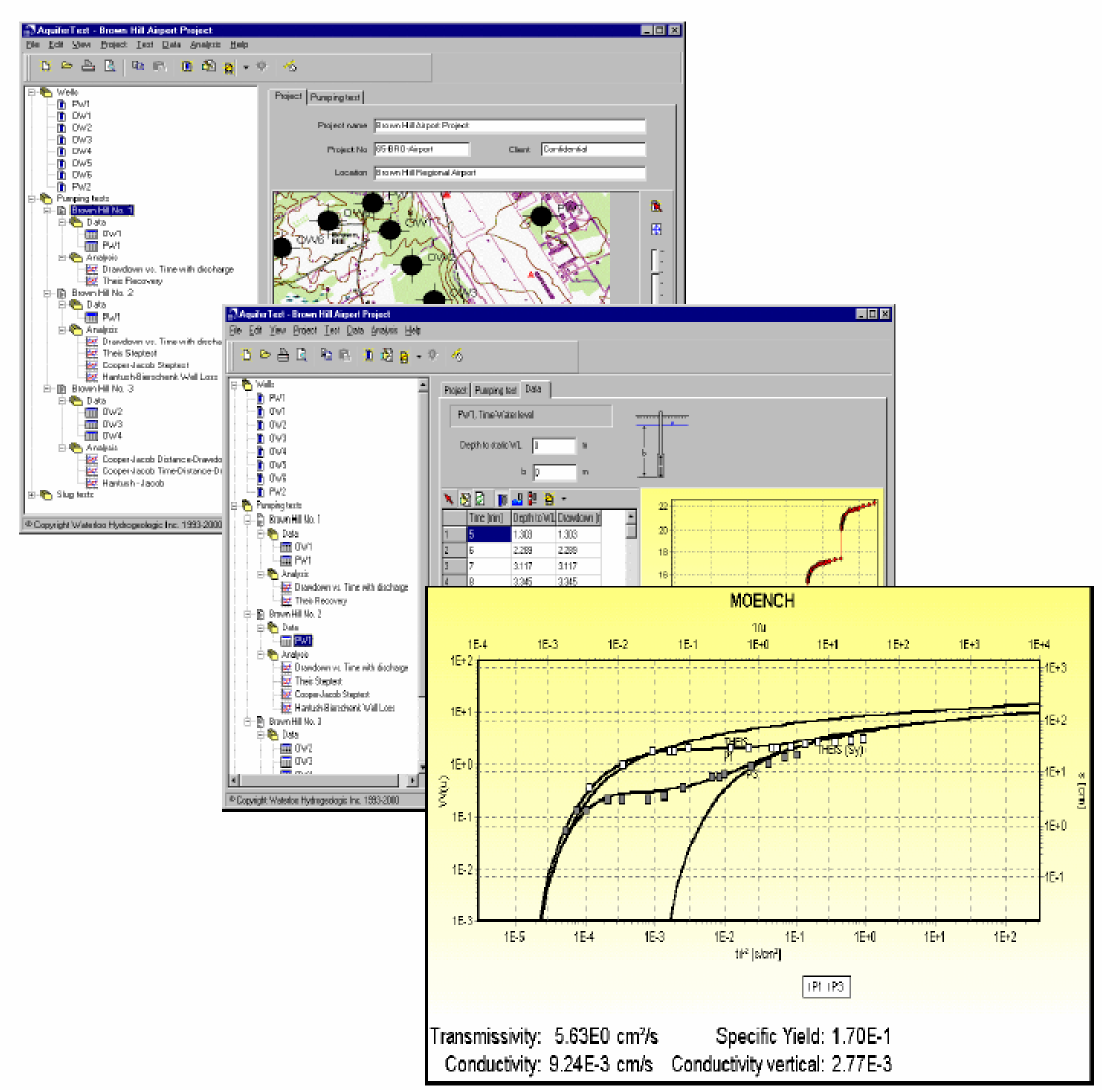
User's Guide for AquiferTest

The intuitive aquifer test analysis package



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Jilin Universty, 2009

Contents

1. Introduction

Congratulations on your purchase of AquiferTest, the most popular software package available for graphical analysis and reporting of pumping test and slug test data!

AquiferTest is designed by hydrogeologists for hydrogeologists giving you all the tools you need to efficiently manage hydraulic testing results and provide a selection of the most commonly used solution methods for data analysis - all in the familiar and easy-to-use Microsoft Windows environment.

