It should be noted that a similar type of deflection is recorded if pumping is taking place nearby a stream or lake and surface water enters the aquifer.

Successive complexities may be added to the geologic environment, and the model modified to incorporate the specific conditions present in the aquifer. For example, models exist for unconfined aquifers (Neuman, 1972), anisotropic aquifers (Hantush and Thomas, 1966), aquifers which are near barriers or lines of recharge, irregularly shaped aquifers and fractured aquifers. As well, specific types of tests and analytical procedures have been developed to deal with large diameter wells, partially penetrating wells and tests involving single boreholes (summarized by Kruseman and de Ridder, 1990). The literature contains numerous new methodologies, which have been developed according to specific aquifer conditions.

For the purposes of this research study, the hydraulic test data for each of the wells were analyzed using both of the standard methods of analysis (Theis and Cooper-Jacob) and several other methods of analysis that are not as widely used. These include the Derivative Method of Analysis, Vertical Fracture Flow Model, Double Porosity Model, and Unconfined Aquifer Model (Neuman). Recovery data were also analyzed using the standard Theis Recovery Method. Not all of the methods were used for each well, as some were deemed inapplicable (this is discussed later).

3.3 Derivative Method

Curve-matching and straight-line procedures are used most frequently to determine the hydraulic parameters of an aquifer. However, in many cases, more than one type curve can be identified that provides a reasonably good match to a drawdown versus time data curve. For example, double porosity and unconfined models predict similar transient drawdown-time curves.

Bourdet *et al.* (1984) introduced the use of derivative curves for the analysis of well-test data, although the technique had been widely applied in the oil industry for many years prior (pressure derivative analysis). One of the major advantages of using this technique, in addition to standard analytical techniques, is that it can be used as a diagnostic tool and can identify the type of flow regime that is present. For example, a radial flow regime has no characteristic behaviour in a type curve; however, the logarithm of the derivative of drawdown (hydraulic head) has a well known value and a definite shape when plotted against the logarithm of time.

The improvement in hydraulic test analysis through the use of derivatives is attributed to the sensitivity of the derivative response to small variations in the rate of drawdown change that occurs during testing, which would otherwise be less obvious with standard drawdown change (hydraulic head) versus time analysis (Spane and Wurstner, 1993). The enhanced sensitivity of the derivative facilitates its use in identifying the presence of wellbore storage, boundaries, and the establishment of radial flow conditions within the test data.

Figure 3.1 shows a few simple sketches of the various log-drawdown derivative versus log-time curves and the standard log-drawdown versus log-time curves that will result in different aquifer environments. In 3.1a, the aquifer is confined, of infinite aerial extent and wellbore storage is present. Wellbore storage produces a characteristic “hump” in the drawdown derivative plot, which increases in amplitude and duration as the associated wellbore storage value increases. In the absence of wellbore storage, there is no “drop” in the derivative before infinite-acting radial flow commences. Infinite-acting radial flow conditions are indicated during testing when the change in drawdown at the point of observation increases in proportion to the logarithm of time. This is also indicated when the derivative curve becomes horizontal. Test data displaying this derivative pattern can be analyzed using Cooper-Jacob’s straight-line method.

The presence of non-radial flow conditions that may be caused by leakage, vertical flow or the presence of boundaries is denoted on the derivative plot by a diagnostic response pattern that deviates significantly from the horizontal radial flow-line region of the graph. On a regular log-drawdown versus log-time graph these changes are subtle. Figure 3.1b shows the effect of a constant head boundary and Figure 3.1c shows the effect of a no-flow boundary. Appendix 2 provides other useful graphs of the derivative that were calculated using the type curves for the various methods used for analysis here (e.g., vertical fracture, unconfined).

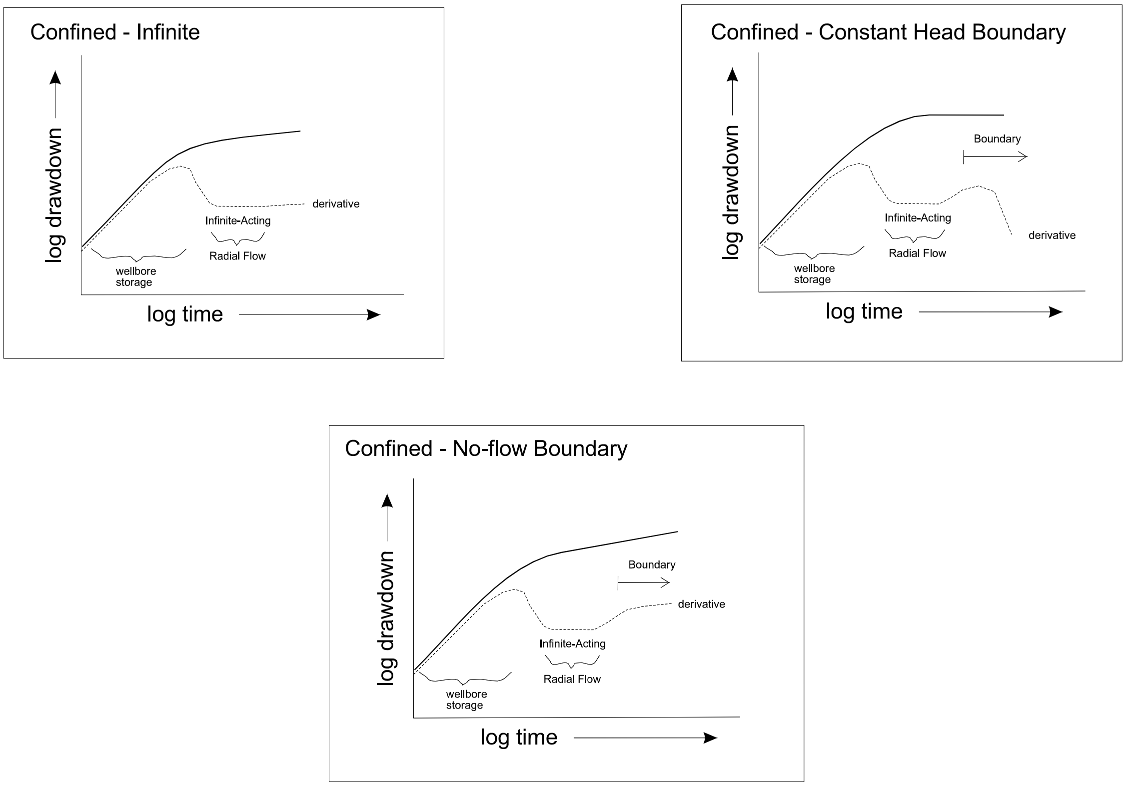


Figure 3.1: Characteristic log-log drawdown versus time and derivative plots for various hydrogeological boundary conditions in confined aquifers (after Spane and Wurstner, 1993).

3.3.1 The DERIV Spreadsheet

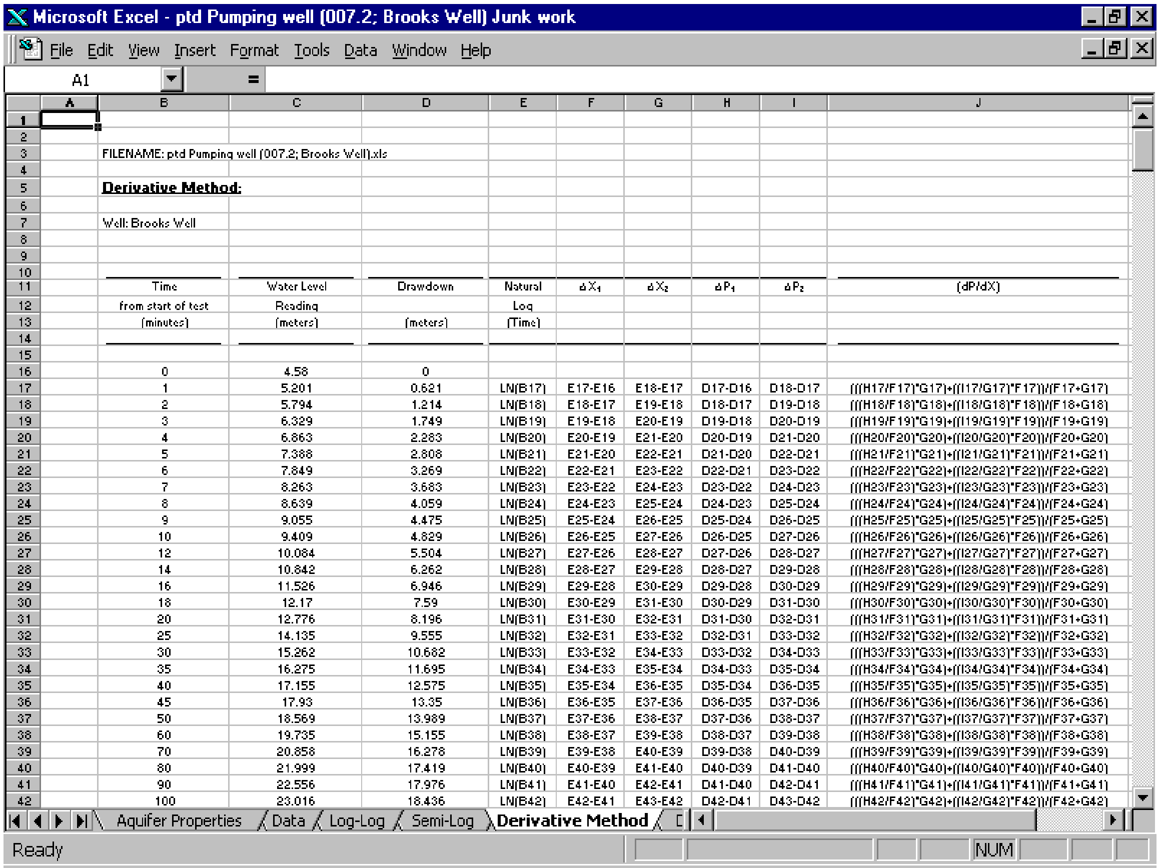
A simple fixed end-point algorithm that could calculate the pressure derivative was included in the Excel spreadsheets that contained the water level data as a function of time (separate tab at bottom of sheet). Although not as sophisticated as the software program *DERIV* (Spane and Wurstner, 1993), which allows the user the flexibility of selecting the type of derivative algorithm that is used (*i.e.*, fixed end-point or least-squares fit) and the abscissal length (L-spacing) over which the derivative is averaged, this simplified algorithm is nonetheless effective. This algorithm calculates the first derivative of the drawdown, with respect to the natural logarithm of the change of time, using the point immediately before and immediately after the point of interest, and averages the two values. A limited number of data points preclude the use of an L-spacing greater than the time interval between measurements. This resulted in a less smooth curve, such that even the slightest deviation will be visible. Equation 3.1

shows the mathematical expression used to calculate the pressure derivative (Spane and Wurstner, 1993).

$$(dP/dX)_i = \left[(\Delta P_1/\Delta X_1)\Delta X_2 + (\Delta P_2/\Delta X_2)\Delta X_1\right]/(\Delta X_1 + \Delta X_2) \qquad 3.1$$

where the subscript 1=point(s) before the point of interest, *i*; subscript 2=point(s) after the point of interest, *i*; and *X*=natural logarithm of the time, *t.* It is further noted that the definition of *t* is a function of the test type (*i.e.*, constant discharge or recovery) and the variable changes accordingly. For recovery tests, *t* is defined as the total test time divided by the time since the pump was shut off.

A minimum of 9 columns is needed for the DERIV program to work (Figure 3.2). Under column B to D are the hydraulic test data: Time, Water Level Reading (Depth to Water) and Drawdown (Water Level Reading minus static water level). The next 6 columns are directly related to the DERIV program and contain the codes for the program to run properly. The setup in Figure 3.2 is not running. To run the program, an equal sign " = " has to be typed into each column entry from column E to J. Excel then automatically executes the calculations seen in Figure 3.3.



Microsoft Excel - ptd Pumping well (007.2; Brooks Well) Junk work

File Edit View Insert Format Tools Data Window Help

A1 =

	A	B	C	D	E	F	G	H	I	J
1										
2										
3		FILENAME: ptd Pumping well (007.2; Brooks Well).xls								
4										
5		**Derivative Method:**								
6										
7		Well: Brooks Well								
8										
9										
10										
11		Time	Water Level	Drawdown	Natural	ΔX_1	ΔX_2	ΔP_1	ΔP_2	(dP/dX)
12		from start of test	Reading		Log					
13		(minutes)	(meters)	(meters)	(Time)					
14										
15										
16		0	4.58	0						
17		1	5.201	0.621	LN(B17)	E17-E16	E18-E17	D17-D16	D18-D17	(((H17/F17)*G17)+((I17/G17)*F17))/(F17+G17)
18		2	5.794	1.214	LN(B18)	E18-E17	E19-E18	D18-D17	D19-D18	(((H18/F18)*G18)+((I18/G18)*F18))/(F18+G18)
19		3	6.329	1.749	LN(B19)	E19-E18	E20-E19	D19-D18	D20-D19	(((H19/F19)*G19)+((I19/G19)*F19))/(F19+G19)
20		4	6.863	2.283	LN(B20)	E20-E19	E21-E20	D20-D19	D21-D20	(((H20/F20)*G20)+((I20/G20)*F20))/(F20+G20)
21		5	7.388	2.808	LN(B21)	E21-E20	E22-E21	D21-D20	D22-D21	(((H21/F21)*G21)+((I21/G21)*F21))/(F21+G21)
22		6	7.849	3.269	LN(B22)	E22-E21	E23-E22	D22-D21	D23-D22	(((H22/F22)*G22)+((I22/G22)*F22))/(F22+G22)
23		7	8.263	3.683	LN(B23)	E23-E22	E24-E23	D23-D22	D24-D23	(((H23/F23)*G23)+((I23/G23)*F23))/(F23+G23)
24		8	8.639	4.059	LN(B24)	E24-E23	E25-E24	D24-D23	D25-D24	(((H24/F24)*G24)+((I24/G24)*F24))/(F24+G24)
25		9	9.055	4.475	LN(B25)	E25-E24	E26-E25	D25-D24	D26-D25	(((H25/F25)*G25)+((I25/G25)*F25))/(F25+G25)
26		10	9.409	4.829	LN(B26)	E26-E25	E27-E26	D26-D25	D27-D26	(((H26/F26)*G26)+((I26/G26)*F26))/(F26+G26)
27		12	10.084	5.504	LN(B27)	E27-E26	E28-E27	D27-D26	D28-D27	(((H27/F27)*G27)+((I27/G27)*F27))/(F27+G27)
28		14	10.842	6.262	LN(B28)	E28-E27	E29-E28	D28-D27	D29-D28	(((H28/F28)*G28)+((I28/G28)*F28))/(F28+G28)
29		16	11.526	6.946	LN(B29)	E29-E28	E30-E29	D29-D28	D30-D29	(((H29/F29)*G29)+((I29/G29)*F29))/(F29+G29)
30		18	12.17	7.59	LN(B30)	E30-E29	E31-E30	D30-D29	D31-D30	(((H30/F30)*G30)+((I30/G30)*F30))/(F30+G30)
31		20	12.776	8.196	LN(B31)	E31-E30	E32-E31	D31-D30	D32-D31	(((H31/F31)*G31)+((I31/G31)*F31))/(F31+G31)
32		25	14.135	9.555	LN(B32)	E32-E31	E33-E32	D32-D31	D33-D32	(((H32/F32)*G32)+((I32/G32)*F32))/(F32+G32)
33		30	15.262	10.682	LN(B33)	E33-E32	E34-E33	D33-D32	D34-D33	(((H33/F33)*G33)+((I33/G33)*F33))/(F33+G33)
34		35	16.275	11.695	LN(B34)	E34-E33	E35-E34	D34-D33	D35-D34	(((H34/F34)*G34)+((I34/G34)*F34))/(F34+G34)
35		40	17.155	12.575	LN(B35)	E35-E34	E36-E35	D35-D34	D36-D35	(((H35/F35)*G35)+((I35/G35)*F35))/(F35+G35)
36		45	17.93	13.35	LN(B36)	E36-E35	E37-E36	D36-D35	D37-D36	(((H36/F36)*G36)+((I36/G36)*F36))/(F36+G36)
37		50	18.569	13.989	LN(B37)	E37-E36	E38-E37	D37-D36	D38-D37	(((H37/F37)*G37)+((I37/G37)*F37))/(F37+G37)
38		60	19.735	15.155	LN(B38)	E38-E37	E39-E38	D38-D37	D39-D38	(((H38/F38)*G38)+((I38/G38)*F38))/(F38+G38)
39		70	20.858	16.278	LN(B39)	E39-E38	E40-E39	D39-D38	D40-D39	(((H39/F39)*G39)+((I39/G39)*F39))/(F39+G39)
40		80	21.999	17.419	LN(B40)	E40-E39	E41-E40	D40-D39	D41-D40	(((H40/F40)*G40)+((I40/G40)*F40))/(F40+G40)
41		90	22.556	17.976	LN(B41)	E41-E40	E42-E41	D41-D40	D42-D41	(((H41/F41)*G41)+((I41/G41)*F41))/(F41+G41)
42		100	23.016	18.436	LN(B42)	E42-E41	E43-E42	D42-D41	D43-D42	(((H42/F42)*G42)+((I42/G42)*F42))/(F42+G42)

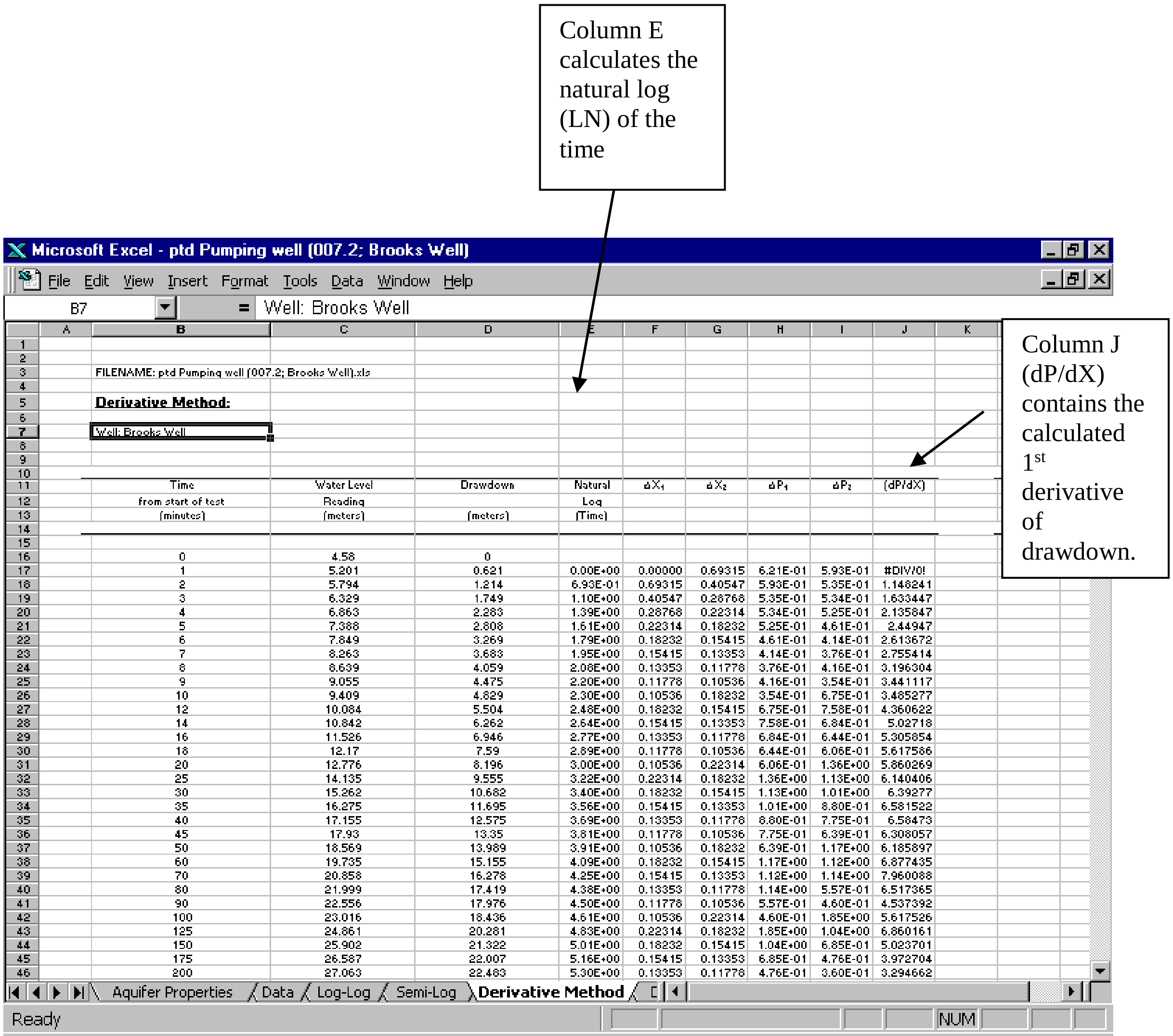
Aquifer Properties / Data / Log-Log / Semi-Log / **Derivative Method**

Ready NUM

An "=" sign has to be typed into the left of each column entry from E to J for the program to execute.

Note: The cell references must be correct or the program will give erroneous values.

Figure 3.2: The DERIV program code setup in MS Excel. (Note: For the program to run, an equal sign " = " has to be typed into the left hand side of each column entry from column E to J).



Time from start of test (minutes)	Water Level Reading (meters)	Drawdown (meters)	Natural Log (Time)	ΔX_1	ΔX_2	ΔP_1	ΔP_2	(dP/dX)
0	4.58	0						
1	5.201	0.621	0.00E+00	0.00000	0.69315	6.21E-01	5.93E-01	#DIV/0!
2	5.794	1.214	6.93E-01	0.69315	0.40547	5.93E-01	5.35E-01	1.148241
3	6.329	1.749	1.10E+00	0.40547	0.28768	5.35E-01	5.34E-01	1.633447
4	6.863	2.283	1.39E+00	0.28768	0.22314	5.34E-01	5.25E-01	2.135847
5	7.388	2.808	1.61E+00	0.22314	0.18232	5.25E-01	4.61E-01	2.44947
6	7.849	3.269	1.79E+00	0.18232	0.15415	4.61E-01	4.14E-01	2.613672
7	8.263	3.683	1.95E+00	0.15415	0.13353	4.14E-01	3.76E-01	2.755414
8	8.639	4.059	2.08E+00	0.13353	0.11778	3.76E-01	4.16E-01	3.196304
9	9.055	4.475	2.20E+00	0.11778	0.10536	4.16E-01	3.54E-01	3.441117
10	9.409	4.829	2.30E+00	0.10536	0.18232	3.54E-01	6.75E-01	3.485277
12	10.084	5.504	2.48E+00	0.18232	0.15415	6.75E-01	7.58E-01	4.360622
14	10.842	6.262	2.64E+00	0.15415	0.13353	7.58E-01	6.84E-01	5.02718
16	11.526	6.946	2.77E+00	0.13353	0.11778	6.84E-01	6.44E-01	5.305854
18	12.17	7.59	2.89E+00	0.11778	0.10536	6.44E-01	6.06E-01	5.617586
20	12.776	8.196	3.00E+00	0.10536	0.22314	6.06E-01	1.36E+00	5.860269
25	14.135	9.555	3.22E+00	0.22314	0.18232	1.36E+00	1.13E+00	6.140406
30	15.262	10.682	3.40E+00	0.18232	0.15415	1.13E+00	1.01E+00	6.39277
35	16.275	11.695	3.56E+00	0.15415	0.13353	1.01E+00	8.80E-01	6.581522
40	17.155	12.575	3.69E+00	0.13353	0.11778	8.80E-01	7.75E-01	6.58473
45	17.93	13.35	3.81E+00	0.11778	0.10536	7.75E-01	6.39E-01	6.308057
50	18.569	13.989	3.91E+00	0.10536	0.18232	6.39E-01	1.17E+00	6.185897
60	19.735	15.155	4.09E+00	0.18232	0.15415	1.17E+00	1.12E+00	6.877435
70	20.858	16.278	4.25E+00	0.15415	0.13353	1.12E+00	1.14E+00	7.960088
80	21.999	17.419	4.38E+00	0.13353	0.11778	1.14E+00	5.57E-01	6.517365
90	22.556	17.976	4.50E+00	0.11778	0.10536	5.57E-01	4.60E-01	4.537392
100	23.016	18.436	4.61E+00	0.10536	0.22314	4.60E-01	1.85E+00	5.617526
125	24.861	20.281	4.83E+00	0.22314	0.18232	1.85E+00	1.04E+00	6.860161
150	25.902	21.322	5.01E+00	0.18232	0.15415	1.04E+00	6.85E-01	5.023701
175	26.587	22.007	5.16E+00	0.15415	0.13353	6.85E-01	4.76E-01	3.972704
200	27.063	22.483	5.30E+00	0.13353	0.11778	4.76E-01	3.60E-01	3.294662

Figure 3.3: The DERIV program sheet. Column J, dP/dX, give us the 1st derivative value of drawdown.

The spreadsheet automatically generates a graph showing the first derivative of the drawdown with respect to time plotted against time (e.g., Figure 3.4).

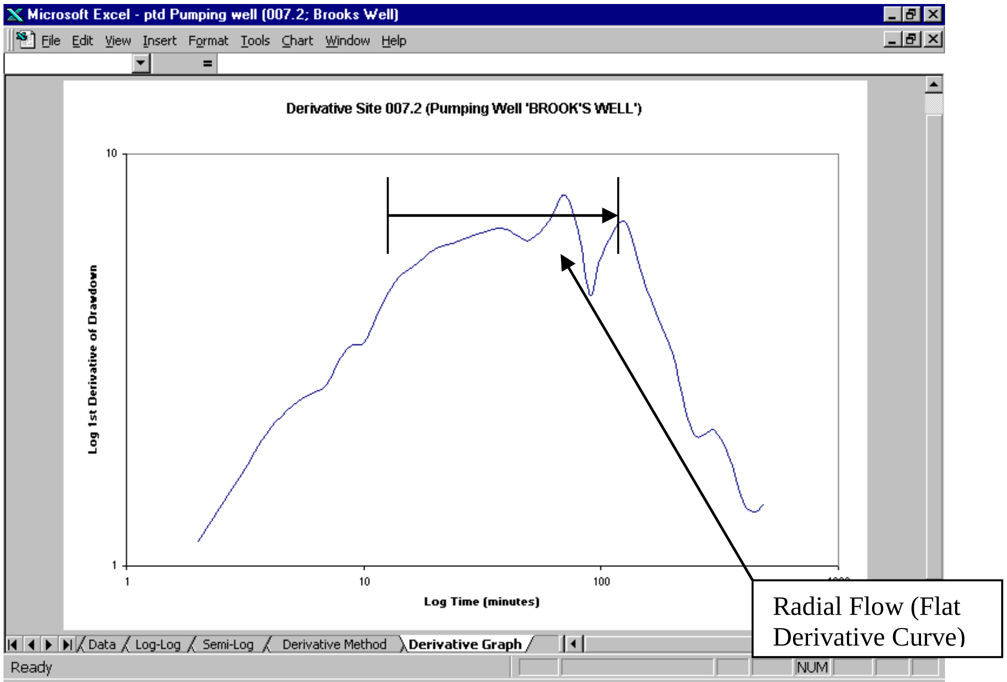


Figure 3.4: Graph of the log 1st derivative versus log time. Graph was constructed using the DERIV program.