AquiferTest has the following key features and enhancements:

- Runs as a native Windows 95/98/NT/2000 32-bit application
- Easy-to-use, all new interface
- Solution methods for unconfined, confined, leaky confined and fractured rock aquifers
- Customizable report templates, with a built-in report designer
- Solution Method Advisor to assist you in choosing an appropriate data analysis method
- Easily create and compare multiple analysis methods for the same data set
- Step test/well loss method
- Pumping test planning "forward solution" method

- Universal Data Logger Import utility (supports a wide variety of column delimiters and file layouts)
- Import well locations and geometry from an ASCII file
- Site map support for .dxf files and bitmap (.bmp) images
- Windows clipboard support for cutting and pasting of data and output graphics directly into your project report
- Export analysis graphs to a graphics file (.bmp, .jpg, .wmf, .emf)
- Dockable, customizable tool bar
- Numerous short-cut keys to speed program navigation

- Units converter
- Microsoft Access database-driven application for enhanced usability and efficiency
- Unlimited free technical support from WHI

For pumping tests, the following solution methods are available:

- Theis (1935)
- Cooper-Jacob Time-Drawdown (1946)
- Cooper-Jacob Distance-Drawdown (1946)
- Cooper-Jacob Time-Distance-Drawdown (1946)
- Hantush-Jacob (1955)
- Neuman (1975)
- Moench (1993)

- Moench Fracture Flow (1984)
- Theis Steptest (1935)
- Cooper-Jacob Steptest (1946)
- Theis Recovery (1935)
- Hantush-Bierschenk Well Loss
- Specific Capacity Test
- Theis Prediction (pumping test planning "forward solution")

For slug tests, the following solution methods are available:

- Hvorslev (1951)
- Bouwer-Rice (1976)
- Cooper-Bredehoeft-Papadopulos (1967)

Data can be imported directly from:

- Microsoft Excel version 4.0, 5.0, or 7.0 files
- Data logger ASCII files with a variety of delimiters and column layouts

AquiferTest provides a flexible, user-friendly environment that you can use to become more efficient in your aquifer testing projects. Data can be directly entered in AquiferTest via the keyboard, imported from a Microsoft Excel (version 4, 5, or 7) workbook file, or imported from any data logger file (in ASCII format). Test data can also be inserted from a Windows text editor, spreadsheet, or database by "cutting and pasting" through the clipboard.

Automatic type curve fitting to a data set using least squares regression can be performed for all graphical solution methods in AquiferTest. However, you are encouraged to use your professional judgement to validate the graphical match based on your knowledge of the geologic and hydrogeologic setting of the test. To easily refine the curve fit, you can manually fit the data to a type curve by simply pressing the arrow keys on your keyboard.

The demonstration exercises in Chapter 5 will introduce you to some of the many features of AquiferTest. The first two exercises evaluate pumping tests in a confined aquifer using the Theis and Cooper-Jacob methods. The third exercise uses the import capabilities of AquiferTest to import water level recovery data from a data logger, and subsequently analyzes it using the Theis Recovery method. The fourth exercise involves the evaluation of a slug test using both the Hvorslev and Bouwer-Rice methods. The fifth exercise uses the Moench method, while the sixth uses the Theis Prediction (forward) solution to answer commonly encountered questions when planning a pumping test.

1.1 Database Concept

A program using a database has many advantages, such as inherent data consistency and integrity, and inter operability (other database programs can access the data in the database). This can be important if you want to share your project data with others on a local area network (intranet) or with project colleagues on another continent via the Internet.

AquiferTest stores its data in a database. Immediately after you enter or make changes to your data, the data are saved to the project database. For example, if you modify the project name, the change is saved to the database as soon as you leave the project name field. It is for this reason that there is no Save or Save as menu items in the program.

1.2 How to Contact Waterloo Hydrogeologic, Inc.

If, after reading this manual and using AquiferTest, you would like to contact Waterloo Hydrogeologic, Inc. with comments or suggestions, or if you need technical assistance, you can reach our office at:

- Waterloo Hydrogeologic, Inc.
- 180 Columbia Street West - Unit 1104
- Waterloo, Ontario, CANADA N2L 3L3
- Phone +1 (519) 746 1798 Fax +1 (519) 885 5262
- E-mail: techsupport@flowpath.com
- Web: www.flowpath.com

To help us handle your technical support questions as quickly as possible, please have the following information ready before you call or include it in a detailed technical support e-mail:

- A complete description of the problem including a summary of key strokes and program events
- Product name and version number
- Product serial number
- Computer make and model number
- Operating system and version number
- Total free RAM
- Number of free bytes on your hard disk

You may send us your questions via e-mail, fax, or call one of our technical support specialists. Please allow up to two business days for a response.

1.3 Waterloo Hydrogeologic, Inc. Training and Consulting

WHI strives to offer the most useful, practical, high quality training in hydro geologic modeling in the industry. Training courses are designed to provide a rapid introduction to essential knowledge and skills, and create a basis for further professional development and real-world practice. Open enrollment courses are offered worldwide each year. For the current schedule of courses, visit WHI on the web or e-mail us at training@flowpath.com.

Waterloo Hydrogeologic, Inc. also offers expert consulting and reviewing services for all numerical modeling projects concerning groundwater flow and solute transport. For further information, please contact us at consulting@flowpath.com.

1.4 Other Software Products by WHI

1.4.1 Other Software Products by WHI

We have developed a number of other useful software products for the groundwater professional, all designed to increase your efficiency and enhance your technical capability, including:

- Visual MODFLOW
- Visual MODFLOW 3D-Explorer
- Visual PEST
- Visual Groundwater
- WHI UnSatSuite
- Visual HELP
- MoNA ToolKit
- AquaChem
- Flowpath II

1.4.2 Visual MODFLOW...

is the environmental industry standard for groundwater modeling. A pre and postprocessor for MODFLOW, MODPATH, and MT3D/RT3D. A complete package for the visualization of model input and results. The largest time-saving breakthrough since the release of MODFLOW.

1.4.3 Visual MODFLOW 3D-Explorer...

is a built-in 3D visualization system for displaying and animating Visual MODFLOW models using state-of-the-art 3D graphics technology. The advanced visualization capabilities of the Visual MODFLOW 3D-Explorer provide you with all the tools you need to create impressive and informative 3D representations of your modeling data using vibrant colors and high-resolution graphics.

1.4.4 Visual PEST

combines the latest version of PEST2000 with the graphical processing and display features of WinPEST for model-independent parameter estimation.

1.4.5 Visual Groundwater.

..is the first software package to combine state-of-the-art graphical technology for 3D visualization and animation capabilities with an easy-to-use graphical interface designed specifically for environmental project applications.

1.4.6 WHI UnSatSuite

.is a fully-integrated software package for modeling 1D unsaturated zone flow and contaminant transport using the industry standard numerical modeling codes - all run under one tightly integrated interface.

1.4.7 Visual HELP

.is the most advanced hydrological modeling environment available for designing landfills, predicting leachate mounding and evaluating potential leachate seepage to the groundwater table.

1.4.8 MoNA ToolKit

provides an integrated data management, visualization, trend analysis, and modeling platform for evaluating the effectiveness of Monitored Natural Attenuation. The MoNA ToolKit combines 3 different software applications (BioTrends, SEQUENCE and BioTracker) into one integrated solution for evaluating, visualizing and modeling natural attenuation processes.

1.4.9 AquaChem

is a fully integrated software package developed specifically for numerical analysis of aqueous geochemical data. These powerful analytical capabilities are complimented by a comprehensive selection of commonly used graphical techniques to portray the chemical characteristics of geochemical and water quality data for single samples and groups of samples. AquaChem is truly one of the most powerful tools available for dealing with the interpretation, analysis and modeling of simple or complex geochemical data sets.

1.4.10 Flowpath II.

is a popular two-dimensional, steady-state, groundwater flow, pathline, and contaminant transport model that computes hydraulic heads, pathlines, travel times, velocities, water balances, and contaminant concentrations (approved by the US EPA and recommended by the UK Environmental Agency).

At WHI, we are continually developing new modeling and visualization applications for the environmental professional. For more information, please contact us.

2. Getting Started

2.1 System Requirements

To run AquiferTest you need the following minimum system configuration:
A CD-ROM drive for software installation

- A hard drive, with at least 35 MB free
- A Pentium processor or better
- 32 MB Ram
- Windows 95/98/2000, or Windows NT 4.0 with Service Pack 3 (or later) installed
- A Microsoft mouse or compatible
- Minimum 600 x 800 screen resolution
- Recommended 1024 x 768 screen resolution

2.2 Installing AquiferTest

AquiferTest is distributed on one CD-ROM. Place the CD into your CD-ROM drive and the initial installation screen should load automatically. Once loaded, an installation interface with several different tabs will be presented.

Please take the time to explore the installation interface, as there is information concerning other WHI products, our worldwide distributors, technical support, consulting, training, and how to contact us.

On the initial Installation tab, you may choose from the following two buttons:

- AquiferTest 3.0 User's Manual
- AquiferTest 3.0 Installation

The User's Manual button will display a PDF document of the manual, which requires the Adobe Reader to view. If you do not have the Adobe Reader, a link has been created in the interface to download the appropriate software.