3.4 Radial Flow Models for Confined Aquifers

There is no prototype model that is suitable for all bedrock aquifers, because each bedrock aquifer is unique. The uniqueness is most attributable to the extent to which fractures are developed, which is in turn dictated by the tectonic setting of the area. The data for this project clearly did not exhibit any readily identifiable trends when plotted either as the derivative of the drawdown versus time nor as log of drawdown versus the log of time, nor as drawdown versus the log of time. Thus, it was important to establish a protocol that could be used not only for this study, but also for the analysis and interpretation of well test data elsewhere.

In order to provide a base for comparison with the results from other methods, simplified ideal flow models were first employed to calculate estimates of the aquifer hydraulic parameters (transmissivity, T, and storativity, S). These radial flow models were also used as a comparative tool in order to characterize the unusual behaviour of the aquifers studied relative to ideal aquifers. Although fractured bedrock aquifers (by definition) do not, in general, meet with the assumptions inherent to radial models for ideal aquifers, the data, or at least a portion of the data, appear to follow a Theis type response. The assumptions and equations for the Theis and Cooper-Jacob methods are discussed in Appendix 1.0.

3.4.1 Theis - Methodology and Results

The method of solution for Theis consists of plotting the drawdown versus time on logarithmic paper for each of the observation wells and the pumping well. The Theis type curve (a graph of *W(u)* versus *1/u*) is plotted on a separate logarithmic graph of the same scale. The field curve is superimposed on the type curve, with the coordinate axes of the two curves kept parallel while matching field data to the type curve. Any point on the overlapping sheets is arbitrarily selected. This point is defined by four coordinate values: *W(u)*, *1/u*, *s* and *t*. Equation A1.1.1 (Appendix 1.1) may be solved for transmissivity by reading off the coordinate value for *s* and *W(u*). Equation A1.1.2 (Appendix 1.1) may then be solved for storativity by reading off the coordinate values for *t* and *1/u* and using the value for transmissivity already determined from Equation A1.1.1.

This type of analysis is often very subjective, particularly when the match is not ideal. Therefore, the Theis curve-matching method is seldom used in data analysis (*i.e*., to calculate *T* and *S*). A favoured approach is to plot some of the data on logarithmic graphs and to observe whether the data do follow the Theis curve. If there is a good match then a faster, less subjective method of analysis, namely the Cooper-Jacob Method (discussed in Appendix 1.2 and Section 3.4.2) can be used. The Cooper-Jacob method linearizes the well function at large pumping times or small pumping well-observation well distances (Appendix 1.2).

The standard methods of analysis, including Theis, assume that the diameter of the well is negligible and, thus, wellbore storage is not a factor. For a well in which wellbore storage is not negligible, the early time data will plot as a straight line of unit slope on a log-log plot of drawdown versus time (*i.e.*, a 45 degree angle if the log intervals are the same for the x- and y-coordinate axes). In relation to Theis, the early data plot on a curve that is less steep than the Theis curve, since water is derived from the wellbore as opposed to from the aquifer.

Because the Theis method is strictly valid for radial flow conditions in the aquifer, it should not be used when flow to the pumping well is non-radial. Radial behaviour results in an exponential relationship between drawdown and radial distance away from the pumping well. Further, the radius of influence for the test increases with time exponentially. Conditions that might contribute to non-radial behaviour include the presence of a major fracture or fault in the vicinity of the well, wellbore storage effects at early time, partially-penetrating wells, unconfined conditions, etc.

In many cases, the well may behave non-radially for a period of time (such as at early time when wellbore storage effects dominate, or at late time if a boundary is encountered), and then revert to radial flow. The problem is that the transition to or from radial flow is often difficult to identify on a log-log plot. If the period of true radial flow is comparatively short, then even in semi-log format, the radial flow period may be difficult to identify.

By using the derivative method first to identify the period or periods in which radial flow occurs, it was possible to identify the time interval that should be used for a Theis curve fit. Analysis then proceeded with the application of the Theis Curve-Matching Method (see Appendix 1.1) on the hydraulic test data. Because the range of data was very different for each site, it was necessary to construct a series of type curves (for different ranges). Of course, when using the Theis method it is imperative that the scale of the data curve and the type curve are the same (same number of log cycles in x and y directions). The values for W(u) as a function of u (for construction of the Theis type curve) are provided in Annex 1.

Table 3.1 lists the transmissivity values calculated using the Theis method. A comparison of these values and those calculated using other methods is provided in Section 4.0.

3.4.2 Cooper-Jacob Methodology and Results

In an ideal aquifer, data corresponding to small values of u (*i.e.*, $u<<0.01$) will fall along a straight line in a semi-log plot of drawdown versus time, and a linear regression can be used effectively to calculate transmissivities and storativities (Cooper-Jacob method, Appendix 1.2). In real aquifers, wellbore storage effects may dominate very early time data, particularly at the pumping well, and late time data may show the onset of steady state conditions. Wellbore storage and boundary effects are not accounted for in the Cooper-Jacob method.

Since this method of analysis is straightforward, it is the preferred method used by the hydrogeological consulting industry for calculating aquifer parameters. However, because the method is based on a simplified form of the Theis equation, this method is strictly speaking a radial flow method that is valid for ideal aquifers only. Use of this method without any consideration to the reasons why there are departures can severely limit the value of the interpretation of the aquifer and its parameters.

Two procedures were examined for this study. In Cooper-Jacob (1) (referred to as Jacob 2.1 in database) only those data that are considered representative of radial flow were used. These data are consistent with those used in the Theis method described above. In Cooper-Jacob (2) (referred to as Jacob 2.2 in database), the range of data selected for linear regression was much less restrictive. All data following the brief period of wellbore storage (if present) were used, regardless of whether they fell along a straight line. This second method offers a relatively unbiased method of selecting data for Cooper-Jacob analysis. As such it may be most representative of the automated parameter estimation packages that are currently in wide use. Table 3.1 compares the results of Cooper-Jacob (1) with the results of Theis and Theis recovery (both radial

Table 3.1: Summary of Aquifer Properties:

Traditional Methods:

Legend: X — **Method Not Applied**; (grey shading) — **S not valid for pumping well**

File	Sub-File/ Test	Well Name or #	Pump/Obs	Pumping Data Theis T (m^2/s)	Pumping Data Theis S	Pumping Data Cooper-Jacob (1) (radial only) T (m^2/s)	Pumping Data Cooper-Jacob (1) (radial only) S	Recovery Data Theis T (m^2/s)
0.01		Well 9	Pump	3.87E-05	1.12E-01	3.98E-05	8.40E-02	4.83E-05
		Well 7	Obs	4.86E-05	4.00E-04	4.19E-05	3.90E-04	1.11E-04
		Well 8	Obs	7.49E-05	4.00E-04	1.10E-04	3.20E-04	8.40E-04
		Well 10	Obs	4.86E-05	4.00E-04	5.93E-05	2.80E-04	1.41E-04
0.02	Test 1	TH 1-81	Obs	3.96E-04	1.48E-03	4.10E-04	1.10E-04	3.66E-04
		TH 3-81	Pump	2.54E-05	7.10E-01	2.65E-05	4.89E-01	2.89E-05
	Test 3	TH 1-81	Pump	3.95E-05	2.01E-01	4.24E-05	1.71E-01	3.78E-05
		TH 3-81	Obs	2.36E-04	2.53E-04	3.40E-04	1.30E-04	"No Data"
	Test 4	TH 3-81	Pump	1.21E-05	5.73E-01	2.23E-05	3.85E-01	"No Data"
0.03	1979	"No Name"	Pump	8.92E-06	7.52E+00	7.01E-06	2.82E-01	9.24E-06
	1989	"No Name"	Pump	3.52E-06	9.30E+00	3.54E-06	6.98E+00	1.29E-05
0.04		PW-1	Pump	1.79E-05	1.55E+01	1.74E-05	6.61E-01	2.65E-05
0.05		Well 4	Pump	3.94E-05	1.45E+00	3.93E-05	1.37E+00	3.72E-05
0.06	0.06.1	Well 1	Pump	5.95E-05	1.18E+00	4.88E-05	8.82E-01	6.08E-05
	0.06.2	Well 2	Pump	1.40E-05	5.30E-01	1.14E-05	5.84E-01	9.04E-06
0.07	007.1 Test 1	TW 89-1	Pump	X	X	7.06E-04	2.49E+02	1.21E-03
		TW 89-2	Obs	4.19E-04	1.90E-03	5.31E-04	1.48E-02	3.13E-03
	007.1 Test 2	TW 89-1	Obs	1.77E-04	3.67E-02	2.37E-04	2.56E-02	1.31E-03
		TW 89-2	Pump	1.85E-04	3.68E+03	2.42E-04	3.26E+03	2.62E-03
	0.07.2	Brook's Well	Pump	2.49E-06	3.80E-01	2.42E-06	3.30E-01	2.06E-06
	007.3.1	Well #1	Pump	1.09E-05	5.17E-01	1.17E-05	4.34E-01	1.28E-05
	007.3.2	Well #2	Pump	1.60E-06	3.30E-01	1.92E-06	2.45E-01	1.57E-06
	007.4.1	Well B	Pump	2.15E-06	2.80E+00	2.02E-06	2.96E+00	2.01E-05
	007.4.2	Well 2	Pump	8.93E-07	3.88E-01	9.51E-07	3.24E-01	7.69E-07
0.08		Well C	Pump	1.06E-04	7.70E-01	1.00E-04	8.28E-01	1.01E-04
0.09	0.09.1	Well #16	Pump	2.69E-05	7.78E+00	2.50E-05	7.81E+00	2.78E-05
	0.09.2	"No Name"	Pump	1.20E-05	9.14E-01	1.16E-05	8.25E-01	1.27E-05
0.10		"No Data"	"No Data"	"No Data"	"No Data"	"No Data"	"No Data"	"No Data"
0.11		"No Data"	"No Data"	"No Data"	"No Data"	"No Data"	"No Data"	"No Data"
0.12		"No Name"	Pump	3.09E-05	5.87E-01	7.12E-06	8.41E-01	"No Data"
0.13		"No Data"	"No Data"	"No Data"	"No Data"	"No Data"	"No Data"	"No Data"
0.14		Well #2	Pump	3.93E-05	3.90E-01	4.43E-05	3.15E-01	5.37E-05
0.15		Well #2	Obs	4.29E-05	1.06E-04	4.38E-05	8.73E-05	4.17E-04
		Well #3	Obs	1.20E-03	2.93E-04	1.42E-03	2.23E-04	9.51E-04
		Well #4	Obs	3.61E-05	2.19E-04	4.09E-05	1.79E-04	8.24E-04
		Well #5	Pump	3.55E-05	6.76E-01	5.22E-05	3.83E-01	4.88E-05
0.16		Well 2	Pump	1.32E-04	9.52E-01	1.13E-04	1.13E+00	1.02E-04

Table 3.2: Cooper-Jacob (1) and Cooper-Jacob (2) (whole segment) and Consultant's Values

(grey shading) S not valid for pumping well

File	Sub-File/ Test	Well Name or #	Pump/Obs	Cooper-Jacob (1) (preferred method)		Cooper-Jacob (2) (whole segment)		Consultant's Values	
				T (m^2/s)	S	T (m^2/s)	S	T (m^2/s)	S
0.01		Well 9	Pump	3.98E-05	8.40E-02	2.11E-05	4.65E+00	7.34E-05	4.00E-04
		Well 7	Obs	4.19E-05	3.90E-04	7.42E-05	1.49E-04	7.34E-05	4.00E-04
		Well 8	Obs	1.10E-04	3.20E-04	2.33E-04	2.61E-04	7.34E-05	4.00E-04
		Well 10	Obs	5.93E-05	2.80E-04	7.59E-05	1.41E-04	7.34E-05	4.00E-04
0.02	Test 1	TH 1-81	Obs	4.10E-04	1.10E-04	5.27E-04	4.69E-05	4.46E-04	2.00E-04
		TH 3-81	Pump	2.65E-05	4.89E-01	6.86E-05	9.04E-03	1.73E-04	2.00E-04
	Test 3	TH 1-81	Pump	4.24E-05	1.71E-01	1.86E-04	1.08E-07	3.02E-04	2.00E-04
		TH 3-81	Obs	3.40E-04	1.30E-04	4.86E-04	3.49E-05	2.31E-04	2.00E-04
	Test 4	TH 3-81	Pump	2.23E-05	3.85E-01	6.67E-05	7.88E-04	2.14E-04	2.00E-04
0.03	1979	"No Name"	Pump	7.01E-06	2.82E-01	8.47E-06	2.67E-01	7.37E-06	X
	1989	"No Name"	Pump	3.54E-06	6.98E+00	1.83E-06	9.02E-01	X	X
0.04		PW-1	Pump	1.74E-05	6.61E-01	2.75E-05	5.28E-01	X	X
0.05		Well 4	Pump	3.93E-05	1.37E+00	4.05E-05	7.03E-01	X	X
0.06	0.06.1	Well 1	Pump	4.88E-05	8.82E-01	7.52E-05	2.42E-01	1.44E-04	6.20E-05
	0.06.2	Well 2	Pump	1.14E-05	5.84E-01	1.25E-05	4.53E-01	2.71E-05	1.70E-04
0.07	007.1 Test 1	TW 89-1	Pump	7.06E-04	2.49E+02	1.40E-03	1.02E+01	6.13E-04	X
		TW 89-2	Obs	5.31E-04	1.48E-02	1.12E-03	6.33E-03	5.56E-04	X
	007.1 Test 2	TW 89-1	Obs	2.37E-04	2.56E-02	6.85E-04	6.47E-03	2.55E-04	X
		TW 89-2	Pump	2.42E-04	3.26E+03	7.61E-04	4.40E+02	2.55E-04	X
	0.07.2	Brook's Well	Pump	2.42E-06	3.30E-01	2.89E-06	2.73E-01	X	X
	007.3.1	Well #1	Pump	1.17E-05	4.34E-01	3.35E-05	4.18E-03	X	X
	007.3.2	Well #2	Pump	1.92E-06	2.45E-01	5.04E-06	3.83E-03	X	X
	007.4.1	Well B	Pump	2.02E-06	2.96E+00	3.45E-06	1.20E+00	2.16E-04	1.68E+00
	007.4.2	Well 2	Pump	9.51E-07	3.24E-01	8.89E-07	3.04E-01	8.76E-05	1.53E-01
0.08		Well C	Pump	1.00E-04	8.28E-01	1.34E-04	1.78E-01	X	X
0.09	0.09.1	Well #16	Pump	2.50E-05	7.81E+00	3.10E-05	4.07E+00	1.00E-03	1.50E-02
	0.09.2	"No Name"	Pump	1.16E-05	8.25E-01	3.87E-06	1.95E-01	X	X
0.10		"No Data"	"No Data"	"No Data"	"No Data"			X	X
0.11		"No Data"	"No Data"	"No Data"	"No Data"			X	X
0.12		"No Name"	Pump	7.12E-06	8.41E-01	7.51E-06	7.42E-01	7.05E-06	X
0.13		"No Data"	"No Data"	"No Data"	"No Data"			X	X
0.14		Well #2	Pump	4.43E-05	3.15E-01	3.22E-04	1.86E-09	3.13E-05	X
0.15		Well #2	Obs	4.38E-05	8.73E-05	5.97E-05	5.15E-05	4.16E-05	X
		Well #3	Obs	1.42E-03	2.23E-04	7.65E-04	2.01E-04	1.12E-04	2.20E-04
		Well #4	Obs	4.09E-05	1.79E-04	6.83E-05	9.15E-05	4.16E-05	9.60E-05
		Well #5	Pump	5.22E-05	3.83E-01	6.92E-05	2.42E-01	4.03E-05	5.20E-04
0.16		Well 2	Pump	1.13E-04	1.13E+00	1.15E-04	1.12E+00	1.43E-04	X

flow models). The results are discussed in Section 4.0. Table 3.2 compares the results for the aquifer parameters calculated using both the preferred methodology described in this report (Cooper-Jacob (1)) and Cooper-Jacob (2), and those reported in the original documentation for the sites.

3.5 Fracture Flow Models

The conceptual model for radial flow conditions is widely recognized. The discharging well, in such a system, creates a cone of depression in the surrounding aquifer in which flow lines converge upon the well from all directions and the equipotential lines are concentric on the center of the well. Drawdown decreases with distance from the pumping well and the velocity increases toward the well.

In bedrock aquifers, there is a greater likelihood that the flow regime is dominated by fracture flow. If the primary porosity is very limited, then much of the flow to the well will be within the fractures. The fractures themselves may constitute the only storage media in the aquifer (crystalline bedrock is an example of a bedrock aquifer with limited primary porosity). These fractures may be uniformly distributed throughout the aquifer or they may occur as discrete fractures somewhat randomly distributed (albeit according to the tectonics to the area). In the former instance (uniform distribution of fractures), the aquifer should behave radially, in that wells should respond according to their radial distance away from the pumping well. In the latter instance, those observation wells that are in hydraulic connection with the pumping well by a major fracture will respond quickly to pumping, and those that are not connected by a major fracture will have a delayed response.

In porous bedrock, the primary porosity may be significant, and there might also be significant flow through fractures (secondary permeability). In this type of aquifer, contributions from both the fractures and the porous matrix may be present. This type of response is typically called double porosity flow (but may also be referred to as uniformly fractured – just to add confusion with the situation described above).

The fracture flow models examined for this study include both single fracture models (here called the vertical fracture flow models) and the uniformly fractured or double porosity flow models.

3.5.1 Vertical Fracture Flow Models

If a well intersects a single vertical planar fracture, as shown in Figure 3.5a, which has a permeability sufficiently large that the ratio of the fracture permeability to the aquifer matrix permeability approaches infinity, then the aquifer's unsteady response to pumping will differ significantly from that predicted by Theis. The solution to this type of flow problem has long been the subject of debate. In fact, the author contends that, to date, there has not been a definitive study on the different types of flow regimes in fractured aquifers. The underlying

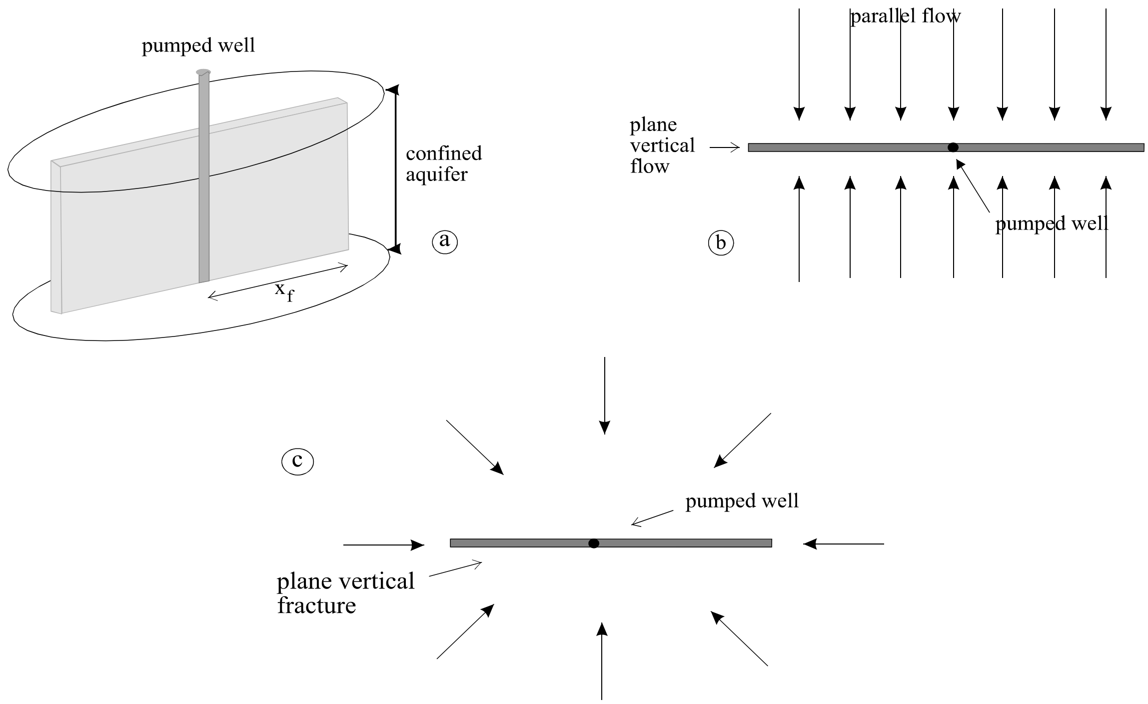


Figure 3.5: Schematic diagram showing a well that intersects a plane vertical fracture of finite length and infinite hydraulic conductivity (after Kruseman and de Ridder, 1990).

concept to the various analytical solutions is that the aquifer is homogeneous, isotropic and of large lateral extent. The aquifer is also confined above and below by impermeable horizons. A single plane, or vertical fracture, of relatively short length and infinite hydraulic conductivity, dissects this aquifer. The fracture is considered to be of zero width so that storage (storativity) can be neglected.

This type of aquifer representation allows the system to be modelled as an "equivalent" anisotropic, homogeneous porous medium. Since the pumping well intersects the fracture midway and since this fracture is of infinite hydraulic conductivity, the drawdown in the fracture will be uniform over its entire length (*i.e.*, there is no hydraulic gradient within the fracture).

At early pumping times, flow toward the fracture is one-dimensional, along the vertical fracture (Figure 3.5b) and is best referred to as linear flow. The flow in the aquifer, however, is horizontal and perpendicular to the fracture (parallel flow). The equipotential lines define a trough of depression, rather than a cone of depression as in radial flow regimes, and the axis of this trough coincides with the ‘extended’ well (essentially infinite hydraulic conductivity as in the wellbore itself). Drawdown in this type of system is a function of perpendicular distance away from the fracture, rather than distance away from the pumping well.

As pumping continues, the flow pattern changes from parallel flow to pseudo-radial flow (Figure 3.5c) regardless of the fracture’s hydraulic conductivity (Gringarten *et al.,* 1975). During this period, most of the well discharge originates from areas farther removed from the fracture. Kruseman and de Ridder (1990) stated “Often, uneconomic pumping times are required to attain pseudo-radial flow, but once it has been attained, the classical methods of analysis can be applied”.

Since drawdown is a function of perpendicular distance to the fracture, rather than radial distance to the pumping well, it is important to consider the positioning of monitoring wells for analyzing the aquifer test data. If all observation wells are located very close to the fracture, anywhere along its length, then the drawdown in these wells will be similar. Since the fracture is considered an ‘extended’ well, the response times in these wells will be instantaneous. Wells located at varying distances away from the fracture will undergo varying amounts of drawdown in addition to having different response times.

Gringarten and Witherspoon (1972) obtained the following general solution for the drawdown in an observation well located a distance, r', away from a pumping well situated on a vertical planar fracture of half length, x_f:

$$s = \frac{Q}{4\pi T} F\left(u_{vf}, r'\right) \qquad 3.2$$

where

$$u_{vf} = \frac{Tt}{S{x_f}^2} \qquad 3.3$$

and

$$r' = \frac{\sqrt{x^2 + y^2}}{x_f} \qquad 3.4$$

In Equations 3.2 to 3.4, it is apparent that the drawdown in an observation well depends not only on the parameter, u_{vf}, (*i.e.*, on the aquifer hydraulic parameters T and S, the vertical fracture half-length, x_f , and the pumping time, t) but also on the geometrical relationship between the location of the observation well and that of the fracture. In Equation 3.4, x and y are the distances between observation well and pumping well, measured along the x- and y-axes, respectively (Figure 3.6).

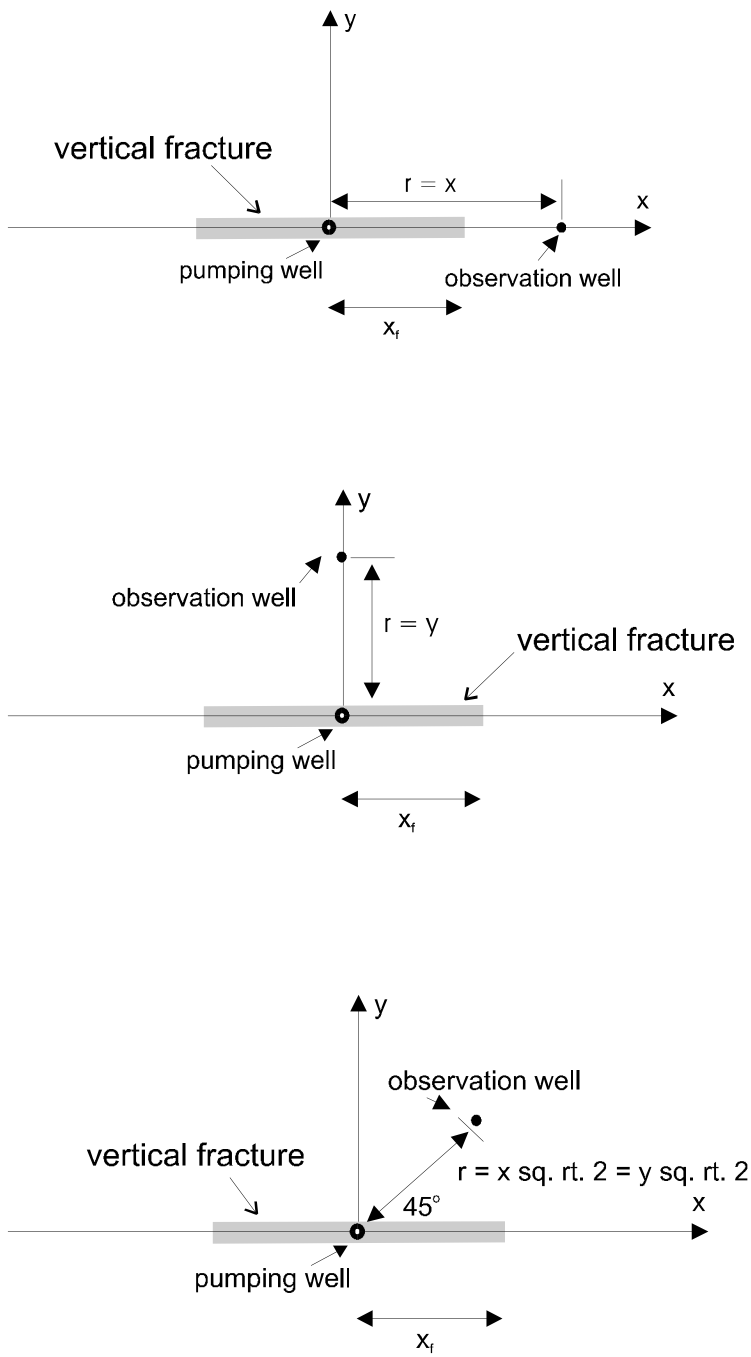


Figure 3.6: Plan view of a vertical fracture with observation wells at three different orientations (after Kruseman and de Ridder, 1990)

Gringarten and Witherspoon (1972) derived simplified expressions for the drawdown in three simple cases; one for an observation well located along the x-axis ($r'=x/x_f$), one for an observation well located along the y-axis ($r'=y/x_f$), and one for an observation well located along a line 45º degrees from the axis of the fracture ($r'=1.4142x/x_f$). These expressions can be plotted as a family of curves for each particular well position (*i.e.*, for different values of r').

If the relative position of the observation well is known, drawdown values versus time can be plotted on log-log paper and the curve matched to one of the type curves. As for the Theis method, this curve-matching process yields a value of T and S for the aquifer. If the position of the observation well is not known relative to the fracture, data from at least two observation wells are required and the curve-matching process becomes one of trial-and-error.

Gringarten and Ramey (1974) and Gringarten *et al.* (1975) derived a similar set of expressions for a pumping well which intersects a single vertical planar fracture in an otherwise, homogeneous, isotropic, confined aquifer. The equation is actually the reduced form of Equation 3.2 for $r'=0$ and results in a single type curve for the pumping well (Annex 4). At early pumping times, when the drawdown in the well is governed by horizontal, laminar flow in the aquifer (*i.e.*, the linear flow period), the data plot as a straight line on a log-log graph with a slope of 0.5. The parallel flow period ends at approximately $u_{vf}=1.6\times10^{-1}$. Furthermore, if the fracture is elongated and the aquifer has a relatively low transmissivity, the parallel flow period may last relatively long. Through a process of curve-matching, Equations 3.2 and 3.4 can be solved for T and the product Sx_f^2.

The pseudo-radial flow period starts at approximately $u_{vf}=2$. During pseudo-radial flow, the drawdown in the pumping well varies according to the standard Theis equation for radial flow plus a constant and can be approximated by the expression (Gringarten and Ramey, 1974):

$$s_w = \frac{2.3Q}{4\pi T}\log\frac{16.69Tt}{Sx_f^{\ 2}} \qquad 3.5$$

For large pumping time, the data can be analyzed by plotting drawdown versus time on semi-log paper and solving Equation 3.5 in a method similar to Cooper-Jacob's straight-line method described earlier.

The type curves for the vertical fracture flow model clearly indicate that the drawdown response in an observation well differs from that in a pumped well. As long as the observation well does not intersect the same fracture as the pumped well, the log-log plot of drawdown versus time in the observation well does not yield an initial straight line of slope 0.5. In fact, far enough from the pumped well (*i.e.*, r'>5), the drawdown response becomes identical to that for radial flow to a pumped well in the Theis equation.

Figure 3.7 shows a semi-log plot of the type curve for the vertical fracture flow model. In contrast to the linear Cooper-Jacob graph, the vertical fracture flow model predicts a broad curvature in the early time data. Jenkins and Prentice (1982) also noted that an arithmetic plot of s versus $t^{1/2}$ yields a straight line if linear flow conditions are present.

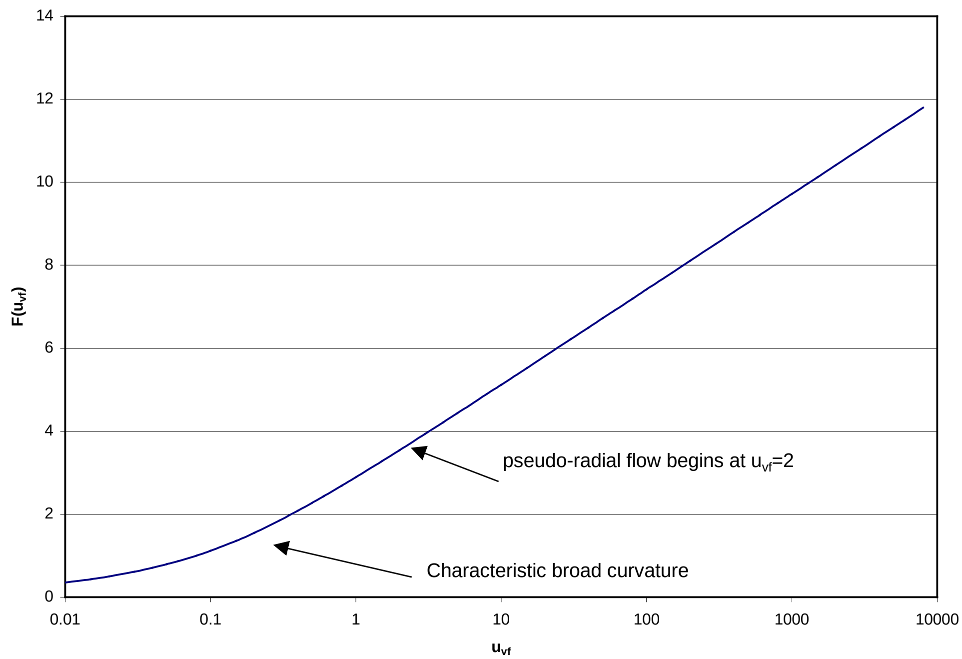


Figure 3.7: Semi-log graph showing type curve for the pumping well located along a vertical fracture (Data from Gringarten et al., 1975).

Gringarten et al's method for the pumping wells (Appendix 1.4 and Annex 4) and Gringarten-Whitherspoon's method for the observation wells (Appendix 1.5 and Annex 5) were used for this study. Both methods involve the use of type curves similar to that of the Theis Method. These methods are applicable to wells penetrating a confined single vertical fracture. Hydraulic test data plotted on log-log scale were matched with the appropriate type curve (Annexes 4 and 5). An arbitrary match point was picked, and the corresponding values of from the x and

Table 3.3: Linear (Fracture Flow) Methods

Legend: (grey shading) **Failed Warren-Root's Validation Test**
X **Method Not Applied**

Note: S_{xf}^2 refers to storativity times fracture half length squared, and T_f and S_f are for fractures

File				Single Vertical Fracture Aquifer				Uniformly Fractured Aquifer			
	Sub-File/ Test	Well Name or #	Pump/Obs	Gringarten et al.'s (for pumping wells)		Gringarten-Whitherspoon's (for observation wells)		Warren-Root's (for pumping wells)		Kazemi et al.'s (for observation wells)	
				T (m^2/s)	Sx_f^2 (m^2)	T (m^2/s)	S	Tf (m^2/s)	Sf	Tf (m^2/s)	Sf
0.01		Well 9	Pump	2.94E-05	1.80E-02			6.02E-05	4.98E+01		
		Well 7	Obs			3.49E-03	2.98E-02			X	X
		Well 8	Obs			2.86E-05	4.47E-06			X	X
		Well 10	Obs			5.06E-05	7.57E-04			3.57E-05	4.20E-04
0.02	Test 1	TH 1-81	Obs			5.40E-04	5.53E-05			2.99E-04	5.91E-03
		TH 3-81	Pump	1.58E-05	5.80E-02			4.04E-05	2.02E-01		
	Test 3	TH 1-81	Pump	3.13E-05	1.51E-02			5.02E-05	1.12E-01		
		TH 3-81	Obs			4.05E-04	2.57E-04			4.23E-04	3.55E-05
	Test 4	TH 3-81	Pump	3.95E-05	9.13E-03			1.54E-05	3.60E-01		
0.03	1979	"No Name"	Pump	X	X			X	X		
	1989	"No Name"	Pump	1.36E-05	6.29E-01			X	X		
0.04		PW-1	Pump	4.18E-02	3.51E+00			X	X		
0.05		Well 4	Pump	2.27E-05	2.45E-01			3.94E-05	6.46E-01		
0.06	0.06.1	Well 1	Pump	7.62E-05	4.80E-03			2.55E-05	3.11E+00		
	0.06.2	Well 2	Pump	1.44E-05	9.04E-03			2.21E-06	8.32E-01		
0.07	007.1 Test 1	TW 89-1	Pump	X	X			9.13E-04	3.41E+01		
		TW 89-2	Obs			1.18E-04	7.29E-04			X	X
	007.1 Test 2	TW 89-1	Obs			1.10E-04	2.72E-04			X	X
		TW 89-2	Pump	X	X			1.02E-03	3.80E+02		
	0.07.2	Brook's Well	Pump	3.39E-06	5.69E-03			X	X		
	007.3.1	Well #1	Pump	X	X			1.22E-05	5.16E-01		
	007.3.2	Well #2	Pump	1.90E-06	9.92E-02			8.41E-07	2.14E+00		
	007.4.1	Well B	Pump	X	X			X	X		
	007.4.2	Well 2	Pump	X	X			X	X		
0.08		Well C	Pump	1.17E-04	2.17E-02			X	X		
0.09	0.09.1	Well #16	Pump	2.09E-05	4.38E-01			X	X		
	0.09.2	"No Name"	Pump	1.14E-05	3.83E-02			X	X		
0.10		"No Data"	"No Data"	"No Data"	"No Data"			"No Data"	"No Data"		
0.11		"No Data"	"No Data"	"No Data"	"No Data"			"No Data"	"No Data"		
0.12		"No Name"	Pump	X	X			X	X		
0.13		"No Data"	"No Data"	"No Data"	"No Data"			"No Data"	"No Data"		
0.14		Well #2	Pump	X	X			2.92E-05	7.37E-01		
0.15		Well #2	Obs			7.83E-03	2.71E-02			X	X
		Well #3	Obs			3.38E-04	3.27E-05			X	X
		Well #4	Obs			1.87E-04	6.02E-03			X	X
		Well #5	Pump	4.74E-05	2.05E-02			2.93E-05	1.56E+00		
0.16		Well 2	Pump	1.16E-04	5.01E-02			5.30E-05	4.33E+00		

y axis of the type curve and the hydraulic test curve were identified. T and S values were then calculated using the appropriate equation.

Table 3.3 lists the values of the aquifer parameters that were calculated using the vertical fracture flow models. These are discussed in greater detail in Section 4.0.

3.5.2 Uniformly Fractured or Double Porosity Flow Models

Barenblatt *et al.* (1960) first considered fractured rock formations as consisting of two overlapping continuum media, porous and fissured, and each filling the entire flow domain. The matrix rock is defined as having some primary porosity. This rock mass has randomly distributed and arbitrarily oriented fractures, which have a secondary porosity of the same order of magnitude as the matrix rock. Streltsova (1976) distinguished this system of blocks and fissures to be purely fractured when it consists entirely of the continuous fracture porosity, and as being doubly porous when it is controlled by the fracture and block hydraulic properties of the same order of magnitude. In the latter instance, the total permeability is due primarily to the fractures and the storativity to the matrix.

The concept of double porosity flow is based on the assumption that there are two superimposed flow fields, each with their own respective drawdown equation. When the pressure in the aquifer is lowered, there is an immediate pressure reduction within the fracture network as a result of the very low storage potential of fractures. In the pseudo-steady state interporosity flow model, it is assumed that there is a re-equilibration of this pressure differential between the matrix and the fissures with no resulting decline in head in the matrix (Streltsova-Adams, 1978). In this situation, the drawdown becomes constant at intermediate times, during the transition period from purely fracture flow to block and fissure flow. At late times, the flow is described by the Theis equation since the flow is from the block and fissure system. Bourdet and Gringarten (1980) showed that the double porosity flow model only applies in a limited area around the pumping well. Outside of that area, the drawdown behaviour is equivalent to a Theis-type model. Alternative models consider transient block-to-fracture flow (Boulton and Streltsova, 1977).

The characteristic drawdown curves, for an aquifer having double porosity, consist of two Theis curves, one for the fissures and one for the fissure/block system, which are separated by a transition flow period where there is little or no drawdown. The log-log family of curves are, in fact, similar to those for an unconfined aquifer (Neuman, 1972). The semi-log graph shows characteristic “asymptotic” drawdown lines (*i.e.*, parallel lines separated by the interflow period). It must be emphasized that the double porosity model is a radial flow model.

The constant discharge data for all of the wells exhibiting a mid-time flattening were examined. The Warren-Root (1963) method for pumping wells (Appendix 1.6) and Kazemi et al. (1969) method for observation wells (Appendix 1.7) were used. Both methods involve the use of the semi-log hydraulic test curve and the identification of two straight lines, the early-time and the late-time straight lines and the transition period that separates the two. The early-time line represents the primary porosity (water from fractures) and the late-time line represents the secondary porosity (water from matrix). The intercept and the slope of the respective lines as well as the location & length of the transition period are then used in the appropriate equations to come up with the required aquifer property values (T and S). A series of 3 tests were then used to verify if the data are suitable for analysis using the double porosity methods.

Table 3.3 provides the values for aquifer parameters calculated using the double porosity methods.

3.6 Unconfined Flow Models

When an aquifer is unconfined, whether porous or not, pumping causes a dewatering of the aquifer and creates a cone of depression in the water table. As pumping continues, the cone expands and deepens, and the flow toward the well becomes non-radial and has a distinct vertical component. When water is pumped from a confined aquifer, the aquifer remains fully saturated, and the cone of depression exhibited by the potentiometric surface reflects the lowering of pressure in the vicinity of the well.

In unconfined aquifers, the water levels in the observation wells tend to decline at a slower rate than that described by the Theis equation. Time-drawdown curves on log-log paper usually show an S-shape, from which three distinct time segments can be identified. At early times, an unconfined aquifer behaves in the same way as a confined aquifer and the shape of the curve is similar to the Theis curve. At intermediate times, the curve flattens reflecting the effect of dewatering that accompanies the falling water table. This flattening is comparable to leakage and may be interpreted as leakage if the test is not sufficiently long to capture the late time response typical of unconfined conditions. At late times, the curve steepens, resembling once again the Theis curve that is characteristic of radial flow.

Under favourable conditions, the early and late time drawdown data can be analyzed using Theis. The storativity calculated using the early time portion of the data should not be used to estimate long term drawdown as it reflects the short-term pumping effect. The late time data can be used to estimate the specific yield, S_y, of the aquifer in lieu of S. Use of the specific yield will provide a more representative estimate of the aquifer's response to pumping at later times.

Neuman (1972) developed a theory of delayed water table response from which he produced the well-known method for analyzing hydraulic test data collected in unconfined aquifers. The assumptions for the method are essentially the same as those for Theis, with the notable exception that the aquifer is unconfined, and that a family of curves as opposed to a single curve must be used for curve matching.

Because the tests for double porosity failed in several wells, and we are fairly confident that the amount of primary porosity is limited, we decided to analyze the data using Neuman's method (Appendix 1.8). This method employs the use of type curves and a curve matching procedure similar to that for the Theis method. Hydraulic test data curves (log-log) are matched with the appropriate type curve (Annex 8) and an arbitrary point is picked and values from the x and y axis of both curves at match-point is used to calculate T and S values.

Table 3.4 lists the hydraulic parameters calculated for the aquifer using this method.

3.6 Recovery Flow Models

Recovery testing is an important part of all aquifer testing programs. Immediately after the pump is shut off for the constant discharge test, the aquifer will begin to recover. This is manifested as a rise in water levels in all of the wells and is referred to as the residual drawdown, *s'*. The residual drawdown is defined as the difference between the original water level prior to pumping and the water level measured at a time *t'* after the cessation of pumping. Recovery testing serves as an independent check on the transmissivity value calculated from the constant discharge data.

The analysis of recovery data is based on the Principle of Superposition. It is assumed that after the pump has been shut off, the well continues to be pumped at the same rate as before, and that an imaginary injection well with a recharge of equal magnitude is superimposed at the pumping well. The Theis recovery equation, which is valid for confined aquifers, is defined as (after Theis, 1935):

$$s' = \frac{Q}{4\pi T}\left\{W(u) - W(u')\right\} \qquad 3.6$$

where

$$u = \frac{r^2 S}{4Tt} \quad \text{and} \quad u' = \frac{r^2 S'}{4Tt'} \qquad 3.7$$

In Equation 3.7, *r* is the radial distance from the pumping well, *S (or* S_a*) and S' (or Sy)* are the storativity during pumping and the storativity during recovery, *T* is the aquifer transmissivity, *t* is the total time (pumping plus recovery time) and *t'* is the recovery time. Often, the storativity values will be slightly different during and

Table 3.4: Unconfined Flow Methods

Legend: X Method Not Applied

Note: S_a refers to storativity and S_y refers to specific yield

File	Sub-File/ Test	Well Name or #	Pump/Obs	Unconfined Aquifer Neumann's T early (m^2/s)	T late (m^2/s))	S_a	S_y
0.01		Well 9	Pump	X	X	X	X
		Well 7	Obs	1.59E-05	1.86E-05	6.61E-05	9.07E-05
		Well 8	Obs	X	X	X	X
		Well 10	Obs	8.37E-05	3.21E-05	1.42E-04	8.65E-04
0.02	Test 1	TH 1-81	Obs	2.32E-01	2.32E-01	2.27E-01	3.92E+01
		TH 3-81	Pump	1.72E-05	1.47E-05	5.68E-01	1.89E+02
	Test 3	TH 1-81	Pump	X	X	X	X
		TH 3-81	Obs	1.27E-04	9.65E-05	1.73E-04	6.02E-02
	Test 4	TH 3-81	Pump	6.18E-06	5.88E-06	5.37E-01	4.50E+02
0.03	1979	"No Name"	Pump	X	X	X	X
	1989	"No Name"	Pump	5.27E-06	1.06E-06	9.81E-01	1.92E+01
0.04		PW-1	Pump	X	X	X	X
0.05		Well 4	Pump	1.34E-05	9.24E-06	1.05E+00	1.72E+02
0.06	0.06.1	Well 1	Pump	2.65E-05	7.94E-06	1.64E+00	3.94E+03
	0.06.2	Well 2	Pump	X	X	X	X
0.07	007.1 Test 1	TW 89-1	Pump	X	X	X	X
		TW 89-2	Obs	X	X	X	X
	007.1 Test 2	TW 89-1	Obs	X	X	X	X
		TW 89-2	Pump	X	X	X	X
	0.07.2	Brook's Well	Pump	X	X	X	X
	007.3.1	Well #1	Pump	6.32E-06	9.79E-06	4.70E-01	5.67E+00
	007.3.2	Well #2	Pump	5.86E-07	9.37E-07	2.90E-01	3.22E+00
	007.4.1	Well B	Pump	X	X	X	X
	007.4.2	Well 2	Pump	X	X	X	X
0.08		Well C	Pump	3.62E-05	2.13E-05	5.83E-01	7.92E+02
0.09	0.09.1	Well #16	Pump	X	X	X	X
	0.09.2	"No Name"	Pump	X	X	X	X
0.10		"No Data"	"No Data"	X	X	X	X
0.11		"No Data"	"No Data"	X	X	X	X
0.12		"No Name"	Pump	X	X	X	X
0.13		"No Data"	"No Data"	X	X	X	X
0.14		Well #2	Pump	X	X	X	X
0.15		Well #2	Obs	X	X	X	X
		Well #3	Obs	X	X	X	X
		Well #4	Obs	X	X	X	X
		Well #5	Pump	1.00E-05	9.49E-06	7.45E-01	2.55E+02
0.16		Well 2	Pump	X	X	X	X

after pumping as a result of aquifer compression. However, when u and u' are sufficiently small (*i.e.*, $u, u'<0.01$), T is constant, and the pumping and recovery storativities are equal (*i.e.*, $S=S'$), Equation 3.6 can be approximated as:

$$s' = \frac{2.3Q}{4\pi T}\log\frac{t}{t'} \qquad 3.8$$

In a homogeneous, isotropic, confined aquifer that is unbounded, a plot of s' versus t/t' on a semi-log scale will yield a straight line, for large values of time. The slope of this line is used to obtain a value for T. Theis recovery analysis does not provide a value for storativity.

Because the bedrock aquifers examined in this project were shown to exhibit non-radial flow under pumping conditions, Equation 3.8 will not strictly apply. Nevertheless, the Theis Recovery Method was used to analyze the recovery data.

Wells that have recovery data available were analyzed using the Theis Recovery Method (Appendix 1.3). A special sub-routine was implemented in the analysis of recovery data. Only the segment (segment of t') in the recovery curve believed to be due to radial flow was picked for the computation of the transmissivity. As often as possible, these segments were selected to coincide with the same radial flow time segment used in the Theis and Cooper-Jacob Method (Section 3.4). For example, if in the Theis and Cooper-Jacob Method, the time segment: t = 50 to 400 minutes was identified as radial flow, then the same time segment during recovery was selected (i.e., t' = 50 to 400 minutes).

Table 3.1 lists the values of parameters calculated using the Theis Recovery method.

4.0 Discussion

4.1 Applying the Derivative Method for Simplifying Data Analysis

The derivative method proved to be a very important component of the overall data analysis procedure used in this study. Its use not only complemented the other standard methods of analysis, but in many cases, provided the only means to identify what portion of the data curve could be attributed to radial flow. As mentioned earlier, it is important when using either the Theis or Cooper-Jacob methods of analysis that only those data that result from radial flow be considered.

Upon examination of all of the derivative plots, it was difficult to identify any clear trends or similarities. This means that either the geology of each site or well placement relative to major fractures is significantly different that the hydraulic responses are also very different. Even at individual sites, there are distinct differences between the derivative plot for the pumping well and for the observation wells. Similarly, differences are noted for subsequent tests at the same site whereby the original observation well becomes the pumping well and the original pumping well becomes the observation well.

By looking at the derivative plots before the standard methods of analysis were implemented, it was possible to pick apart the hydraulic response of the aquifer and identify the various flow periods exhibited by the data. The following points summarize the findings related to the use of the derivative method:

- Overall, the derivatives show a large degree of variability, primarily because the data were not smoothed, but also because there are a variety of hydraulic irregularities influencing the responses. For example, minor changes in pumping rates can cause the derivative to drop or rise suddenly (e.g. site 001, pumping well 9).

- Wellbore storage effects are limited to the pumping well, and are manifest as an increase in the derivative with time, followed by a decline (looks like a hump). In most cases, the pumping wells examined for this study do not exhibit wellbore storage, probably because the wells were pumped at sufficient rates to overcome the delayed aquifer response associated with water storage in the borehole. When present, wellbore storage is limited to early pumping times (generally less than 10 minutes).

- If wellbore storage is not evident (such as in observation wells), or once wellbore storage has ended, one would expect the derivative to stabilize (level out) if radial flow conditions are present. This occurs in only a few of the well tests. A particularly good example is at site 002. The pumping wells and observation wells (tests 1, 2 and 3) exhibit a fairly limited period of radial flow early on in the test (times less than 10 minutes).

- At most of sites, the derivative gradually increases in both the pumping and observation wells for a fairly long time before it either levels off (sites 003, 004 and 005) or drops. This long period of ramping up is likely the result of linear flow in the aquifer, whereby the rate of increase in drawdown with time gradually increases with time (characteristic of linear flow).

- The time intervals over which radial flow takes place, although sometimes obscured or of short duration, could be identified. Typically, these followed the linear flow period identified earlier. Only those time periods exhibiting radial flow were used for fitting a straight line in the Cooper-Jacob method or for curve matching in the Theis method. The significance of applying radial flow models to non-radial flow regimes is discussed in Section 4.2.

- Following the radial flow period, the derivative in many cases declines over a fairly long time period. This decline is attributed to the dewatering effects of unconfined flow conditions in the aquifer, but alternatively in some cases might be attributed to double porosity flow in the aquifer.

- If the test is not terminated too early, then radial flow may once again occur in the aquifer and is manifest as a second period of levelling off. Radial flow models can also be used on the data that fall in this second period of levelling off.

4.2 Application of Various Flow Models in Different Geological Regimes

Following an examination of all of the derivative responses and the drawdown time responses, the presence of several different types of flow regimes were indicated in the bedrock aquifers. These differences occurred not only between different sites and between different wells, but also at different time during pumping.

In general, the drawdown-time data plotted in log-log format for most of the wells were dissimilar to that predicted by Theis. The derivative plots indicated that only during brief time periods was radial flow observed. Therefore, it was possible to utilize the radial flow models (Theis and Cooper-Jacob). However, great care was taken to insure that only those data that reflect radial flow were analyzed.

There were two main differences observed in the data. First, the rate of change of drawdown measured at early time was less than predicted by Theis, resulting in almost a straight-line response in log-log format at early time. Second, a transition period at mid- to late-time (apparent as a levelling off of the drawdown time curve), is generally present.

The linear appearance of many of the graphs at early time (up to 1000 minutes) is likely attributable to linear flow. Without prior knowledge of detailed geology of the various sites, it is difficult to determine the origin for this linear flow. In most instances, linear flow results from a vertical or sub-vertical fracture, fault or shear zone in the vicinity of the pumping well. However, linear flow may also result from a horizontal planar fracture intersecting the well. Any observation well that intersects the same dominant fracture as the pumping well will experience an equal and almost instantaneous rate of drawdown with time as the pumping well, and both the pumping well and observation well will exhibit linear flow.

Unfortunately, there were insufficient data to confirm the orientation of any fractures present. Information on the orientation of fractures intersected by pumping well and its associated observation wells can be gained either by examination of outcrop, regional structural geology maps (to identify any major vertical or sub-vertical faults), borehole geophysics (horizontal to sub-vertical features), surface geophysics (vertical features), borehole imaging, or cores. Bedded bedrock units that have not undergone significant deformation are most likely to host sub-horizontal fracture planes as these may correspond to bedding. In contrast, bedrock that has been folded or faulted as a result of tectonic deformation, may host a range of fracture orientations (corresponding both to bedding and to regional structure).

If there are a sufficient number of observation wells present at the site (these located at varying distances from the pumping well and in different directions), then it may be possible to infer the presence of horizontal bedding planes by virtue of the somewhat radial responses measured in the observation wells. If a single bedding plane is intersected by all of the observation wells, their hydraulic responses will be very fast, they will tend to be linear in nature (straight line at early time on a log-log plot), but they will respond in order of their radial distances from the pumping well. In the presence of a vertical or sub-vertical fracture, only those wells situated along the fracture or in close proximity to it, will respond linearly while those well displaced from the fracture will exhibit a more Theis like response.

For the purposes of this study, we assumed that any major fractures would be in a vertical orientation, and that the analytical methods of analysis would be appropriate for vertical fractures. Regardless of the exact orientation of the fractures, linear flow methods were used to analyze the data. These linear flow models (such as Gringarten et al., 1975 for pumping wells and Gringarten and Witherspoon, 1972 for observation wells) were only used on data sets that exhibited linear flow.

When linear flow dominates at early time, the hydraulic response of both the pumping well and its observation wells reflect the presence of a highly transmissive planar conduit. In this situation, the use of either the Theis or

Cooper-Jacob methods is not strictly valid. Further, it is emphasized that the T values yielded by employing the planar fracture flow model will represent the transmissivity of the surrounding aquifer, not the actual fracture. These linear flow models take into account the aquifer's response at early time, but provide an estimate of T for the entire aquifer.

Once linear flow is complete at later times, and under pseudo-radial flow conditions, a radial flow model, such as Cooper-Jacob or Theis, can be used. The presence of an early time non-radial flow period can be anticipated to reduce the absolute drawdown measured in observation wells situated in the aquifer, and possibly the rate of drawdown as well, because of the influence of a dominant linear fracture. Thus, both the Jacob method and the Theis methods might overestimate slightly the magnitude of T. The degree to which T is overestimated likely will be a function of size of the fracture and the duration of the linear flow period preceding radial flow.

The second deviation from Theis occurred at mid- to late-time when the hydraulic test data exhibited a flattening. Not only was it difficult to fit the Theis curve to the data in some instances, but it was equally difficult to fit a straight line (Cooper-Jacob) through the data at mid- times.

Our initial interpretation of the flattening was that it is related to double porosity flow in the bedrock. Under conditions of double porosity flow, the water is transmitted at early time through the fractures. Typically there is minimal amount of water stored in the fractures, and the aquifer tries to make the transition to matrix flow. During this transition period, the drawdown-time curve flattens. Once the transition has been made to include matrix storage, then water is transmitted through the fractures, but is derived from the porous matrix.

Two different analytical models were used to analyze the data when a flattening was observed; the Warren-Root method for pumping wells and the Kazami et al. method for observation wells. In most wells, the tests that were used to verify if the double porosity flow models are valid failed. What this means is that either the data are not suitable for double porosity analysis (i.e., there may be insufficient data, or wellbore storage dominates too much at early time) or that double porosity flow cannot account for the observed responses.

Because the tests for double porosity failed, we investigated other possibilities that could account for the flattening observed at mid-time. One possibility is that some of the aquifers are unconfined. Concurrent studies being conducted at Simon Fraser University to investigate groundwater flow in fractured bedrock are suggesting that the flattening observed in the drawdown-time data is the result of unconfined conditions in the aquifer. In those cases under investigation, the primary porosity of the bedrock is very low, suggesting that there is unlikely to be much in the way of access to matrix storage at late time. The low primary porosity also implies that fractures alone are the means by which water is transmitted and stored in the aquifer. To determine if the aquifers might be responding to unconfined flow, Neuman's method for unconfined aquifers was used. The suitability of Neuman's method, however, does not preclude the possibility of double porosity flow.

In order to compare the results of each method, the various transmissivity and storativity values that were obtained were plotted. Because transmissivity, and to some degree storativity, are log-normally distributed (i.e., order of magnitude variations), the $\log_{10}$ values were plotted and regressed. In most cases, a comparison was made between one of the specialized methods and the Theis method. All data were initially plotted and then the outlying data points were removed. The following points summarize the results of our comparisons. Reference is made to specific diagrams in each case.

- **Cooper-Jacob (1) versus Theis**: When the radial flow data were used in each of the Cooper-Jacob (1) method (referred to as Jacob 2.1 in database) and the Theis method, the log transmissivity values are in relatively close agreement as is evident in the regression equation y=1.0274x+0.136 (Figure 4.1a). The R^2 value, reflecting the "goodness of fit" of the data to a straight line, is also very close to unity (.9642).

  Consideration of the slope relation between $\log T_{\text{Cooper-Jacob}}$ and $\log T_{\text{Theis}}$, would indicate that on average the transmissivity values calculated using Cooper-Jacob are very slightly higher than those calculated using Theis. Butler (1990) demonstrated that in non-homogeneous aquifers, the Theis and Cooper-Jacob methods yield estimates of transmissivity that are distinctly different (the lower T values calculated using the Theis method were attributed to well inefficiencies in the pumping wells, which caused greater absolute drawdown in the well). Wei (Groundwater Section, MoELP) investigated this relation for pumping wells in British Columbia, and found that for the few available pumping test results, the results were consistent with those described by Butler (1990). Wei recommended that use of Cooper-Jacob method for pumping wells would provide a more reliable estimate of T, because these would not be influenced by well inefficiency.

  In this study, estimates of T from both pumping and observation well data were available. We determined that the results are consistent with those of Butler (1990), and that T values calculated from Cooper-Jacob are very slightly higher than those calculated using Theis. Upon examination of Table 3.1, it appears that this slope relation is not being affected by a few extraneous data points, nor is there an identifiable difference between pumping wells and observation wells (i.e., both pumping and observation wells demonstrate variation between methods). While Cooper-Jacob did render slightly higher estimates of T, the relation is necessarily not the result of well inefficiency, because observation wells also gave higher estimates. To further investigate this relation, it would be necessary to separate out the pumping well T values from the observation well T values and undertake a statistical comparison.

Log storativity values calculated using Cooper-Jacob and Theis were also similar (Figure 4.1b). The regression equation was y=1.0207x-0.0577 (slope slightly higher than unity) with similar scatter to T variations (0.9708), indicating that storativity values calculated using Cooper-Jacob are slightly greater than those calculated using Theis. These higher values may be a consequence of the slightly higher T values (S is calculated using T as a variable). Pumping well and observation well storativities have been identified in Figure 4.1b. The high values for pumping well storativities are the direct result of the well radius being used in the equation.

- **Cooper-Jacob (2) versus Theis:** Figure 4.2a compared the log transmissivity values calculated using the second procedure for Cooper-Jacob and Theis. While Cooper-Jacob (1) used only the radial flow portion of the data curve, Cooper-Jacob (2) used all of the data following wellbore storage, regardless of whether they fell on a straight line or not. Figure 4.2a represents the extreme situation where no consideration is given to emphasizing the linear portion of the semi-log data curve. The implication is that if one uses automated curve-matching software, and does not eliminate those portions of the curve that are not representative of radial flow conditions, then the estimates of T will not be valid ones. The regression line equation in this case is y=1.0516x+.4177, and there is significant scatter in the data as reflected in the R^2 value of 0.8294. The higher intercept ($\log_{10}$) indicates that Cooper-Jacob (2) is overestimating T by at least a half order of magnitude.

  The relation is more deviant for log storativity values calculated using Cooper-Jacob (2) and Theis (Figure 4.2b). The regression line y=0.92x-.675 and the R^2 value 0.75 suggest storativity values calculated using Cooper-Jacob (2) are lower, and there is much more scatter. In figure 4.2b, pumping well and observation well storativities are identified.

- **Theis versus Linear flow:** Figure 4.3 shows the relation between log transmissivity values calculated using one of the vertical fracture flow models and Theis. In general, there is fairly good agreement between the two, which suggests that vertical fracture flow models (that utilize all of the data) are giving estimates of T that are similar to, but lower than, those obtained using Theis (for the radial data only). The regression line is y=0.8751x-.5349 and R^2 value is 0.8611.

  If there are major vertical or sub-vertical fractures in the vicinity of the pumping wells, then the application of a vertical fracture flow model is appropriate. The transmissivity that is calculated is representative of the aquifer away from the fracture, assuming that all of the assumptions inherent to the analytical model are met (refer to Appendices 1.4 and 1.5) and so it is reasonable that this value should be similar to estimates of T calculated using Theis. The fact that good agreement was noted in this study, suggests that the vertical fracture flow models are likely appropriate in several of the bedrock aquifers studied.

Despite the relatively good agreement between the aquifer T values calculated using the vertical fracture flow model and Theis, in general, those values calculated using latter method are slightly higher. As discussed in the previous section, it can be anticipated that application of the Theis method will overestimate T in a linear flow regime, because drawdown in the aquifer is lower in the presence of a fracture. The results of this study concur. This implies that if a radial flow model is used in a situation when linear flow is present, the actual aquifer T values are likely to be higher than calculated. If Cooper-Jacob (1) is used to calculate T in an aquifer influenced by a vertical fracture, then the estimates of T should be even higher than those determined using Theis (refer to Figure 4.1a).

- **Theis versus Uniformly Fractured (Double Porosity):** T and S values calculated using the uniformly fractured (or double porosity) flow models and Theis were compared (Figure 4.4). Figure 4.4a shows the relation between the log T values calculated for all data (y=1.1799x+.7498, R^2 is 0.8177). If only those data that pass the tests for application of the technique are used (Figure 4.4b), then the regression line is y=1.1381x+.7276 and the R^2 value is improved (.9638). A similar relation is observed for log storativity values (Figure 4.4c for all data and Figure 4.4d for data that satisfy the tests). Storativity values for pumping and observation wells have been identified.

  On the basis of the limited results, it is very difficult to determine if the double porosity models are valid for some of the aquifers. Whether all the data or only those data that pass the tests for use of this method are used, the T values are notably higher if calculated using the fractured aquifer methodology. This relation may be real or it may be coincidental. If it is real, the higher values may indicate that the Theis method underestimates the transmissivity. In order to form some strong conclusions in this respect a detailed site investigation with several observation wells and a well-defined geological interpretation is needed. Work is ongoing in this respect at SFU (M.Sc. Thesis, Abbey).

- **Theis versus Neuman:** In an attempt to assess Neuman's method (for unconfined aquifers), a comparison of the log T values obtained at early time (T_a) and at late time (T_b) were compared to those from Theis (Figure 4.5a and 4.5b, respectively). In both instances, there is moderately good agreement (y=0.978x-.3447 with R^2=0.8447 and y=0.9185x-.8064 with R^2=0.8605, respectively). On the basis of these regression analyses, there appears to be a better correlation with T values calculated from early time data than those calculated from late time data. This is somewhat surprising, given that the radial flow periods identified using the derivative method and subsequently used for analysis with the radial flow models, all tended to occur at later times. One would expect the late time Neuman T_b values to be closer to those calculated using Theis. Furthermore, the T values obtained using Theis were all overestimates if the ones calculated using Neuman (both early and late time) are reliable. There may be serious implications associated with this relation.

A comparison was also made between the log T values calculated using the early time portion of the curve (T_a) and the late portion (T_b) (Figure 4.6). It appears that the early T values are greater than the late time T values. This relationship is typical of unconfined aquifers in that during late time, the aquifer's response is slowed down as a result of dewatering.

- **Theis versus Theis Recovery:** Figure 4.7 shows the relation between the log T values calculated using Theis Recovery (on recovery data only) and Theis (constant discharge test data). If all of the data are used for this comparison (Figure 4.7a) then the regression equation is calculated as y=1.1003x+.7425 with an R^2 value of .7637. The reason for the poor fit (low R^2) is related to the fact that it was not always possible to select the same time interval for recovery analysis that was used for the pumping data analysis (i.e., those data that reflect radial flow conditions). For example, radial flow tended to occur at late times during pumping, and because recovery tests are of shorter duration (only 12 to 24 hours), it was impossible to select the same time interval. Figure 4.7b uses only those transmissivities that were calculated using the exact same time intervals. As predicted, the regression equation provides a slope that is much closer to unity (y=1.0141x+0.0749), and the R^2 fit is much improved (0.982).

- **Original Reported Estimates versus Theis:** Figure 4.8a shows the relation between the original reported consultants' estimates of transmissivity (as provided in the individual consulting reports) and those calculated using the radial flow data (Theis Method). Note that two outliers were removed before graphing. The regression line equation is y= -0.0756-4.2619 with an R^2=.0155. The poor relation and fit indicates that perhaps the methodologies currently used do not discriminate sufficiently between the linear and radial flow portions of the curve, and thus, poorly represent the T values of bedrock aquifers. The large scatter indicates that there are no consistencies (i.e., T values are not consistently over- or under-estimated). Many of the reports used in this study did not indicate which method was used to calculate the T and S values. Several indicated that Cooper-Jacob was used (but provided no indication of time interval used), and one used a method unfamiliar to the author.

- **Original Reported Estimates versus Jacob (2):** Figure 4.8b shows the relation between the original reported consultants' estimates of transmissivity and those calculated using all of the hydraulic test data after wellbore storage (Cooper-Jacob (2)). Cooper-Jacob (2) is considered a very impractical method of analysis and may perhaps reflect the transmissivities generated by automated curve matching programs in the absence of scrutiny. Figure 4b shows marginally better agreement between the original reported T values and Cooper-Jacob (2) (the regression equation is y= -0.1096x-4.4407 with an R^2 value of .0218) than that observed between Consultants' T values and Theis (discussed previously and shown in Figure 4.8a).

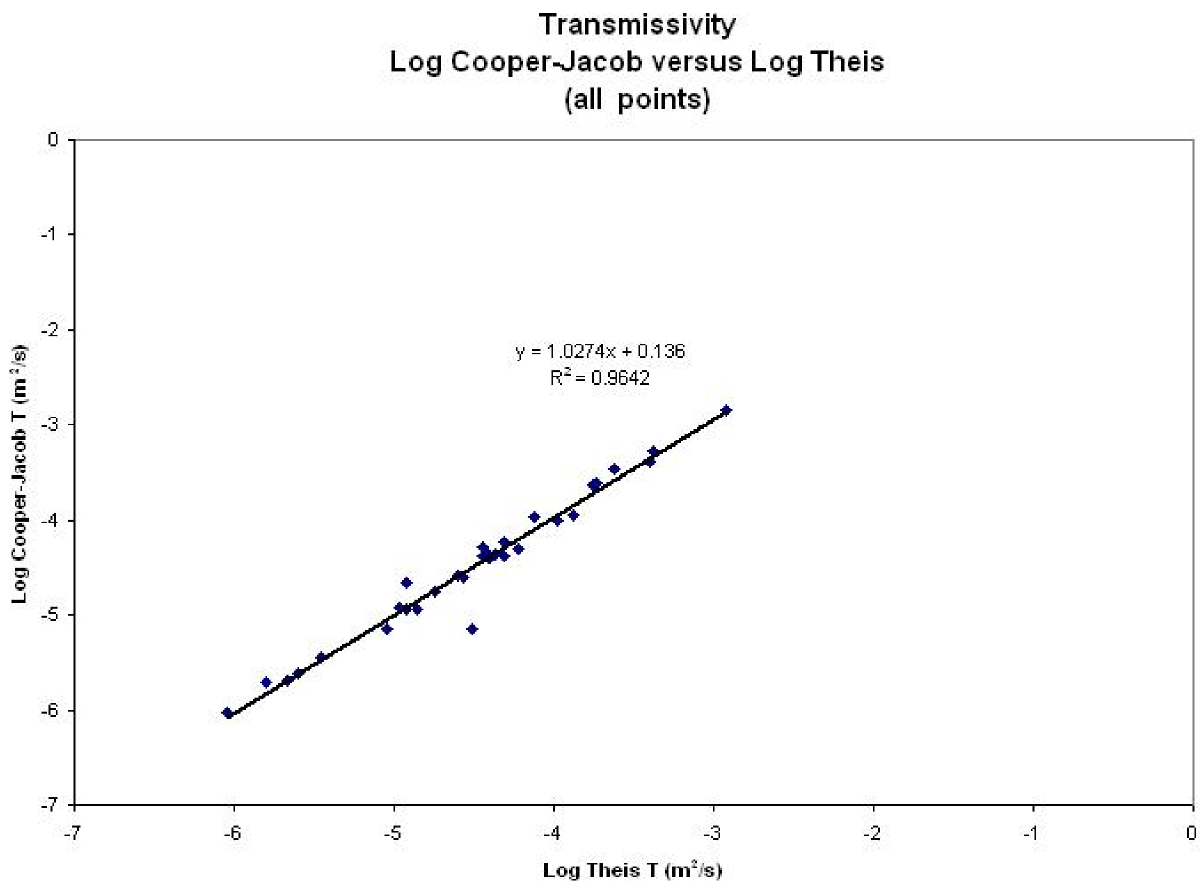


Figure 4.1a: Relation between log transmissivity values calculated using Cooper-Jacob (1) and Theis.

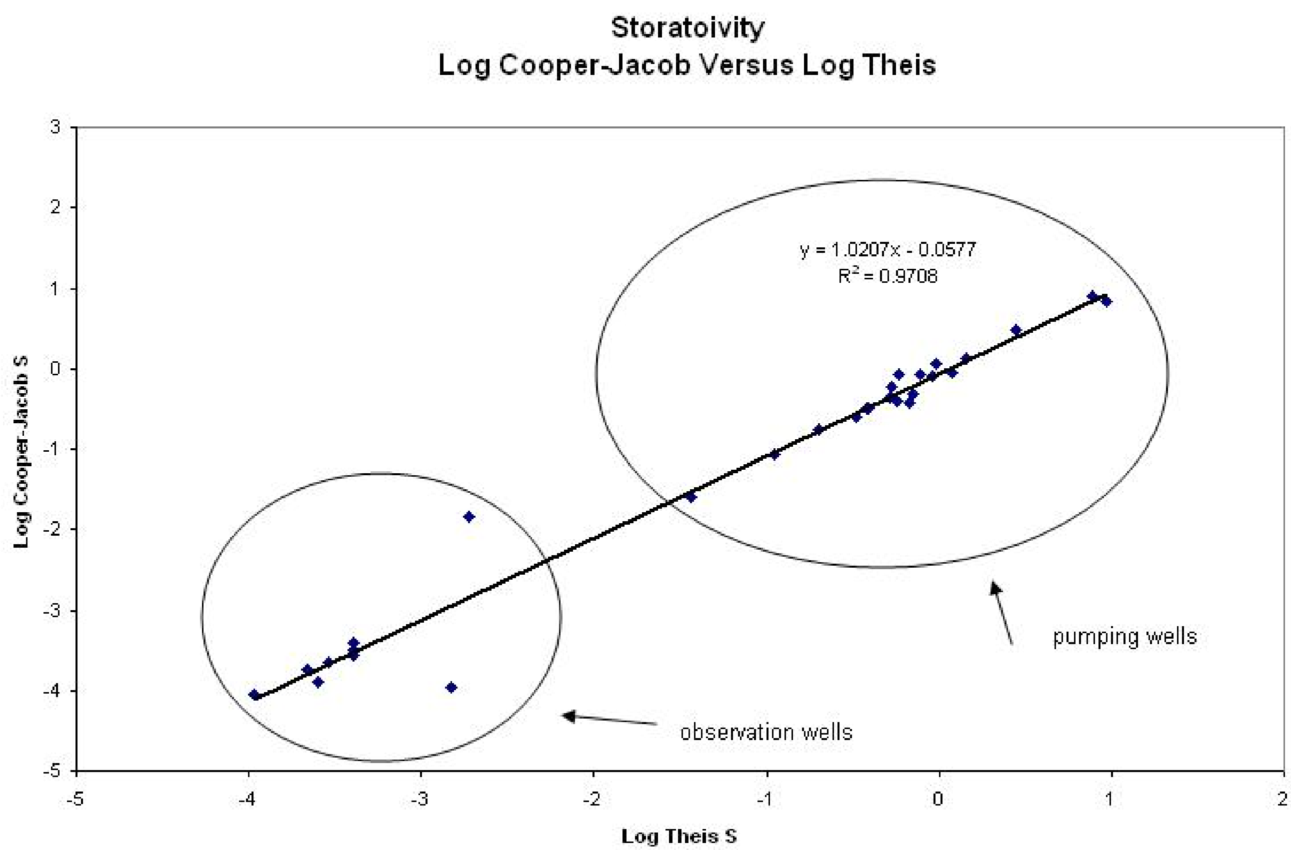


Figure 4.1b: Relation between log storativity values calculated using Cooper-Jacob (1) and Theis.

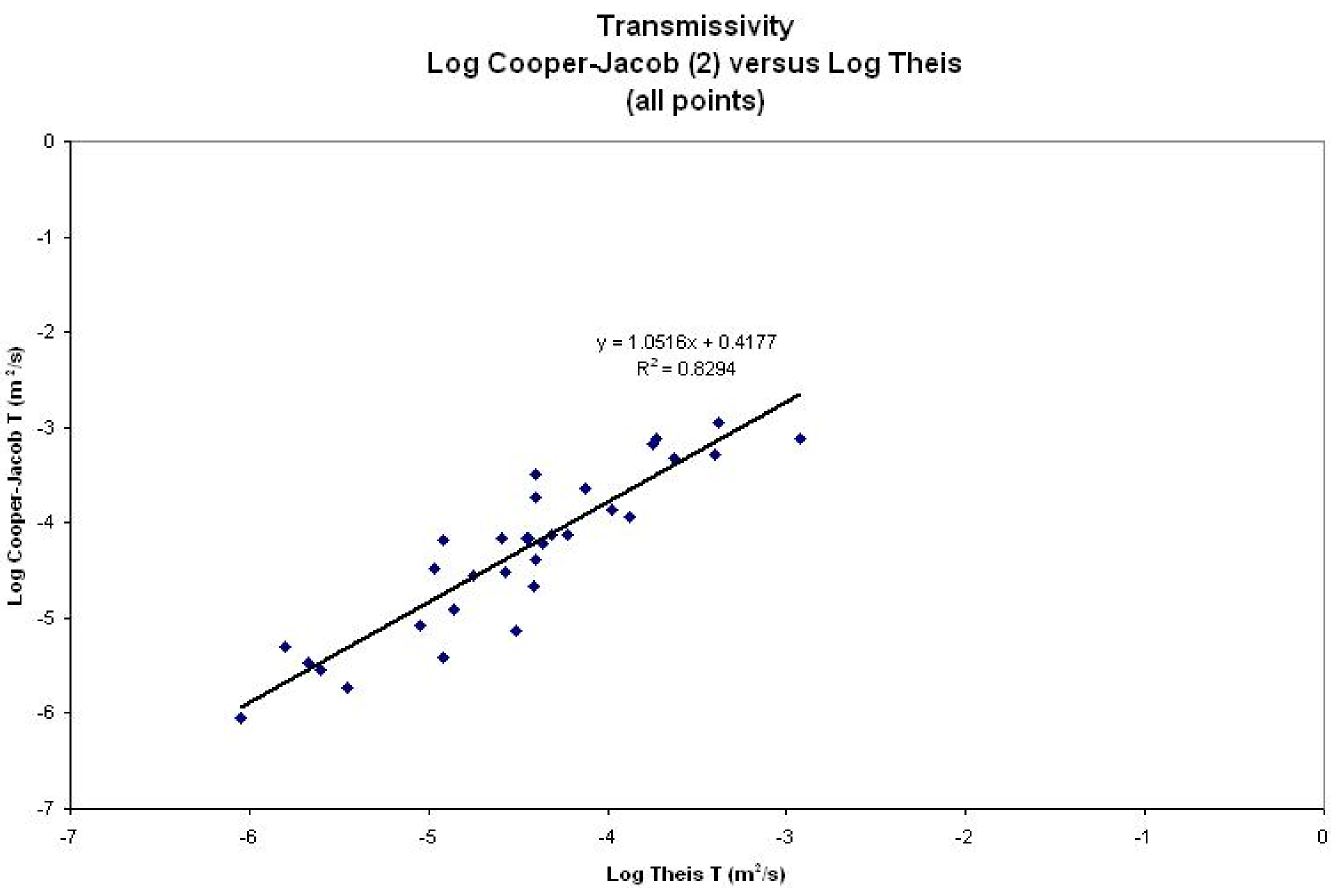


Figure 4.2a: Relation between log transmissiviy values calculated using Cooper-Jacob (2) and Theis

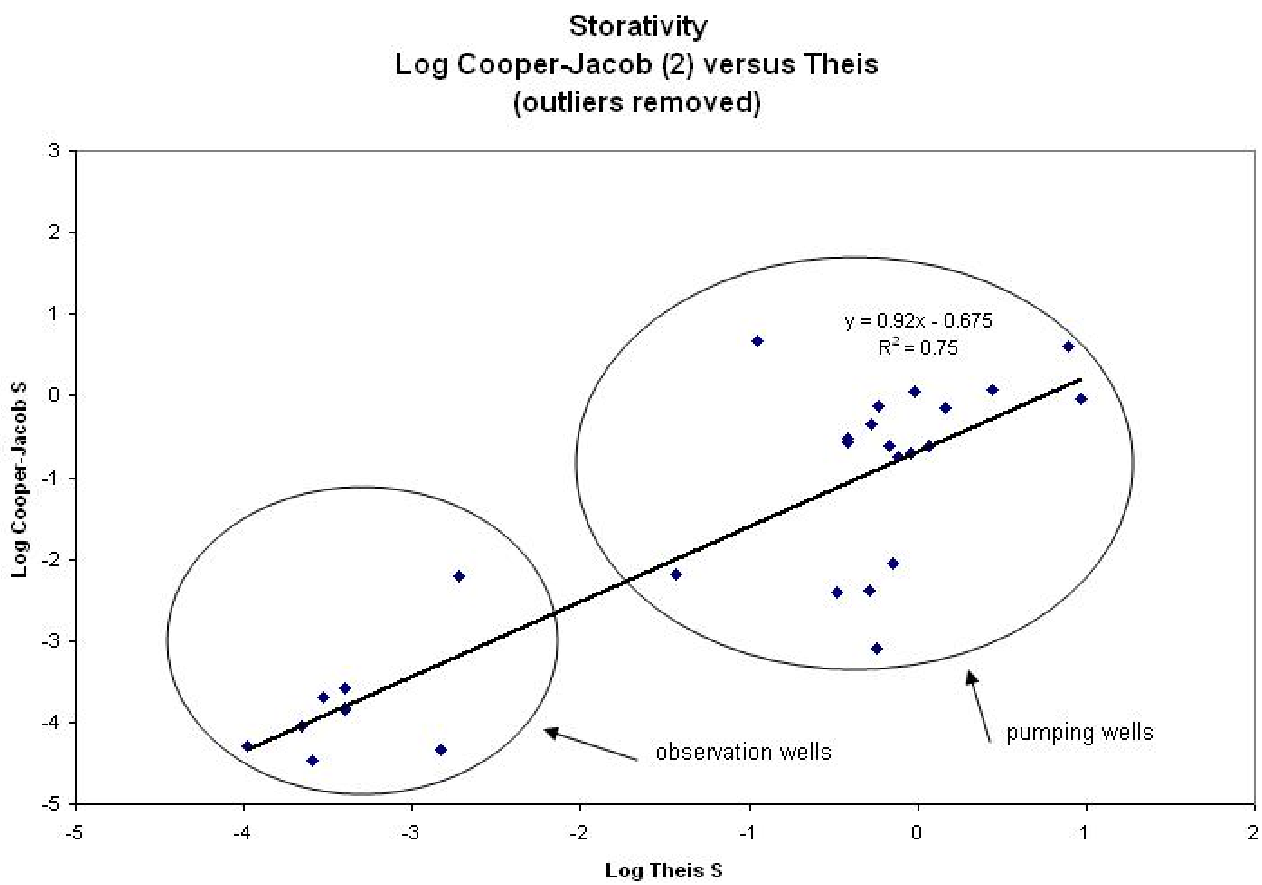


Figure 4.2b: Relation between log storativity values calculated using Cooper-Jacob (2) and Theis

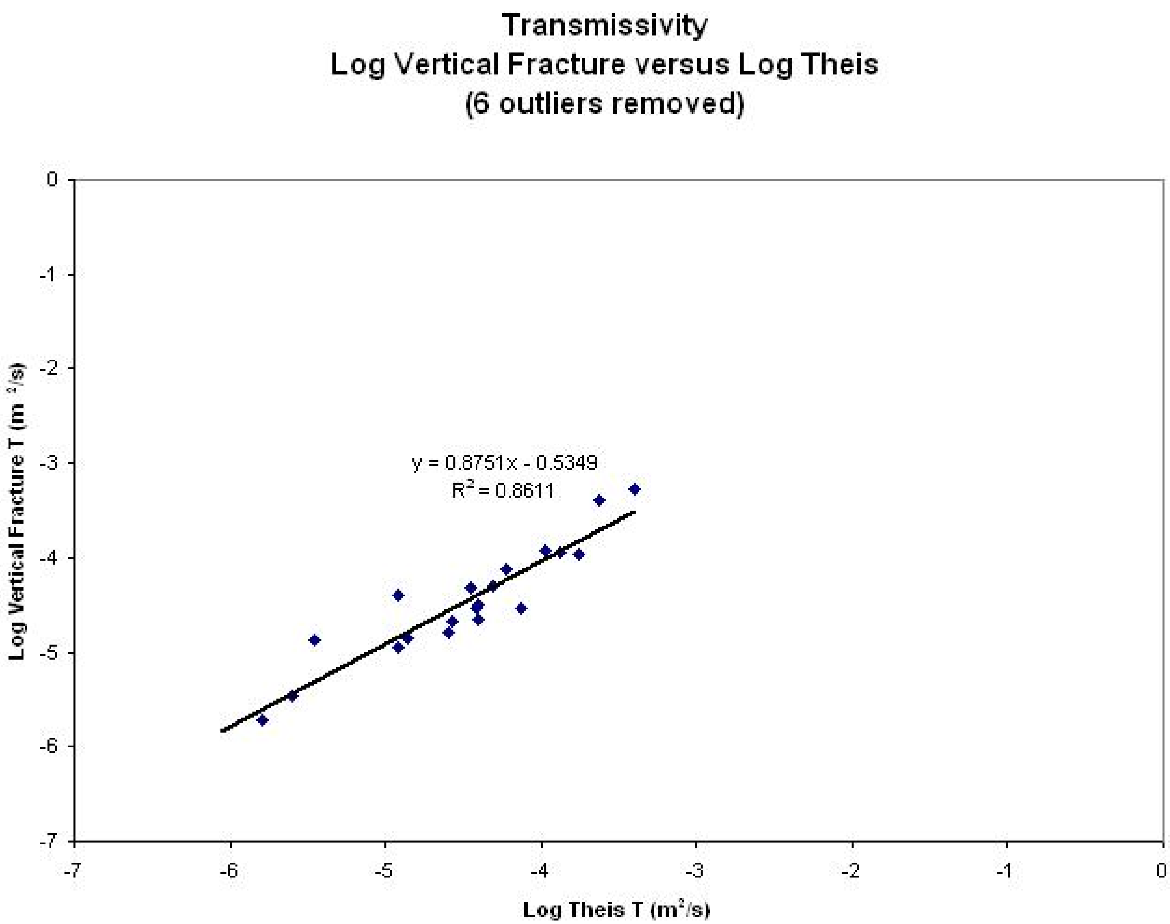


Figure 4.3: Relation between log transmissivity calculated using a vertical fracture flow model and Theis

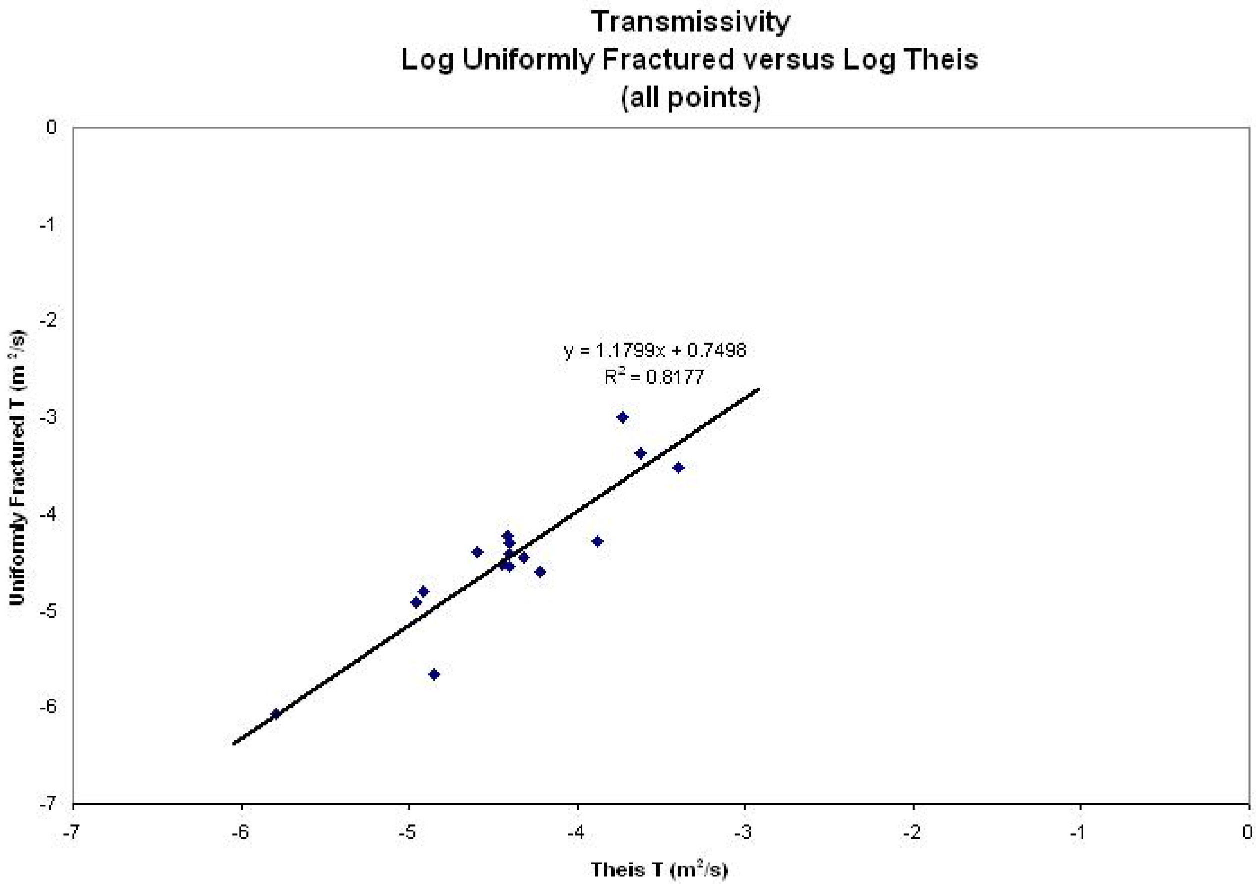


Figure 4.4a: Relation between log transmissivities calculated using the uniformly fractured (double porosity) flow model and Theis for all data that exhibit mid-time flattening

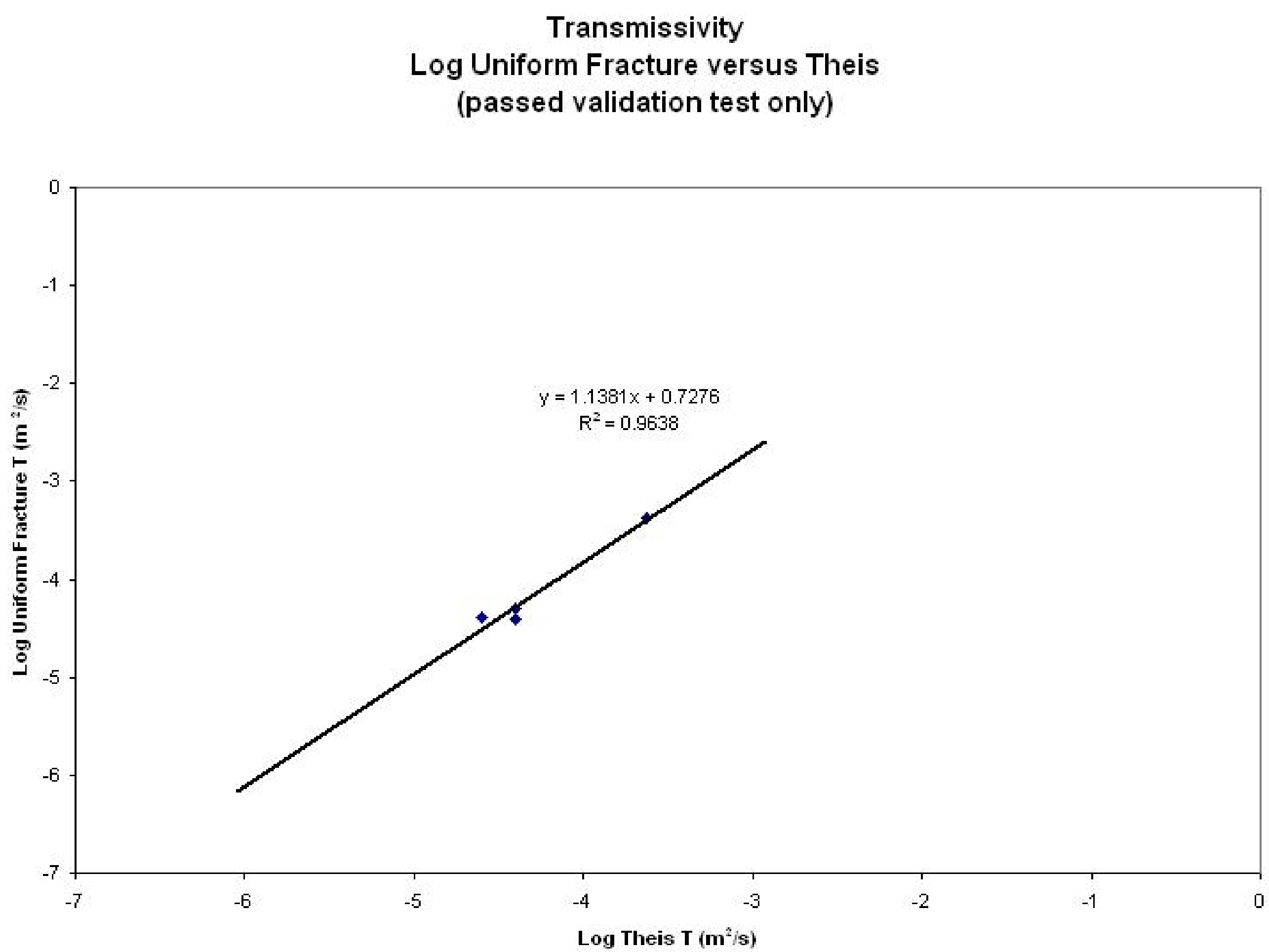


Figure 4.4b: Relation between log transmissivity values calculated using a uniformly fractured (double porosity) flow model and Theis for only those data that passed the validation tests.

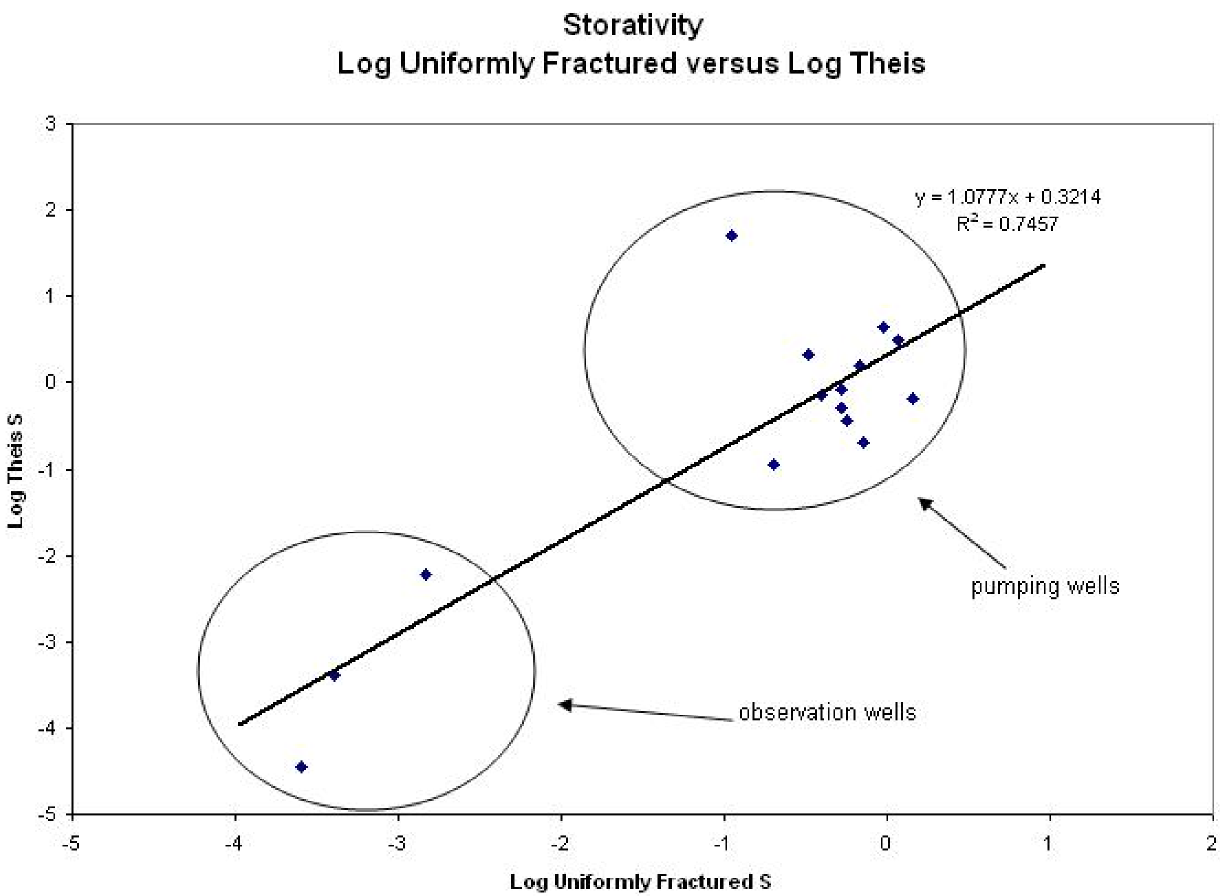


Figure 4.4c: Relation between log storativities calculated using uniformly fractured (double porosity) flow model and Theis.

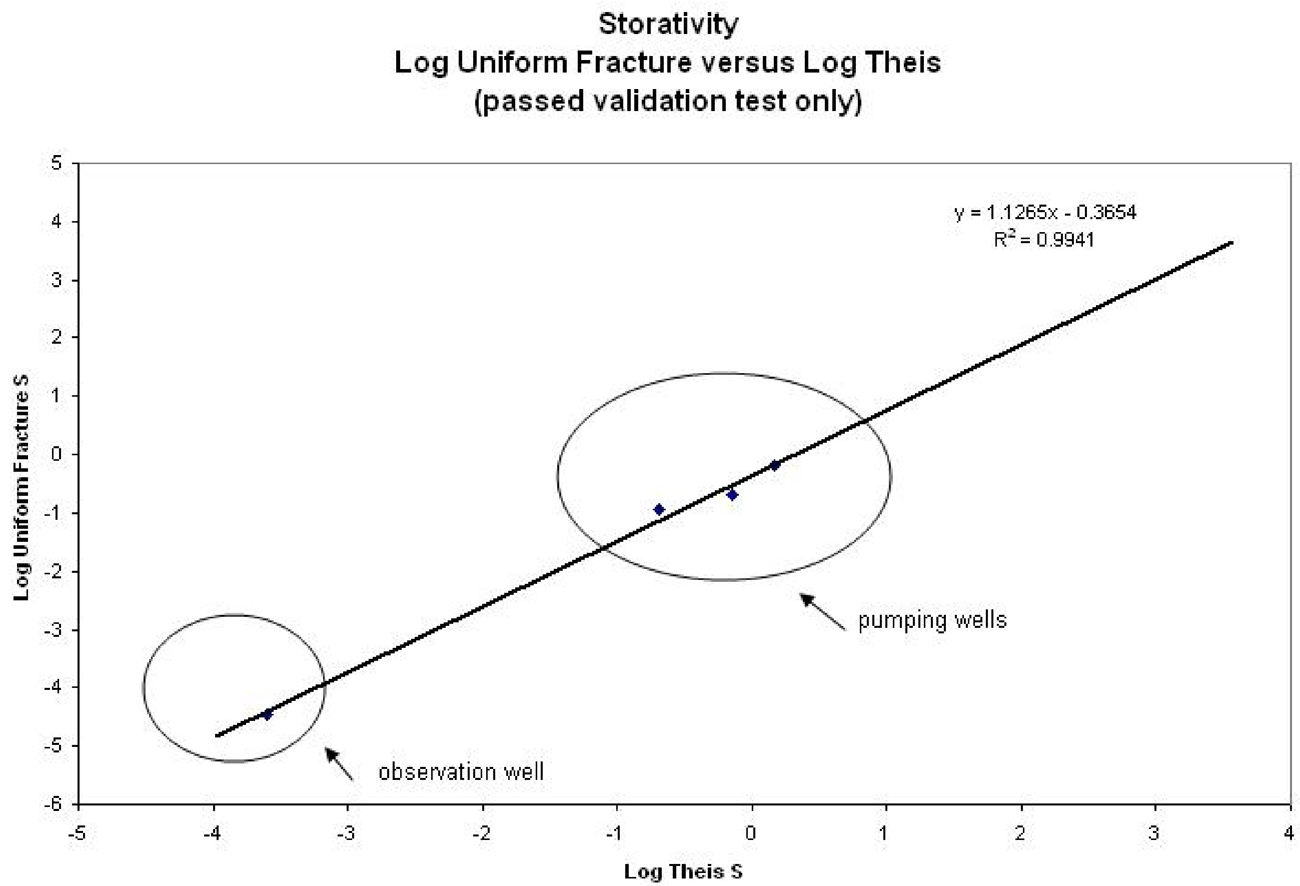


Figure 4.4d: Relation between log storativity values calculated using a uniformly fractured (double porosity) flow model and Theis for only those data that passed the validation tests.

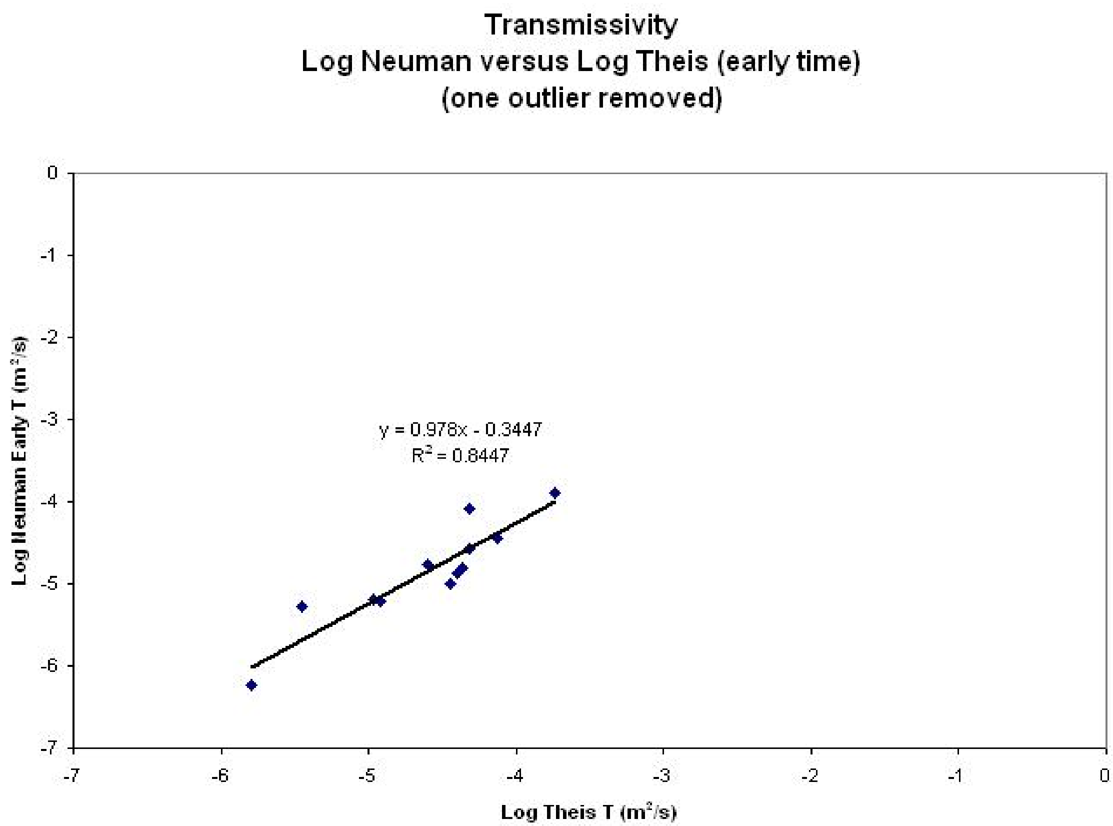


Figure 4.5a: Relation between log transmissivity values calculated using the Neuman on early time data and Theis.

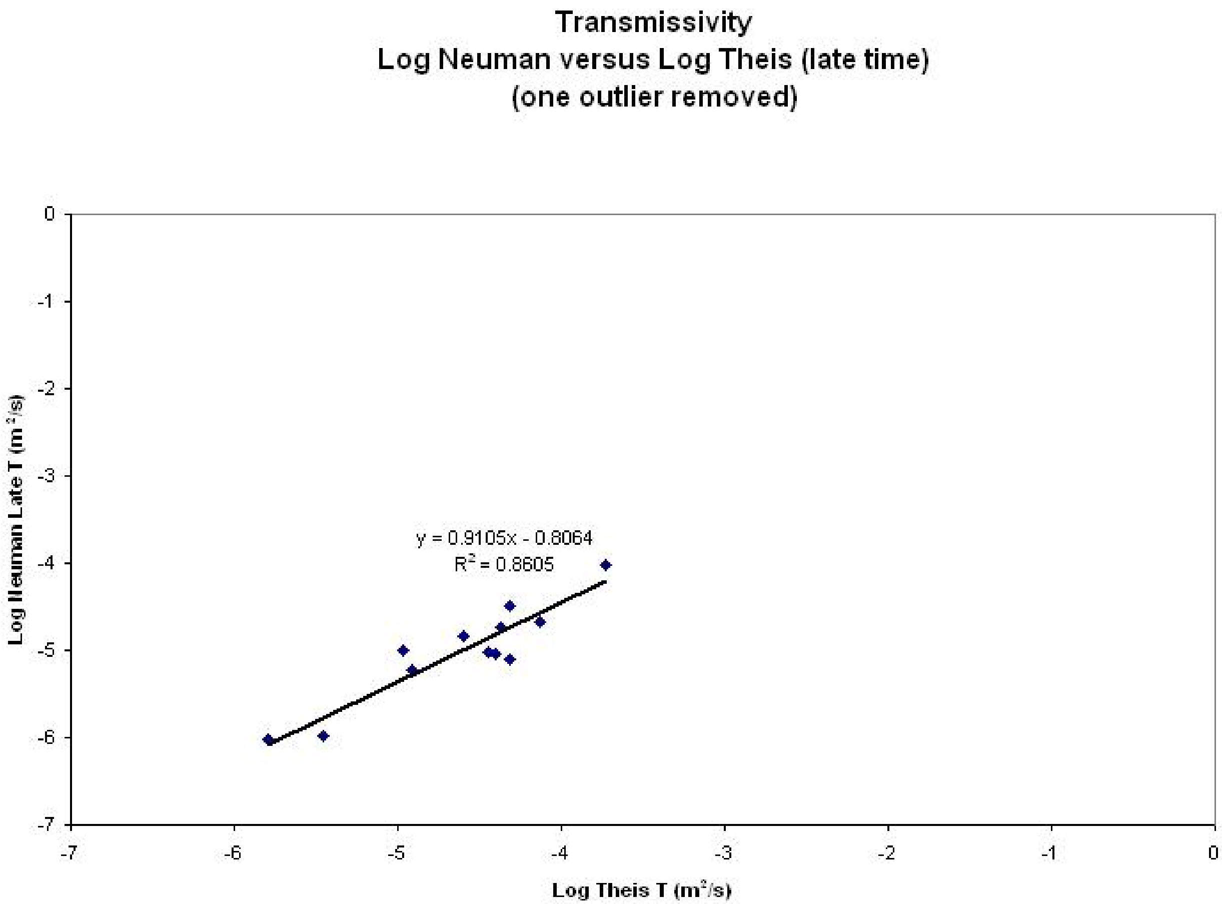


Figure 4.5b: Relation between log transmissivity values calculated using Neuman on late time data and Theis

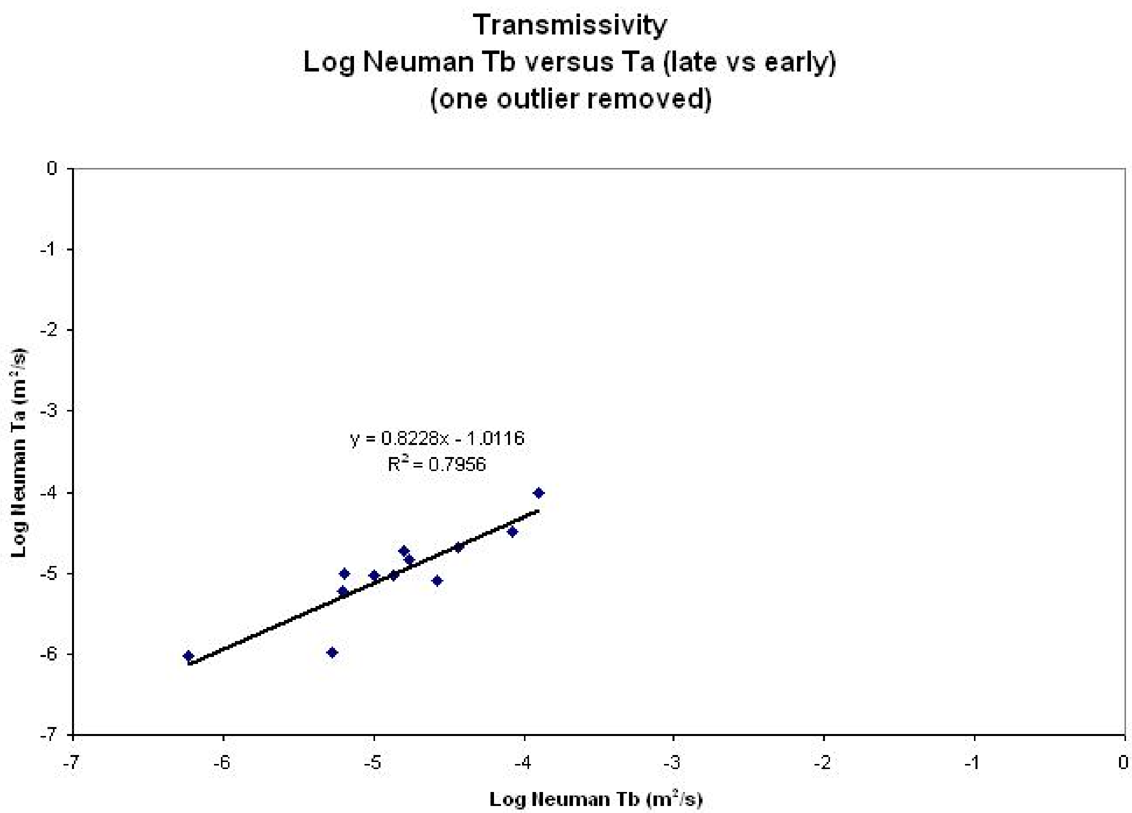


Figure 4.6: Relation between log early and late time transmissivities calculated using Neuman

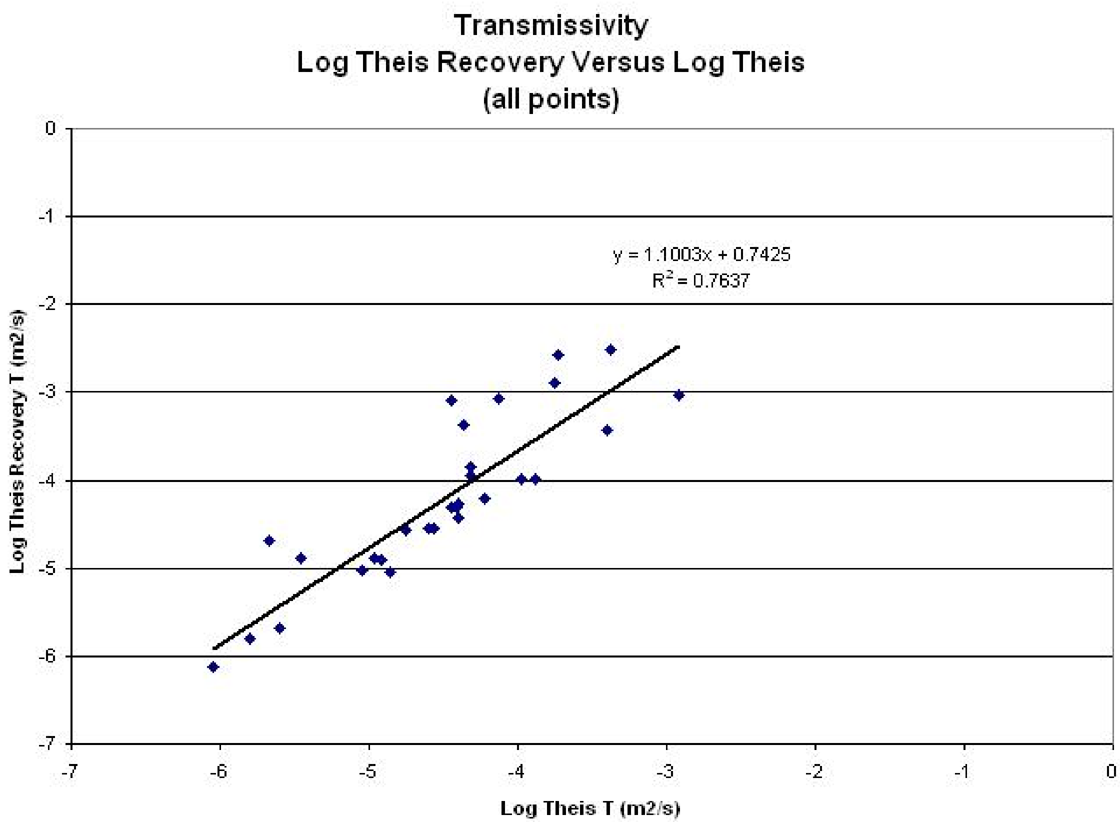


Figure 4.7a: Relation between log transmissivites calculated using Theis Recovery and Theis for all data

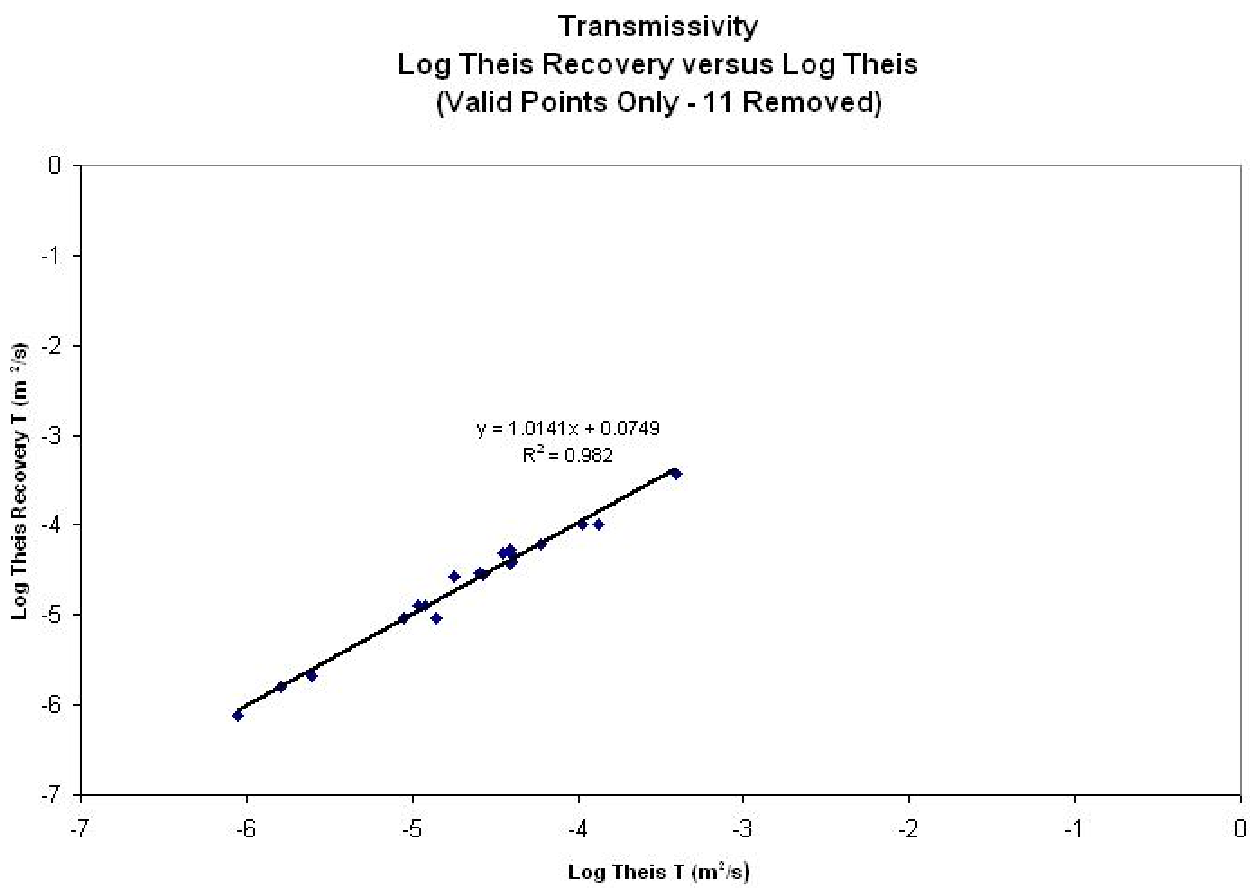


Figure 4.7b: Relation between log transmissivity values calculated using Theis Recovery and Theis

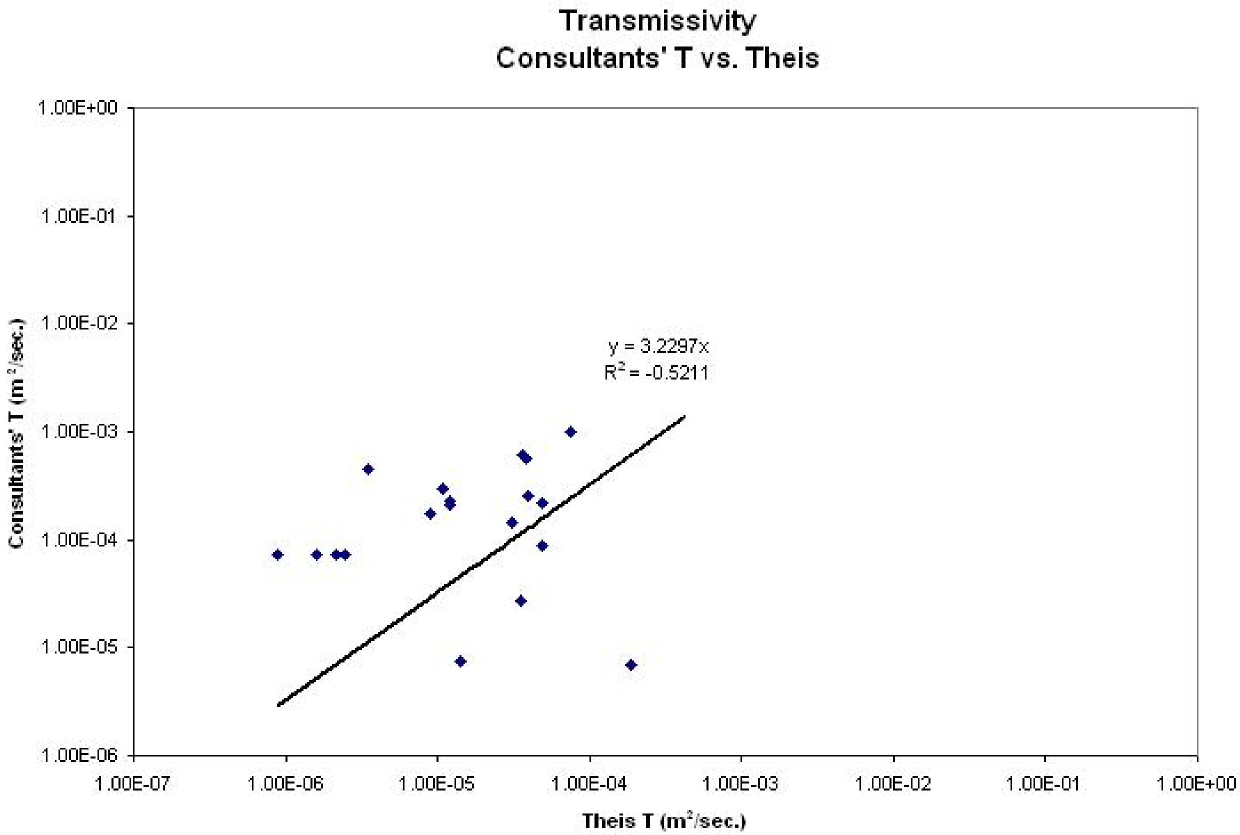


Figure 4.8a: Relation between Consultants' T values and those calculated using Theis

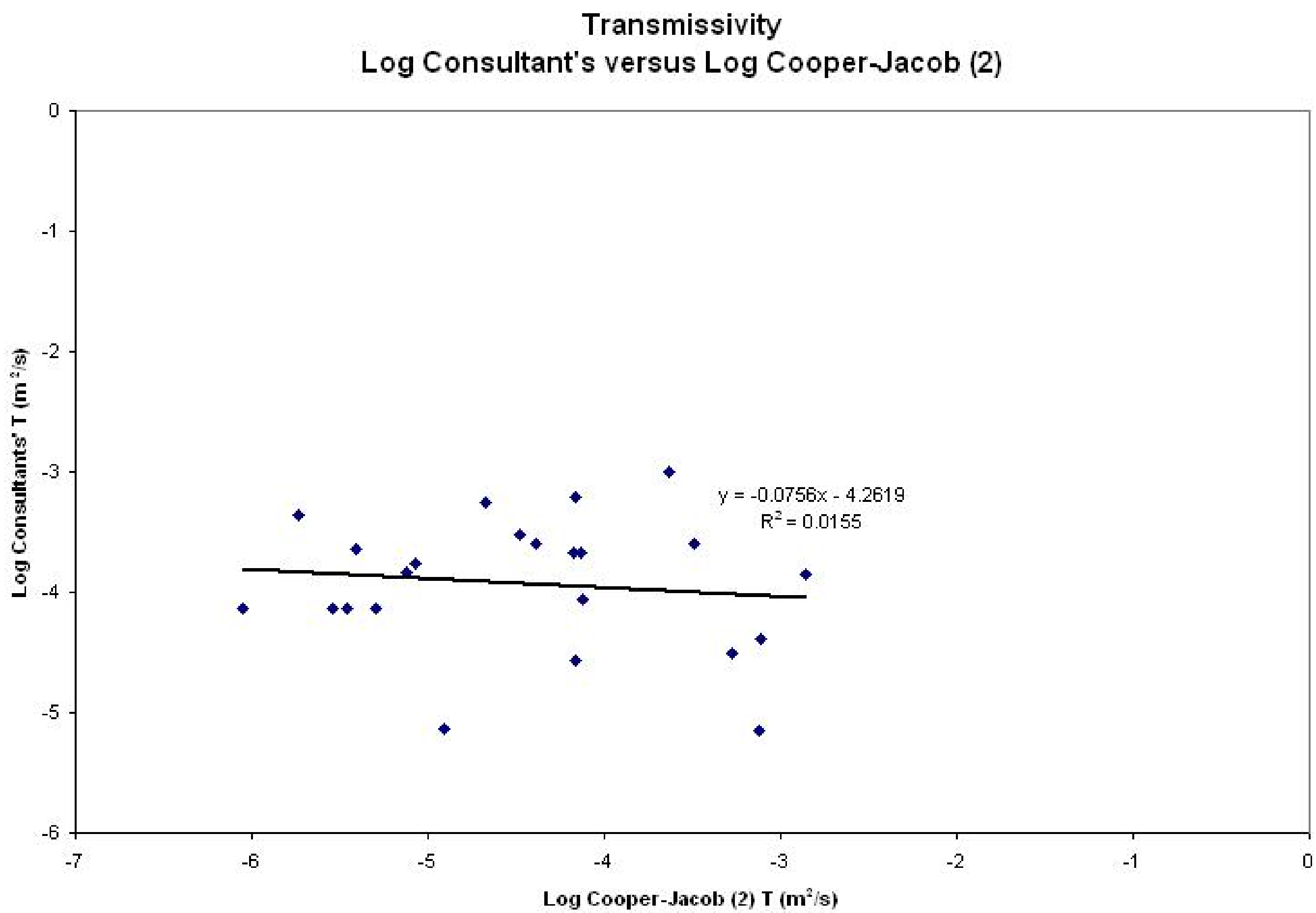


Figure 4.8b : Relation between log Consultants' T values and those calculated using Cooper-Jacob (2)

4.3 Estimation of Transmissivity in Bedrock Aquifers

Radial flow models can provide a representative value of transmissivity for bedrock aquifers if their use is restricted to the radial flow data only. If the aquifer is relatively homogeneous and isotropic with little to no secondary permeability (i.e., the aquifer behaves as a porous medium), then the drawdown versus time curve should resemble Theis, and either the Theis method or the Cooper-Jacob method of analysis can be used. In this situation, it should not be difficult to curve-fit or apply a linear regression for Cooper-Jacob analysis. It is noted, however, that a well defined Theis curve was rarely observed in the data used for this study, which implies that most if not all of the bedrock aquifers examined are likely not of the porous nature.

If the aquifer is uniformly fractured, but with little to no primary permeability, then there should be a predominantly radial response to pumping. All of the water will derive from fractures, but the wells will respond according to their radial distance away from the pumping well. Unfortunately, there were insufficient data to confirm whether or not the radial distance-drawdown relation is valid. What is needed to investigate this further are several observation wells, each at varying distances to the pumping well and in different azimuth directions to the pumping well.

The majority of the aquifers in this study appear not to be of the double porosity type, although we have insufficient data to confirm this statement. Many of the pump test curves exhibit a flattening at mid time, which could either be attributed to double porosity type flow or to unconfined conditions. As the tests for double porosity conditions failed in most wells, this may be an indication that double porosity does not occur, or at least is not of widespread occurrence. A more simplistic explanation for the flattening of the drawdown-time curve at mid-times is that the aquifers are behaving in an unconfined manner. Fractures that are present in the bedrock, begin to de-water (as opposed to acting as confined units that release water by expansion of the water itself and compression of the matrix).

By far the most striking feature of the well test data is that they invariably reflect some form of linear flow (whether related to vertical, sub-vertical or sub-horizontal fractures, that are in turn related to faults, shear zones or bedding planes). If there is a dominant fracture (fault or shear zone) in the vicinity of the pumping well, then the linear flow is likely to dominate at early time. What happens in terms of hydraulic response after the period of linear flow is largely determined by whether the aquifer is confined, unconfined or of the double porosity type. The linear flow response will be superimposed on the other prevalent responses at a particular site. The closer a well is to a major fault or shear zone, the longer the influence of the linear flow will be.

When analyzing the hydraulic test data in linear flow regimes, only the early time data reflect linear flow. At late time, the response becomes somewhat radial in nature, and transmissivity, calculated using one of the radial flow models on these late time data, will yield a representative, but perhaps slightly high, T value for the aquifer. Alternatively, a linear flow model can be used over the entire data curve to produce a value of the aquifer transmissivity. It should be noted that the value of T determined using a vertical fracture flow model is not representative of the fractured portion of the aquifer in close proximity to the fault or shear zone. Rather it is representative of the aquifer matrix away from any influence of linear flow. This can have some significant implications if a water supply is being assessed. The question that needs to be asked is “is it important to know the aquifer’s T value or is it more important to know the likely hydraulic response in the vicinity of the fracture?” If the former is selected, then by implication, it will be possible to predict the long-term response of the aquifer to pumping at distances far from the fracture. If the latter is selected, then one might strive to estimate the hydraulic response for wells that are situated either along the fracture or at close proximity to it. The problem is that there are no analytical methods for determining the T value of the fracture itself, because the existing analytical models assume that that fracture has an infinite T. The analytical method also does not recognize that a zone of fracturing may extend beyond the fault plane. Dr. Allen has been experimenting with the use of vertical dyke models in faulted aquifers.

It is suggested that merely recognizing the presence of a major fracture by virtue of the hydraulic responses that are measured in wells nearby will provide sufficient information to be able to gauge the response in nearby wells, both along and near the fracture. For example, those wells situated along strike of a major vertical fracture can be expected to have a drawdown that is of similar magnitude to that measured in the pumping well. The further away the well is in a perpendicular direction to the fracture, the more Theis-like its response will be. Air photos and geological maps can be useful for identifying the extent of major faults in an area.

5.0 Conclusions and Recommendations

The derivatives and drawdown versus time data support the fact that many of the bedrock aquifers studied exhibit linear flow for a major portion of the test (early to mid time). This means that use of a linear flow model is probably more suitable in many bedrock aquifers. Furthermore, results of the derivative analysis also indicate that many of these bedrock aquifers behave either as double porous aquifers or as unconfined aquifers because the derivative of drawdown versus time undergoes a decline midway through the test. Because the tests to check if the data are suitable for analysis using the double porosity method were failed by several datasets, we have concluded that it is more likely the unconfined conditions exist. Unconfined conditions and double porosity both result in very similar hydraulic responses in an aquifer.

5.1 Guidelines for Hydraulic Testing In Fractured Rocks

The work conducted for this research project has enabled us to recommend the following guidelines to the Ministry for analyzing hydraulic test data in bedrock aquifers.

5.1.1 Duration of Tests

The question of how long to run a constant discharge test for in a bedrock aquifer is a difficult one to answer. Currently, the BC Ministry recommends that like unconfined aquifers, bedrock aquifers be tested for 72 hours (3 days). The reason this time period is stipulated is to insure that all boundaries are identified. The drawdown time curve is then extrapolated to the 100 day mark.

In a previous assessment of these guidelines, Dr. Allen voiced concern for the long pumping periods that were required in coastal, island or arid area aquifers, where water supplies may have diminished significantly by the end of the summer. To undertake a pumping test at those critical times would severely stress the aquifer. Results of this study have shown that the aquifers tested often display linear flow at early time, and may later become unconfined at mid- to late times. Only at times greater than 1000 minutes do the data show radial type flow is present in the aquifer. This would mean that unless a non-standard method of analysis is used (such as vertical fracture) that relies on early time data, then it will likely be necessary to carry the test for the full 72 hours in order to obtain a long enough period for radial flow for analysis. In order to minimize the environmental effects of long-duration tests, it is recommended that specialized methods of analysis (such as for vertical fractures) be considered.

5.1.2 Selecting a Suitable Method of Analysis

The use of simplified radial flow models, without recognition of the fact that really a more appropriate method should be used, can lead to a misinterpretation of the hydrogeology of the site. The original reported estimates of transmissivity calculated by consultants showed no general relation to those values calculated using the consistent methodology utilized in this study (i.e., use of the derivative method followed by the use of a radial flow model for the appropriate time interval or a specialized analytical method). There were no references made in the consulting reports to either the presence of deviations from Theis nor their possible origin. It is recommended that data be scrutinized very closely in an attempt to at least identify the time periods over which Theis is not applicable, and if possible to implement a specialized method of analysis.

5.1.3 Automated Curve Matching Programs

The results of this study indicate that the less subjective one is in selecting the appropriate time range of data for interpretation (using Theis or Cooper-Jacob), the more error is introduced into the estimate of transmissivity and storativity. In ideal aquifers that are confined, homogeneous and isotropic, with no boundaries to affect the flow regime, radial flow as exhibited by the Theis curve is easily identifiable, and most data plot directly on a Theis shaped curve. As complexities are added to the site, the persistence of radial flow diminishes, and linear (one dimensional as along a fault) or spherical (as in an unconfined aquifer) flow can dominate.

One of the biggest problems associated with automated curve-matching algorithms is that they do not permit user intervention, which may be critical in cases where testing has been undertaken under less than ideal conditions. Most of the analytical models that are pre-programmed into these packages are for a single type of flow regime (i.e., confined or unconfined or uniformly fractured). When dealing with variably fractured bedrock it is important to remain open to a variety of flow types and to analyze the data according to the dominant type present. However, it is equally important to recognize the presence of other types of flow (including for example wellbore storage and linear flow).

5.3 Future Work

In our recommendations for future work we would like to highlight two specific areas where additional work should be undertaken. We have also taken the liberty to recommend that a short course be offered to strengthen the findings of this report and to promote the transfer of the technology offered in this report.

5.3.1 Detailed Studies

1) First we recommend that the Groundwater Section of the Ministry screen incoming groundwater site investigation reports for the possibility of conducting a detailed site investigation in fractured bedrock. It would be of great value to have a series of observation wells, with one or more possible pumping wells at a site. Dr. Allen of Simon Fraser University would be very much interested in conducting hydraulic tests at a site where several observation wells are available in close proximity to the pumping well. Her current research is aimed at investigating the hydraulics of fractured rock aquifers, and most studies conducted to date have involved a limited number of widely separated wells.

2) The BC Ministry might also investigate the possibility of a collaborative effort with other sectors of the BC Ministry or Environment Canada that examine groundwater contamination. Data from sites in fractured bedrock aquifers that

are not strictly assessed for water supply, may be available. At many contaminated sites, a network of wells and piezometers situated close proximity is often available, and in many cased, several wells may have been hydraulically tested.

3) We also suggest that the information on the geology of the various sites be assembled and compared to the results of this study. This could be done relatively quickly using well logs, well yields, air photos and local geology. There was insufficient time and it was beyond the scope of this study to examine the geology of each site, but this could be easily be undertaken provided the information is available. This type of study could be undertaken by a high school volunteer (career placement) or work–study student (both positions required no funding internally or externally). Dr. Allen may be able to arrange to have the geology examined next year by a volunteer high school student. Alternatively, a co-op student could complete this assignment for a work term.

4) It was beyond the scope of this work to investigate the possible inconsistencies between estimates of T for pumping wells that are derived from both Theis and Cooper-Jacob (as reported by Butler, 1990). However, this could be done very quickly by separating out the observation well data from the pumping well data, and comparing the Theis and Cooper-Jacob T and S values. It may be useful to compare the results from this study to those results documented by M. Wei. It is recommended that a rigorous statistical approach be implemented.

5.3.2 Unconfined Aquifers

This study focused on bedrock aquifers, and although more questions appear to have been raised as a result of this work, it is important to recognize the importance of the unconsolidated / unconfined aquifers for which well test data are available. It is proposed that a similar study be undertaken for the unconfined aquifers identified in *wudbase.xls* (water utility database summary table) assembled by M. Wei (Groundwater Section). Investigating the use of the derivative method would also be a major component to such a study.

5.3.3 Workshop

In order to transfer the technology or methodology developed as part of this research contract, it is recommended that a short course or workshop be organized. The scope for this workshop could include a summary of the theory in implementation of the various analytical methods utilized in this project, and a review of techniques for analyzing hydraulic test data using Excel spreadsheets.

Dr. Allen would be prepared to offer this workshop at a time that is mutually convenient for both herself and the Groundwater Section personnel, provided that both the advertisement of such a course and a location (and computing facilities) for holding such a workshop are arranged.

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APPENDIX 1.0

METHODS USED IN THE ANALYSIS OF HYDRAULIC TEST DATA.

**Referenced from: Kruseman, G.P. and de Ridder N.A., 1989, Analysis and Evaluation of Pumping Test Data 2nd ed., Published by ILRI, The Netherlands. Please refer to this publication for more information regarding the analysis methods described below.*

A1.1) THEIS METHOD: CURVE-MATCHING (for ideal confined aquifers)

Assumptions

The 5 basic:

1) Aquifer has infinite aerial extent and is horizontal;
2) Aquifer is homogeneous and of uniform thickness;
3) Potentiometric surface is horizontal prior to pumping;
4) The pump test is run at a constant discharge rate;
5) The well fully penetrates the aquifer.

Assumptions strictly for Theis Method:

6) Aquifer is confined and non-leaky;
7) Drawdown continues to change with time resulting in a gradient in the hydraulic head. (non-steady flow);
8) Water is removed from storage is assumed to discharged instantaneously with a resulting decline in head;
9) Diameter of well is negligible; the amount of water stored in the well is insignificant (no wellbore storage).

Equations

$$T = \frac{Q*}{4*\pi*s}*W(u) \qquad \text{(A1.1.1)}$$

$$S = \frac{u*4*T*t}{r^2} \qquad \text{(A1.1.2)}$$

where:

T – aquifer Transmissivity (meters squared per second).
S – aquifer Storativity (dimensionless).
Q - Discharge (cubic meters per second).
π – 3.1415
s – drawdown at matchpoint (meters).
t – time at matchpoint (sec.).
W(u) – from the y-axis at matchpoint of the type curve used.
u – from the x-axis at the matchpoint of the type curve used.
r – distance of observation well from pumping well (effective radius if pumping well) (meters).

Procedure A1.1.1

1) Prepare a type curve of the Theis well function on log-log paper by plotting values of W(u) against the arguments 1/u using Annex 1;
2) Plot the observed data curve s versus t on another sheet of log-log paper of the same scale;
3) Superimpose the data curve on the type curve and, keeping the coordinate axes parallel, adjust until a position in found where most of the plotted points of the data curves fall on the type curve;
4) Select an arbitrary match point A on the overlapping portion of the two sheets and read its coordinates W(u), 1/u, s, t;
5) Substitute the values of W(u), s, and Q into Equation A1.1.1 and solve for T;
6) Calculate S by substituting the values of T, t, r, and u into Equation A1.1.2.

A1.2) JACOB METHOD 1: TIME-DRAWDOWN (for ideal confined aquifers)

Assumptions

The 5 basic (see Theis Curve-Matching Method above), plus:
6) Flow to well is non-steady;
7) Values of u are small (u<< 0.01) (i.e. r is small; t is large).

Equations

$$T = \frac{2.3 * Q}{4 * \pi * \Delta s} \qquad \text{(A1.2.1)}$$

$$S = \frac{2.25 * T * t_0}{r^2} \qquad \text{(A1.2.2)}$$

where:

T – aquifer Transmissivity (meters squared per second).
S – aquifer Storativity (dimensionless)
Q – pumping discharge rate (cubic meters per second).
Δs – slope of the drawdown curve in semi-log scale for 1 log cycle.
t_0 – x-intercept of the drawdown curve in semi-log scale (sec.).
r – radius of well (effective radius if pumping well) (meters).

Procedure A1.2.1

1) For one of the piezometers, plot the values of s vs. the corresponding time t on semi-log paper (t on log scale), and draw a straight line through the plotted points;
2) Extend the straight line until it intercepts the time axis where s = 0, and read the value of t_0;
3) Determine the slope of the straight line, i.e. the drawdown difference Δs per log cycle of time;
4) Substitute the values of Q and Δs into Equation A1.2.1 and solve for T. Using the known values of T and t_0, calculate S from Equation A1.2.2.

A1.3) THEIS RECOVERY METHOD **(for ideal confined aquifers)**

Assumptions

The 5 basic (see Theis Curve Matching above) plus:

5) S is the same before and after the pump is turned off; in fractured or compressible matrix aquifers, S may not remain the same;
7) Non-steady state;
8) u << 0.01;
9) Q is assumed to be same for both pumping and recovery.

Equation

(see Jacob Time-Drawdown Method above)

Procedure A1.3.1

1) For each value of s', calculate the value of t/t';
2) For one of the piezometers, plot s' versus t/t' on semi-log paper (t/t' on logarithmic scale);
3) Fit a straight line through the plotted points;
4) Determine the slope of the straight line, i.e. the residual drawdown difference Δs' per log cycle of t/t';
5) Substitute the known values of Q and Δs' into Equation A1.2.1 and calculate T.

4.1.1.1.1 Remarks

- S cannot be determined by this method.
- Wellbore storage effects will not be observed.
- The well will recover at a rate that reflects a constant pumping rate.

A1.4) GRINGARTEN ET AL.'S METHOD: CURVE-MATCHING (for Pumping wells in an aquifer with a single vertical fracture).

Assumptions

1) The aquifer is confined and of infinite aerial extent;
2) The thickness of the aquifer is uniform over the area that is influenced by the test;
3) The well fully penetrates a fracture;
4) The well is pumped at a constant rate;
5) Prior to pumping, the piezometric surface is horizontal over the area that is influenced by the test;
6) The flow towards the well is in an unsteady state.
7) The aquifer is confined, homogeneous, and isotropic, and is fully penetrated by a single vertical fracture;
8) The fracture is plane (i.e. storage in the fracture can be neglected),and its horizontal extent is finite;
9) The well is located on the axis of the fracture;
10) With a decline in head, water is instantaneously removed from storage in the aquifer;
11) Water from the aquifer enters the fracture at the same rate per unit area (i.e. a uniform flux exist along the fracture, or the fracture conductivity is high although not infinite);
12) The diameter of the well is very small (i.e. well-bore storage can be neglected);

13) The well losses are negligible.

Equations

$$T = \frac{Q}{4 * \pi * s} * F(U_{vf})$$
(A1.4.1)

$$Sx_f^{\;2} = \frac{T * t}{U_{vf}}$$
(A1.4.2)

$$Sx_f^{\;2} = 16.59 * T * t$$ (A1.4.3)

where:

T – aquifer Transmissivity (meters squared per second).
S – aquifer Storativity (dimensionless).
Q – pumping discharge rate (cubic meters per second).
t – time at matchpoint (sec.).
s – drawdown at matchpoint (meters).
$F(U_{vf})$ - from the y-axis at matchpoint of the type curve used.
U_{vf} – from the x-axis at matchpoint of the type curve used.
Sx_f^2– product of Storativity and fracture half-length (x) squared.

Procedure A1.4.1

1) Using Annex 4, prepare a type curve on a log-log paper by plotting $F(U_{vf})$ versus U_{vf};
2) On another sheet of log-log paper of the same scale, prepare the data curve by plotting s (drawdown) versus t (time);
3) Match the data curve with the type curve and select a matchpoint A on the superimposed sheets; note for A the values of $F(U_{vf})$, U_{vf}, s (drawdown), and t (time);
4) Substitute the values of $F(U_{vf})$ and s and the known value of Q (discharge rate) into Equation A1.4.1 and calculate T;
5) Substitute the values of U_{vf} and t and the calculated value of T into Equation A1.4.2 and solve for the product Sx_f^2.

4.1.1.1.2 Remarks

- For large values of pumping time (i.e. $t > = 2Sx_f^2 / T$), the data can be analyzed with Procedure A1.4.2, which is similar to the procedure used in the Jacob Time Drawdown Method.

Procedure A1.4.2

1) If the semi-log plot of s (drawdown) versus t (time) yields a straight line. Determine the slope of this line, Δs;
2) Calculate the aquifer transmissivity T from Equation A1.2.1;
3) As T is known and the value of t_0 can be read from the graph, find Sx_f^2 from Equation A1.4.3.

4.1.1.1.3

4.1.1.1.4

4.1.1.1.5 Remarks

- No separate values of x_f and S can be found with Gringarten et al.'s method. To obtain such values, one must have drawdown data from at least two observation wells;
- Procedures A1.4.1 and A1.4.2 can only be applied to data from perfect wells (i.e. wells that have no well loses). Such wells seldom exist, but Procedure A1.4.2, being applied to late-time drawdown data, allows the aquifer transmissivity to be found;
- If the early-time drawdown data are influenced by well-bore storage, the initial straight line (linear segment on log-log graph) in the data plot may not have a slope of 0.5, but instead a slope of 1, which indicates a large storage volume connected with the well. This corresponds to a fracture of large dimensions rather than the assumed fracture. Gringarten et al.'s method will not be applicable and the data should be analyzed by the Ramey-Gringarten's Curve Matching Method.

A1.5) GRINGARTEN-WHITHERSPOON'S METHOD: CURVE-MATCHING (for Observation wells in an aquifer with a single vertical fracture).

Assumptions

*same as Gringarten et al.'s Method listed above

Equations

$$T = \frac{Q}{4 * \pi * s} * F(U_{vf,} r) \qquad \text{(A1.5.1)}$$

$$S = \frac{T * t}{U_{vf} * x_f^{\;2}} \qquad \text{(A1.5.2)}$$

$$x_f = \frac{r}{r'} \qquad \text{(A1.5.3)}$$

where:

T – aquifer Transmissivity (meters squared per second).
S – aquifer Storativity (dimensionless).
Q – pumping discharge rate (cubic meters per second).
t – time at matchpoint (sec.).
s – drawdown at matchpoint (meters).

$F(U_{vf}, r')$ – from the y-axis at matchpoint of the type curve.
U_{vf} / r' – from the x-axis at matchpoint of the type curve used.
x_f – fracture half-length (meters).
r – distance of the observation well from the pumping well (meters).

Procedure A1.5.1

1) If the location of the observation well is known with respect to the location of the fracture, choose the appropriate set of type curves (for $r' = x / x_f$; $r' = y / x_f$; $r' = x * \sqrt{\ } 2 / x_f$; $r' = y * \sqrt{\ } 2 / x_f$);
2) Using Annex 5, prepare the selected type curve on log-log paper by plotting $F(U_{vf}, r')$ versus U_{vf} / r';
3) On another sheet of log-log paper of the same scale, plot s versus t for the observation well;
4) Match the data curve with one of the type curves and note the value of r' for that curve;
5) Knowing r and r', calculate the fracture half-length, x_f from Equation A1.5.3;
6) Select a matchpoint A on the superimposed sheets and note for A the values of $F(U_{vf}, r')$, U_{vf}, s (drawdown), t (time);
7) Substitute the values of $F(U_{vf}, r')$ and s (drawdown) and the known value of Q (discharge rate) into Equation A1.5.1 and calculate T;
8) Knowing U_{vf} / r' and r', calculate the value of U_{vf};
9) Substitute the values of U_{vf}, t (time), x_f and T into Equation A1.5.2 and solve for S.

4.1.1.1.6

4.1.1.1.7 Remarks

- If the geometrical relationship between the observation wells and the fracture are not known, a trial-and-error matching procedure will have to be applied to all three sets of type curves. Data from at least two observation wells are required for this purpose. The trial-and-error procedure should be continued until matching positions are found that yield approximations of the fracture location and its dimensions, and estimates of the aquifer parameters consistent with all available observation well data.
- For r' >5, the observation well data can be analyzed with the Theis method from which aquifer parameters T and S can be obtained.

A1.6) WARREN-ROOT'S: STRAIGHT-LINE METHOD (for Pumping wells in fractured bedrock aquifers exhibiting double porosity).

Assumptions

1) The aquifer is confined and of infinite aerial extent;
2) The thickness of the aquifer is uniform over the area that will be influenced by the test;
3) The well fully penetrates a fracture;
4) The well is pumped at a constant rate;
5) Prior to pumping, the piezometric surface is horizontal over the area that will be influenced by the test;
6) The flow towards the well is in an unsteady state.

Equations

$$T_f = \frac{2.3 * Q}{4 * \pi * slope} \qquad \text{(A1.6.1)}$$

$$S_f = \frac{2.25 * T_f * t_1}{r_w^2} \qquad \text{(for early-time straight-line)} \qquad \text{(A1.6.2)}$$

$$S_f + \beta * S_m = \frac{2.25 * T_f * t_2}{r_w^2} \qquad \text{(for late time straight line)} \qquad \text{(A1.6.3)}$$

$$w = 10^{\frac{-2 * 1/2 * S_v}{slope}} \qquad \text{(A1.6.4)}$$

$$S_f = w * S_f + \beta * S_m \qquad \text{(A1.6.5)}$$

$$\gamma = \alpha * r^2 * \frac{K_m}{K_f} \qquad \text{(A1.6.6)}$$

where:

T_f – Transmissivity of fracture(s) (meters squared per second).
S_f – Storativity of fracture(s) (dimensionless)
S_m – Storativity of matrix (dimensionless)
t_1 – intercept of the early time line (x-axis intercept) (sec.).
t_2 – intercept of the late-time line (x-axis intercept) (sec.).
r – distance of the observation well from the pumping well (effective radius if pumping well) (meters).
w – undefined factor
S_v – drawdown at center of transition period (meters).
slope – slope of the late-time straight-line.
β = 1/3 for uniform horizontally fractured aquifer; 1 for uniform orthogonally fractured aquifer.
γ - Interprosity flow coefficient (dimensionless)
α– shape factor, parameter characteristics of the geometry of the fractures and aquifer matrix of a fractured aquifer of the double porosity type (dimensionless: reciprocal area).
K_m – hydraulic conductivity of matrix.
K_f - hydraulic conductivity of fracture

Procedure A1.6.1

1) On a sheet of semi-log paper, plot s vs. t (t on logarithmic scale);
2) Draw straight line through the early-time points and another through the late-time points; the two lines should plot as parallel lines;
3) Determine the slope of the lines (i.e. the drawdown difference per log cycle of time);
4) Substitute the values of slope and Q into Equation A1.6.1 and calculate T_f;

5) Extend the early-time straight line until it intersects the time axis where drawdown = 0, and determine t_1;
6) Substitute the values of T_f, t_2, and r into Equation A1.6.2, and calculate S_f;
7) Extend the late-time straight line until it intercepts the time axis where drawdown = 0, and determine t_2.
8) Substitute the values of T_f, t_2, r and β into Equation A1.6.3, and calculate $S_f + S_m$;
9) Calculate the separate values of S_f and S_m.

4.1.1.1.8 Remarks

- The two parallel lines can only be obtained at low γ values (i.e. $\gamma < 10^{-2}$).
- At higher γ values, only the late-time straight line, representing the fracture and block flow, will appear, provided of course that pumping time is long enough. The analysis then yields values of T_f and $S_f + S_m$.
- To obtain separate values of S_f and S_m when only one straight line is present, Procedure A1.6.2 can be applied.

Procedure A1.6.2

1) Follow Procedure A1.6.1 to obtain values of T_f and S_f from the 1st straight line, or if not present, values of T_f and $S_f + S_m$ from the second straight line;
2) Determine the center of the transition period of constant drawdown and determine ½ S_v;
3) Calculate the value of *w* using Equation A1.6.4;
4) Substituting the values of *w* and β into Equation A1.6.5, determine the value of S_m if S_f is known, or vice versa.

4.1.1.1.9 Remark

- To estimate the center of the transition period with constant drawdown, the preceding and following curved-line segment should be present in the time-drawdown plot.

- A validation method is available to test if the assumptions of this method are correct for a given well data. This validation method is described in Validation Test A1.6.

Validation Test A1.6 (Warren-Root's Validation Test)

This test is done to see if the Warren-Root's Method is valid for the well data it was applied to.

Equations

$$t > \frac{100 * (S_f + S_m) * r_w^{\ 2}}{T_f} \qquad \text{A1.6.7}$$

$$t > \frac{(1-w)*(S_f + S_m)*r^2}{1.3*\gamma*T_f}$$

A1.6.8

$$\gamma = \frac{1.26}{10^{\frac{4*\pi*T_f*S}{2.3*Q}}}$$

A1.6.9

$$t > \frac{60*r^2}{2*T_f}$$

A1.6.10

Procedure A1.6.3

1) Test the condition that u* > 100 (underlies Warren-Root's Method). Substitute the appropriate values into Equation A1.6.7. Time (t) when late-time line is extrapolated on the left side of the equation should be greater than the product of the terms on the right side of the equation, or else the Warren-Root's Method is not valid for the well data.
2) Test that the late-time line is valid for use in the calculation of the aquifer properties. Substitute the appropriate values into Equation A1.6.8. Time (t) when late-time line is extrapolated on the left side of the equation should be greater than the product of the terms on the right side of the equation, or else, the late-time line is not valid for use in the calculation of the aquifer properties.
3) Test to see if the assumption that the early-time line is obscured by well-bore. Substitute the appropriate values into Equation A1.6.10. Time (t) is when well bore effects become negligible. Visually check the semi-log graph of the well data (drawdown vs. log time) to see if the early-time line has indeed been obscured by well-bore.

A1.7) KAZEMI ET AL.'S: STRAIGHT-LINE METHOD (for Observation wells in fractured bedrock aquifers exhibiting double porosity)

*Please see Warren-Root's Straight Line Method (same procedures).

4.1.1.1.9.1 A1.8) NEUMANN'S METHOD: CURVE-MATCHING

Assumptions

1) The aquifer is unconfined;
2) The aquifer has a seemingly infinite aerial extent;
3) The aquifer is homogeneous and of uniform thickness over the area influenced by the test;
4) Prior to pumping, the water table is horizontal over the area that will be influenced by the test;
5) The aquifer is pumped at a constant discharge rate;
6) The well fully penetrated the aquifer;
7) The aquifer is isotropic or anisotropic;
8) The flow to the well is in an unsteady state;
9) The influence of the unsaturated zone upon the drawdown in the aquifer is negligible;
10) $S_y/S_a > 10$;

11) An observation well screened over its entire length penetrates the full thickness of the aquifer;
12) The diameter of the pumped and observation well are small, i.e. storage in them can be neglected.

Equations

$$T = \frac{Q}{4 * \pi * s} * W(U_a, U_b, \beta) \quad \text{(A1.8.1)}$$

$$S_a = \frac{U_a * 4 * T * t}{r^2} \quad \text{(A1.8.2)}$$

$$S_y = \frac{U_b * 4 * T * t}{r^2} \quad \text{(A1.8.3)}$$

where

U_a and U_b – from match point.
S_a – water released from storage.
S_y – water released from de-watering

Procedure A1.8.1

1) Construct the family of Neuman type curves by plotting $W(U_a, U_b, \beta)$ vs. $1/U_a$ and $1/U_b$ for a practical range of values of β on a log-log paper, using Annex 8;
2) Prepare the observed data curve on another sheet of log-log paper of the same scale by plotting the values of the drawdown s against corresponding time t for a single well;
3) Match the early-time data curve with one of the type A curves. Note the β value of the selected type A curve;
4) Select an arbitrary point A on the overlapping portion of the two sheets and note the values of s, t, $1/U_a$ and W (U_a, β) for this point;
5) Substitute these values into Equation A1.8.1 and A1.8.2 and, knowing Q and r, calculate T and S_a;
6) Move the observed data curve until as many as possible of the late-time data fall on the type B curve with the same β as the as the selected type A curve;
7) Select an arbitrary point B on the superimposed sheets and note the values of s, t, $1/U_b$ and $W(U_b, \beta)$ for this point;
8) Substitute these values into Equation A1.8.1 and A1.8.3 and, knowing Q and r, calculate T and S_y. The two calculations should give the approximately the same value for T.

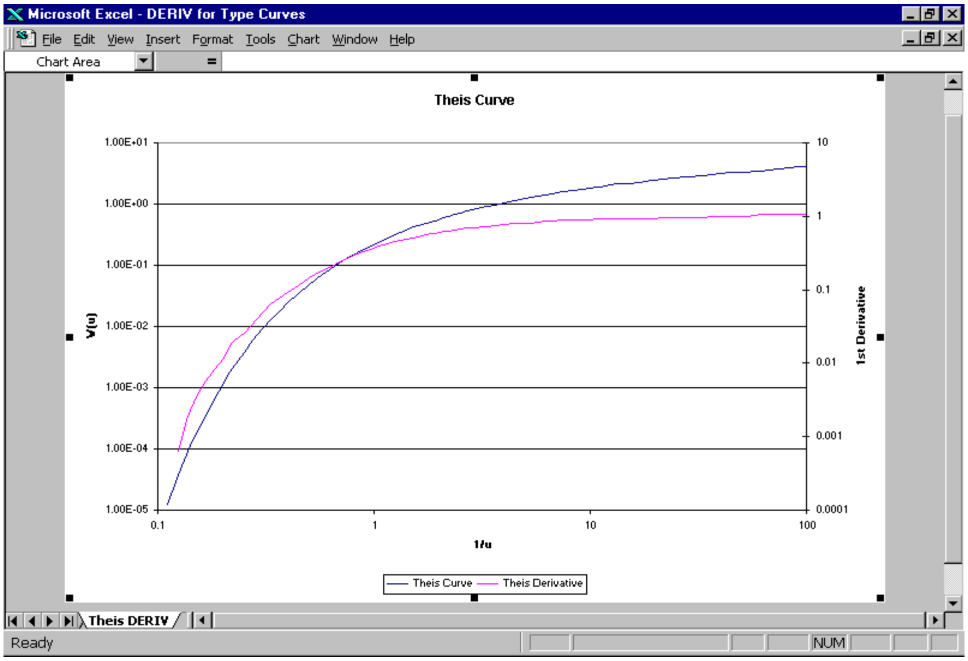
4.1.1.1.10

4.1.1.1.11 Remarks

- the value of S_y/S_a should be checked and it should be greater than 10.

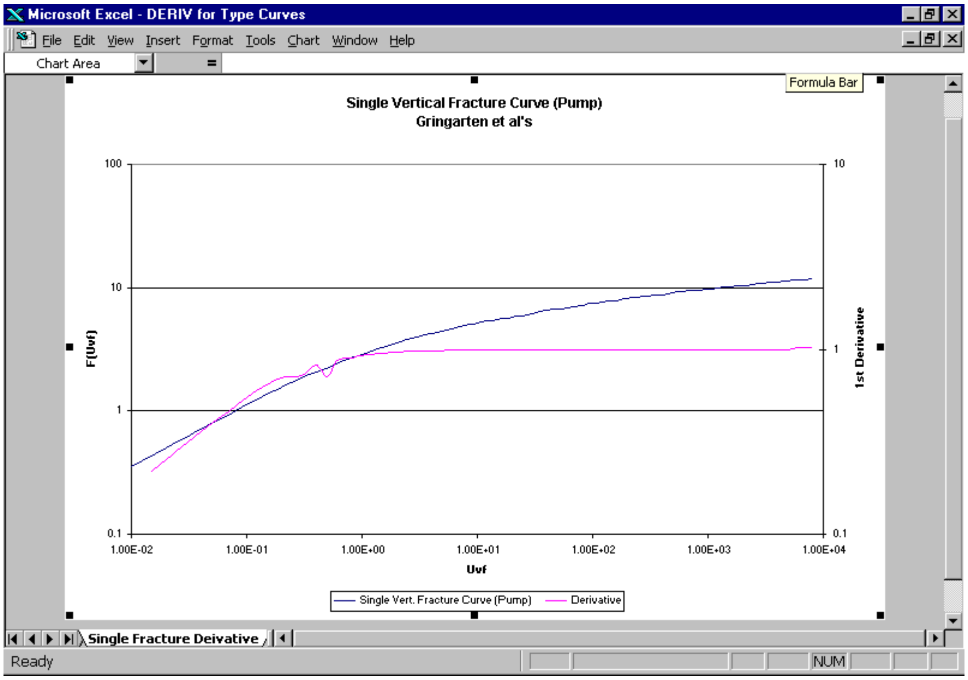
APPENDIX 2.0
HYDRAULIC TYPE CURVES ANALYZED USING DERIV.

2.1 The Theis Curve and the 1st Derivative

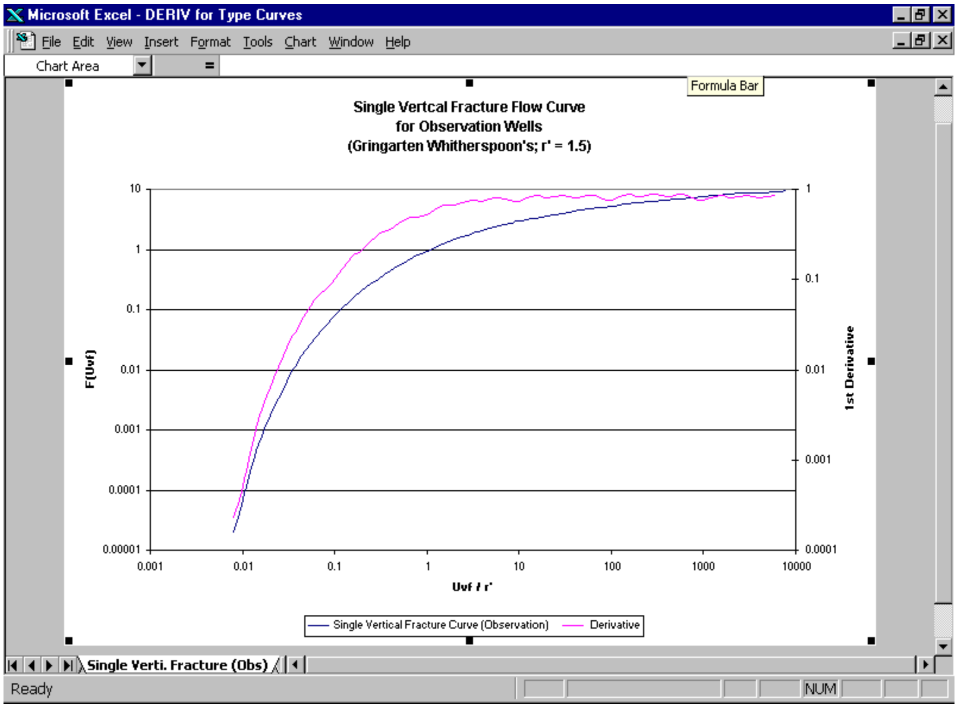


2.2 The Single Vertical Fracture Curve and the 1st Derivative

2.2.1 Pumping Well Curve

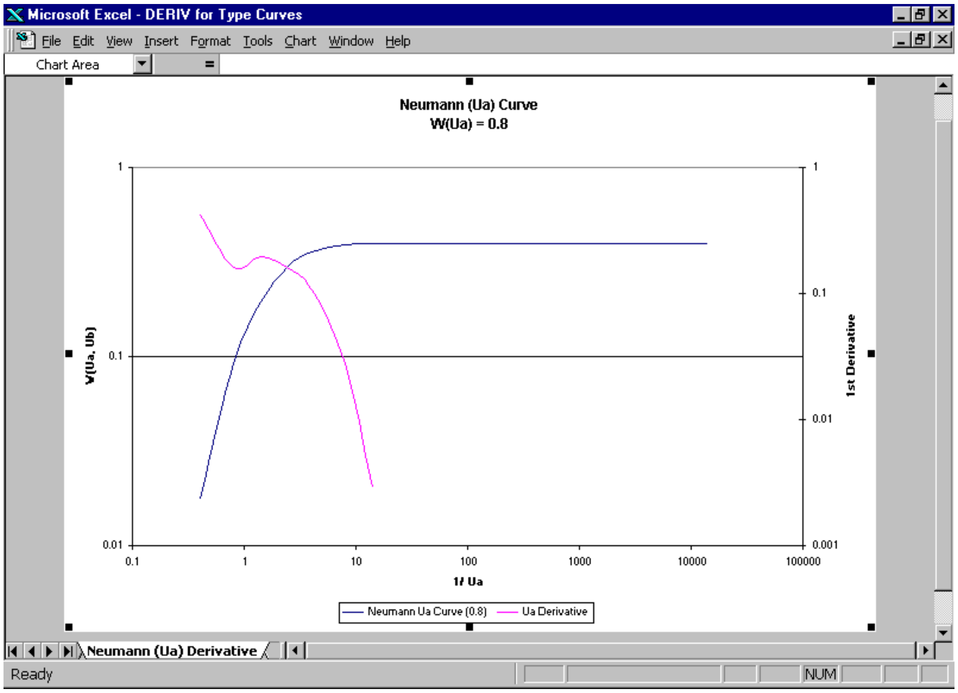


2.2.2 Observation Well Curve

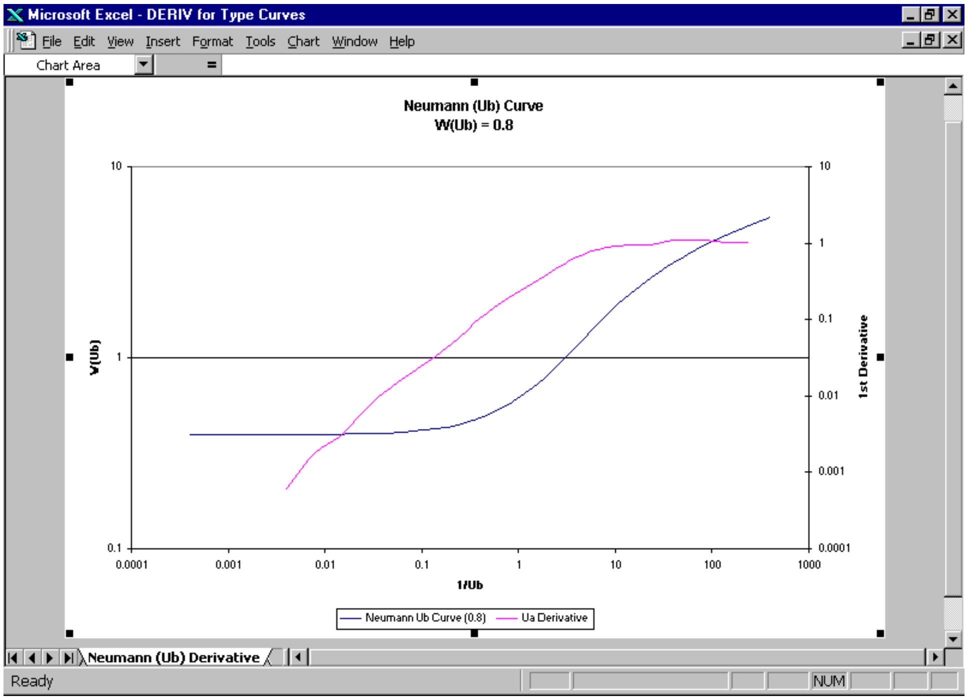


2.3 The Neuman Type Curve and the 1st Derivative

2.3.1 The Ua (Early-Time) Curve

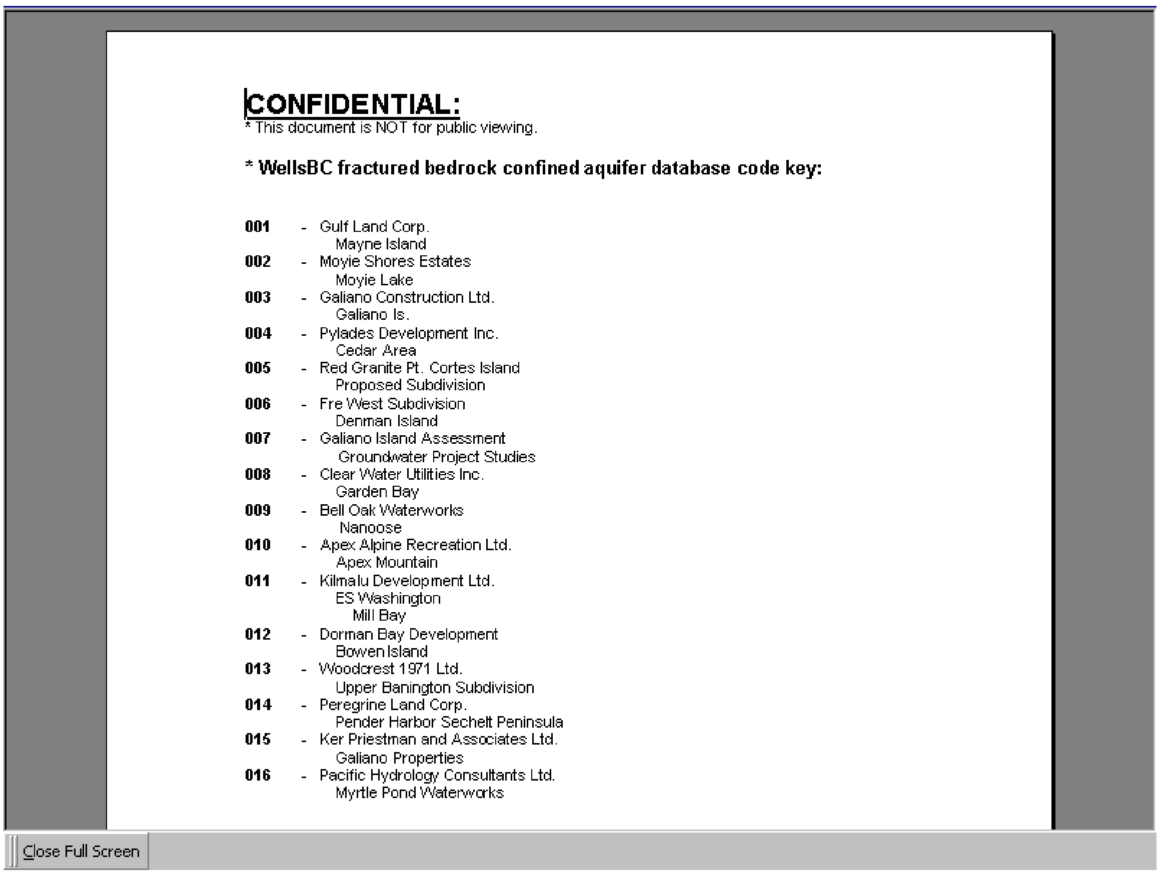


2.3.2 The Ub (Late-Time) Curve



APPENDIX 3.0
<u>FILE CODE KEY</u>

This report contains 16 hydraulic test data files from the British Columbia Ministry of Environment, Lands and Parks. The original names of these files contain confidential references to companies or firms, who completed the hydraulic work and whose data are contained in the aforementioned files. In keeping the references confidential, generic 'working' names in the form of numeric digits were assigned to each of these files. The key to these 'working' names are listed in Figure A1.1.



<u>CONFIDENTIAL:</u>
* This document is NOT for public viewing.

*** WellsBC fractured bedrock confined aquifer database code key:**

001 - Gulf Land Corp.
Mayne Island
002 - Moyie Shores Estates
Moyie Lake
003 - Galiano Construction Ltd.
Galiano Is.
004 - Pylades Development Inc.
Cedar Area
005 - Red Granite Pt. Cortes Island
Proposed Subdivision
006 - Fre West Subdivision
Denman Island
007 - Galiano Island Assessment
Groundwater Project Studies
008 - Clear Water Utilities Inc.
Garden Bay
009 - Bell Oak Waterworks
Nanoose
010 - Apex Alpine Recreation Ltd.
Apex Mountain
011 - Kilmalu Development Ltd.
ES Washington
Mill Bay
012 - Dorman Bay Development
Bowen Island
013 - Woodcrest 1971 Ltd.
Upper Banington Subdivision
014 - Peregrine Land Corp.
Pender Harbor Sechelt Peninsula
015 - Ker Priestman and Associates Ltd.
Galiano Properties
016 - Pacific Hydrology Consultants Ltd.
Myrtle Pond Waterworks

Close Full Screen

Figure A1.1. File Name Code Key. (*Note: Confidential information*).

ANNEX 1
<u>VALUES USED IN THE PLOTTING OF THEIS TYPE CURVES.</u>

**Referenced from: Wenzel, 1942*

u	1/u	W(u)
1.00E-15	1E+15	33.96
2.00E-15	5E+14	33.27

3.00E-15	3.333E+14	32.86
4.00E-15	2.5E+14	32.58
5.00E-15	2E+14	32.35
6.00E-15	1.667E+14	32.17
7.00E-15	1.429E+14	32.02
8.00E-15	1.25E+14	31.88
9.00E-15	1.111E+14	31.76
1.00E-14	1E+14	31.66
2.00E-14	5E+13	30.97
3.00E-14	3.333E+13	30.56
4.00E-14	2.5E+13	30.27
5.00E-14	2E+13	30.05
6.00E-14	1.667E+13	29.87
7.00E-14	1.429E+13	29.71
8.00E-14	1.25E+13	29.58
9.00E-14	1.111E+13	29.46
1.00E-13	1E+13	29.36
2.00E-13	5E+12	28.66
3.00E-13	3.333E+12	28.26
4.00E-13	2.5E+12	27.97
5.00E-13	2E+12	27.75
6.00E-13	1.667E+12	27.56
7.00E-13	1.429E+12	27.41
8.00E-13	1.25E+12	27.28
9.00E-13	1.111E+12	27.16
1.00E-12	1E+12	27.05
2.00E-12	5E+11	26.36
3.00E-12	3.333E+11	25.96
4.00E-12	2.5E+11	25.67
5.00E-12	2E+11	25.44
6.00E-12	1.667E+11	25.26
7.00E-12	1.429E+11	25.11
8.00E-12	1.25E+11	24.97
9.00E-12	1.111E+11	24.86
1.00E-11	1E+11	24.75
2.00E-11	5E+10	24.06
3.00E-11	3.333E+10	23.65
4.00E-11	2.5E+10	23.36
5.00E-11	2E+10	23.14
6.00E-11	1.667E+10	22.96
7.00E-11	1.429E+10	22.81
8.00E-11	1.25E+10	22.67
9.00E-11	1.111E+10	22.55
1.00E-10	1E+10	22.45
u	1/u	W(u)
2.00E-10	5E+09	21.76
3.00E-10	3.333E+09	21.35
4.00E-10	2.5E+09	21.06
5.00E-10	2E+09	20.84
6.00E-10	1.667E+09	20.66
7.00E-10	1.429E+09	20.5

8.00E-10	1.25E+09	20.37
9E-10	1.111E+09	20.25
1.00E-09	1E+09	20.15
2.00E-09	500000000	19.45
3.00E-09	333333333	19.05
4.00E-09	250000000	18.76
5.00E-09	200000000	18.54
6.00E-09	166666667	18.35
7.00E-09	142857143	18.2
8.00E-09	125000000	18.07
9E-09	111111111	17.95
1.00E-08	100000000	17.84
2.00E-08	50000000	17.15
3.00E-08	33333333	16.74
4.00E-08	25000000	16.46
5.00E-08	20000000	16.23
6.00E-08	16666667	16.05
7.00E-08	14285714	15.9
8.00E-08	12500000	15.76
9E-08	11111111	15.65
1.00E-07	10000000	15.54
2.00E-07	5000000	14.85
3.00E-07	3333333.3	14.44
4.00E-07	2500000	14.15
5.00E-07	2000000	13.93
6.00E-07	1666666.7	13.75
7.00E-07	1428571.4	13.6
8.00E-07	1250000	13.46
9E-07	1111111.1	13.34
1.00E-06	1000000	13.24
2.00E-06	500000	12.55
3.00E-06	333333.33	12.14
4.00E-06	250000	11.85
5.00E-06	200000	11.63
6.00E-06	166666.67	11.45
7.00E-06	142857.14	11.29
8.00E-06	125000	11.16
0.000009	111111.11	11.04
1.00E-05	100000	10.94
2.00E-05	50000	10.24
3.00E-05	33333.333	9.84
4.00E-05	25000	9.55
5.00E-05	20000	9.33
6.00E-05	16666.667	9.14
u	1/u	W(u)
7.00E-05	14285.714	8.99
8.00E-05	12500	8.86
0.00009	11111.111	8.74
1.00E-04	10000	8.63
2.00E-04	5000	7.94
3.00E-04	3333.3333	7.53

4.00E-04	2500	7.25
5.00E-04	2000	7.02
6.00E-04	1666.6667	6.84
7.00E-04	1428.5714	6.69
8.00E-04	1250	6.55
0.0009	1111.1111	6.44
1.00E-03	1000	6.33
2.00E-03	500	5.64
3.00E-03	333.33333	5.23
4.00E-03	250	4.95
5.00E-03	200	4.73
6.00E-03	166.66667	4.54
7.00E-03	142.85714	4.39
8.00E-03	125	4.26
0.009	111.11111	4.14
0.01	100	4.04
0.02	50	3.35
0.03	33.333333	2.96
0.04	25	2.68
0.05	20	2.47
0.06	16.666667	2.3
0.07	14.285714	2.15
0.08	12.5	2.03
0.09	11.111111	1.92
0.1	10	1.82
0.2	5	1.22
0.3	3.3333333	0.91
0.4	2.5	0.7
0.5	2	0.56
0.6	1.6666667	0.45
0.7	1.4285714	0.37
0.8	1.25	0.31
0.9	1.1111111	0.26
1	1	0.219
2	0.5	0.049
3	0.3333333	0.013
4	0.25	0.0038
5	0.2	0.0011
6	0.1666667	0.00036
7	0.1428571	0.00012
8	0.125	3.8E-05
9	0.1111111	1.2E-05

ANNEX 4

VALUES USED IN THE PLOTTING OF TYPE CURVES FOR GRINGARTEN ET AL.'S CURVE MATCHING METHOD.

**Referenced from: Kruseman, G.P. and de Ridder N.A., 1989, Analysis and Evaluation of*

Pumping Test Data 2nd ed., Published by ILRI, The Netherlands (taken from Annex 18.2, p. 362 in the book).

U(Vf)	F(Uvf)
1.00E-02	0.3544
1.50E-02	0.4342
2.00E-02	0.5014
3.00E-02	0.614
4.00E-02	0.709
5.00E-02	0.7926
6.00E-02	0.868
8.00E-02	1.001
0.1	1.117
0.15	1.358
0.2	1.551
0.3	1.852
0.4	2.083
0.5	2.21
0.6	2.429
0.8	2.685
1	2.889
1.5	3.269
2	3.543
3	3.935
4	4.216
5	4.435
6	4.615
8	4.899
10	5.12
15	5.523
20	5.809
30	6.213
40	6.5
50	6.723
60	6.905
80	7.192
100	7.415
150	7.82
200	8.108
300	8.513
400	8.801
500	9.024
600	9.206
800	9.494
1000	9.717
1500	10.12
2000	10.41
3000	10.82
4000	11.1
5000	11.33
6000	11.51
8000	11.8

ANNEX 5

VALUES USED IN THE PLOTTING OF TYPE CURVES FOR GRINGARTEN-WHITHERSPOON'S CURVE-MATCHING METHOD.

**Referenced from: Kruseman, G.P. and de Ridder N.A., 1989, Analysis and Evaluation of*

Pumping Test Data 2nd ed., Published by ILRI, The Netherlands (taken from Annex 18.1, p. 356 in the book).

*Note: for Observations wells located along the fracture (x-axis) only.

Values of the function F(uvf,r')
for an observation well located along the fracture
(after Merton, 1987)

	F (u vf)	
u vf	r'=1.5	r'=1.2
0.001	0	0
0.0015	0	0
0.002	0	0.00003
0.003	0	0.00022
0.004	0	0.0007
0.006	0	0.00255
0.008	0.00002	0.00539
0.01	0.00007	0.00894
0.015	0.00056	0.01964
0.02	0.00176	0.03168
0.03	0.00639	0.05703
0.04	0.01348	0.08244
0.06	0.03243	0.13136
0.08	0.05494	0.17728
0.1	0.0792	0.22045
0.15	0.14256	0.31879
0.2	0.20601	0.40671
0.3	0.32742	0.56084
0.4	0.4395	0.69414
0.6	0.63686	0.91757
0.8	0.80463	1.10086
1	0.94961	1.25609
1.5	1.24251	1.56406
2	1.46988	1.79964
3	1.81206	2.15055
4	2.06691	2.40995
6	2.43868	2.78646
8	2.70918	3.05936
10	2.92189	3.27379
15	3.31338	3.66747
20	3.59396	3.94956
30	3.99237	4.34951
40	4.27634	4.63445
60	4.67891	5.0373
80	4.96559	5.32384
100	5.1886	5.54636
150	5.59415	5.95151
200	5.88219	6.23907
300	6.2879	6.64448
400	6.57631	6.9325
600	6.98295	7.33884
800	7.27204	7.6268
1000	7.49606	7.85073
1500	7.89972	8.25429
2000	8.18476	8.53926
3000	8.58471	8.93978
4000	8.86906	9.22463
6000	9.27127	9.62655
8000	9.55646	9.91271

ANNEX 8

VALUES USED IN THE PLOTTING OF TYPE CURVES FOR NEUMANN'S CURVE-MATCHING METHOD.

**Referenced from: Kruseman, G.P. and de Ridder N.A., 1989, Analysis and Evaluation of Pumping Test Data 2nd ed., Published by ILRI, The Netherlands (taken from Annex 5.1, p. 303 in the book).*

Referenced from Krauseman, G.P.; de Ridder, N.A., 1989, Analysis and Evaluation of Pumping Test Data, 2nd ed.
ILRI Publication #47. Taken from Annex 5.1 p.303-305.

Annex 5.1

Values of the Neumann functions W(Ua, β) for unconfined aquifers (after Neumann 1975)

Tables of values of the function W(Ua, β)

	β																		
1/Ua	0.001	0.004	0.01	0.03	0.06	0.1	0.2	0.4	0.6	0.8	1	1.5	2	2.5	3	4	5	6	7
0.4	0.0248	0.0243	0.0241	0.0235	0.023	0.0224	0.0214	0.0199	0.0188	0.0179	0.017	0.0153	0.0138	0.0125	0.0113	0.00933	0.00772	0.00639	0.00503
0.8	0.145	0.142	0.14	0.136	0.131	0.127	0.119	0.108	0.0988	0.0915	0.0849	0.0713	0.0603	0.0511	0.0435	0.0317	0.0234	0.0174	0.0131
1.4	0.358	0.352	0.345	0.331	0.318	0.304	0.279	0.244	0.217	0.194	0.175	0.0136	0.107	0.0846	0.0678	0.0445	0.0302	0.021	0.0151
2.4	0.662	0.648	0.633	0.601	0.57	0.54	0.483	0.403	0.343	0.296	0.256	0.0182	0.133	0.101	0.0767	0.0476	0.0313	0.0214	0.0152
4	1.02	0.992	0.963	0.905	0.849	0.792	0.688	0.542	0.438	0.36	0.3	0.0199	0.14	0.103	0.0797	0.0478		0.0215	
8	1.57	1.52	1.46	1.35	1.23	1.12	0.918	0.659	0.497	0.391	0.317	0.0203	0.141						
14	2.05	1.97	1.88	1.7	1.51	1.34	1.03	0.69	0.507	0.394									
24	2.52	2.41	2.27	1.99	1.73	1.47	1.07	0.696											
40	2.97	2.8	2.61	2.22	1.85	1.53	1.08												
80	3.56	3.3	3	2.41	1.92	1.55													
140	4.01	3.65	3.23	2.48	1.93														
240	4.42	3.93	3.37	2.49	1.94														
400	4.77	4.12	3.43	2.5															
800	5.16	4.26	3.45																
1400	5.4	4.29	3.46																
2400	5.54	4.3	3.46																
4000	5.59	4.3	3.46																
8000	5.62	4.3	3.46																
14000	5.62	4.3	3.46	2.5	1.94	1.55	1.08	0.696	0.507	0.394	0.317	0.0203	0.141	0.103	0.0797	0.0478	0.0313	0.0215	0.0152

Referenced from Krauseman, G.P.; de Ridder, N.A., 1989, Analysis and Evaluation of Pumping Test Data, 2nd ed.
ILRI Publication #47. Taken from Annex 5.1 p.303-305.

Annex 5.1

Values of the Neumann functions W(Ub, β) for unconfined aquifers (after Neumann 1975)

Tables of values of the function W(Ub, β)

	β																		
1/Ub	0.001	0.004	0.01	0.03	0.06	0.1	0.2	0.4	0.6	0.8	1	1.5	2	2.5	3	4	5	6	7
0.0004	5.62	4.3	3.46	2.5	1.94	1.56	1.09	0.697	0.508	0.395	0.318	0.204	0.142	0.103	0.078	0.0479	0.0314	0.0215	0.0153
0.0008															0.0781	0.048	0.0315	0.0216	0.0153
0.0014														0.103	0.0783	0.0481	0.0316	0.0217	0.0154
0.0024														0.104	0.0785	0.0484	0.0318	0.0219	0.0156
0.004								0.697	0.508	0.395	0.318	0.204	0.142	0.104	0.0789	0.0487	0.0321	0.0212	0.0158
0.008									0.509	0.396	0.319	0.205	0.143	0.105	0.0799	0.0496	0.0329	0.0228	0.0164
0.014								0.698	0.51	0.397	0.321	0.207	0.145	0.107	0.0814	0.0509	0.0341	0.0239	0.0173
0.024								0.7	0.512	0.399	0.323	0.209	0.147	0.109	0.0838	0.0532	0.0361	0.0257	0.0189
0.04								0.703	0.516	0.403	0.327	0.213	0.152	0.113	0.0879	0.0568	0.0393	0.0286	0.0215
0.08						1.56	1.09	0.71	0.524	0.412	0.337	0.224	0.162	0.124	0.098	0.0661	0.0478	0.0362	0.0284
0.14					1.94	1.56	1.1	0.72	0.537	0.425	0.35	0.239	0.178	0.139	0.113	0.0806	0.0612	0.0486	0.0398
0.24				2.5	1.95	1.57	1.11	0.737	0.557	0.447	0.374	0.265	0.205	0.166	0.14	0.106	0.0853	0.0714	0.0614
0.4				2.51	1.96	1.58	1.13	0.763	0.589	0.483	0.412	0.307	0.248	0.21	0.184	0.149	0.128	0.113	0.102
0.8	5.62	4.3	3.46	2.52	1.98	1.61	1.18	0.829	0.667	0.571	0.506	0.41	0.357	0.323	0.298	0.266	0.245	0.231	0.22
1.4	5.63	4.31	3.47	2.54	2.01	1.66	1.24	0.922	0.78	0.697	0.642	0.562	0.517	0.489	0.47	0.445	0.43	0.419	0.411
2.4	5.63	4.31	3.49	2.57	2.06	1.73	1.35	1.07	0.954	0.889	0.85	0.792	0.763	0.745	0.733	0.718	0.709	0.703	0.699
4	5.63	4.32	3.51	2.62	2.13	1.83	1.5	1.29	12	1.16	1.13	1.1	1.08	1.07	1.07	1.06	1.06	1.05	1.05
8	5.64	4.35	3.56	2.73	2.31	2.07	1.85	1.72	1.68	1.66	1.65	1.64	1.63	1.63	1.63	1.63	1.63	1.63	1.63
14	5.65	4.38	3.63	2.88	2.55	2.37	2.23	2.17	2.15	2.15	2.14	2.14	2.14	2.14	2.14	2.14	2.14	2.14	2.14
24	5.67	4.44	3.74	3.11	2.86	2.75	2.68	2.66	2.65	2.65	2.65	2.65	2.64	2.64	2.64	2.64	2.64	2.64	2.64
40	5.7	4.52	3.9	3.4	3.24	3.18	3.15	3.14	3.14	3.14	3.14	3.14	3.14	3.14	3.14	3.14	3.14	3.14	3.14
80	5.76	4.71	4.22	3.92	3.85	3.83	3.82	3.82	3.82	3.82	3.82	3.82	3.82	3.82	3.82	3.82	3.82	3.82	3.82
140	5.85	4.94	4.58	4.4	4.38	4.38	4.37	4.37	4.37	4.37	4.37	4.37	4.37	4.37	4.37	4.37	4.37	4.37	4.37
240	5.99	5.23	5	4.92	4.91	4.91	4.91	4.91	4.91	4.91	4.91	4.91	4.91	4.91	4.91	4.91	4.91	4.91	4.91
400	6.16	5.59	5.46	5.42	5.42	5.42	5.42	5.42	5.42	5.42	5.42	5.42	5.42	5.42	5.42	5.42	5.42	5.42	5.42