The Installation button will initiate the installation of the software on your computer. AquiferTest must be installed on your hard disk in order to run.

Please follow the installation instructions, and read the on-screen directions carefully. Once the installation is completed, you must re-boot your computer for the system changes to take effect.

After the installation is complete and your system has re-booted, you should see the blue WHI icon on your Desktop screen labeled AquiferTest 3.0. To start working with AquiferTest, double-click this icon.

Note: To install the software from the CD-ROM without the aid of the installation interface, you can:

- Open Windows Explorer, and navigate to the CD-ROM drive
- Open the Installation folder
- Double-click on the Setup32.exe to initiate the installation

Follow the on-screen installation instructions, which will lead you through the install and subsequently produce a desktop icon for you.

2.3 Online Help

This book is supplied to you in two forms: as a printed book, and as an online help file. To view the online help version of this manual, select Help, then Contents.

3. Theoretical background

3.1 Definition of Symbols

π = 3.14159265359
β = type curve number (Neuman, Moench)
α = block geometry parameter (Moench Fracture Flow)
γ = dimensionless fitting parameter for delayed drawdown used in Moench solution
Δh ΔH = Hantush component in Moench solution
Δh ΔN = Neuman component in Moench solution
Δh_w = drawdown in the well due to both aquifer drawdown and well loss
Δs = change in drawdown
$\beta_{t(n)}$(t-t n) = adjusted time
b = aquifer thickness (confined aquifer)
b = depth from water level to bottom of well screen (unconfined aquifer)
b'= thickness of the leaky layer
B = leakage factor (Hantush)
B = linear well loss coefficient (Hantush-Bierschenk)
C = well bore storage coefficient
C_s = specific capacity
c = hydraulic resistance
D = initial saturated thickness
g = gravitational constant
F = shape factor
H = displacement as a function of time (slug tests)
h = hydraulic head
H_0 = initial displacement (slug tests)
h_0 = initial hydraulic head (static conditions for pumping test)

h_D = dimensionless drawdown
h_{DT} = Theis component of Moench solution
h_t = head in well at time t > t 0
J_0 = zero order Bessel function of the first kind (Cooper-Bredehoeft-Papadopulos slug test method)
J_1 = first order Bessel function of the first kind (Cooper-Bredehoeft-Papadopulos slug test method)
wK'= vertical hydraulic conductivity of the leaky layer
K_h = horizontal hydraulic conductivity
K_v = vertical hydraulic conductivity
L = length of the screen
p = non-linear well loss fitting coefficient
Q = pumping well discharge
q(t) = function of rate of inflow or outflow at time t
Q_i = constant pumping rate for the i th period
Q_n = constant pumping rate for the n th period
R = gravel pack radius
R cont = contributing radial distance
r = radius of pumping or observation well (slug test, Moench and Fracture Flow methods)
r_c = effective radius of well casing (Cooper-Bredehoeft-Papadopulos slug test method)
r_d = dimensionless radial distance
r_{eff} = effective piezometer radius which accounts for gravel pack porosity (Bouwer-Rice method)
r_w = effective radius of open well interval (Cooper-Bredehoeft-Papadopulos slug test method)
r_0 = distance defined by the intercept of the zero drawdown and the straight line through the data points (Cooper-Jacob distance-drawdown method)
s = drawdown (h-h 0)
s_w = drawdown inside the well
S = storativity (specific storage S s*b)
s'= residual drawdown
S'= storativity values during recovery
S_y = specific yield
t = time since pumping began
T = transmissivity
t'= elapsed time from the end of pumping
t_0 = time at which the straight line fit intersects the time axis (Cooper-Jacob)
t_D = dimensionless time
t_i = start time for the i th pumping period
t_i'= end time for the i th pumping period
T_L = time lag (Hvorslev test, T 0 is the time when h/h 0 = 0.37)
t_n = start time for the n th pumping period
u = analytical parameter (Theis)
u'= analytical parameter (Theis Recovery)
u_A = type A curve for early time
u_B = type B curve for later time

W(u) = well function
W_D = well bore storage
x = Cartesian coordinate
y = Cartesian coordinate
Y_0 = zero order Bessel function of the second kind (Cooper- Bredehoeft-Papadopulos slug test method)
Y_1 = first order Bessel function of the second kind (Cooper-Bredehoeft-Papadopulos slug test method)
z_D = dimensionless depth of the piezometer

3.2 Pumping Tests and Slug Tests

With AquiferTest, you can analyze two types of test results:

[1] Pumping tests, where water is pumped from a well and the change in water level is measured inside one or more observation wells (or, in some cases, inside the pumping well itself). You can have data in three different forms:

- Time versus water level
- Time versus discharge
- Discharge versus water level

[2] Slug (or bail) tests, where a slug is inserted into a well (or removed from a well) and the change in water level in the side well is measured. You can have data in one form:

Time versus water level

For pumping tests, the following analysis methods are available:

- Theis (1935)
- Cooper-Jacob Time-Drawdown (1946)
- Cooper-Jacob Distance-Drawdown (1946)
- Cooper-Jacob Time-Distance-Drawdown (1946)
- Hantush-Jacob (1955)
- Neuman (1975)
- Moench (1993)
- Moench Fracture Flow (1984)
- Theis Steptest (1935)
- Cooper-Jacob Steptest (1946)
- Theis Recovery (1935)
- Hantush-Bierschenk Well Loss (1964)
- Specific Capacity Test
- Theis Prediction (pumping test planning "forward solution")

For slug tests, the following analysis methods are available:

- Hvorslev (1951)
- Bouwer-Rice (1976)
- Cooper-Bredehoeft-Papadopulos (1967)

3.3 Radial Flow to a Well in a Confined Aquifer

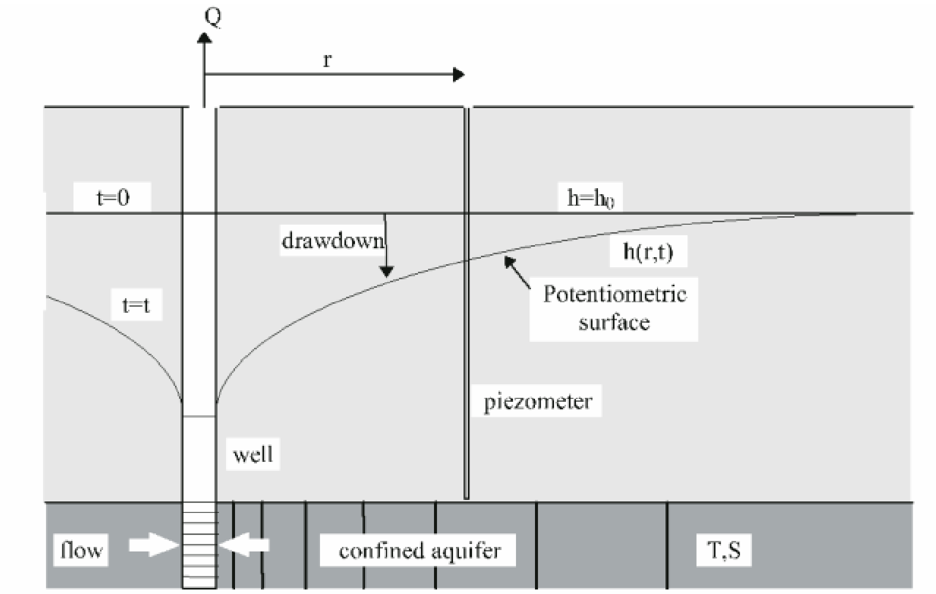
The partial differential equation that describes saturated flow in two horizontal dimensions in a confined aquifer is:

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} = \frac{S}{T}\frac{\partial h}{\partial t}$$

Written in terms of radial coordinates, the equation becomes:

$$\frac{\partial^2 h}{\partial r^2} + \frac{1}{r}\frac{\partial h}{\partial r} = \frac{S}{T}\frac{\partial h}{\partial t}$$

The mathematical region of flow, illustrated below, is a horizontal one-dimensional line through the aquifer, from r = 0 at the well to r = ∞ at the infinite extremity.



The initial condition is:

$$h(r,0) = h_0 \quad for\ all\ r$$

where h_0 is the initial hydraulic head (i.e., the piezometric surface is initially horizontal).

The boundary conditions assume that no drawdown occurs at an infinite radial distance:

$$h(\infty,t) = h_0 \quad for\ all\ t$$

and that a constant pumping rate, Q, is used:

$$\lim_{r \to 0} \left(r \frac{\partial h}{\partial r}\right) = \frac{Q}{2\pi T} \quad for\ t > 0$$

The solution of the above equation describes the hydraulic head at any radial distance, r, at any time after the start of pumping.

3.4 Theis Method (confined)

Theis (1935) developed an analytical solution for the equations presented in the previous section as follows:

$$s(r,t) = \frac{Q}{4\pi T} \int_u^\infty \frac{e^{-u}du}{u} \qquad u = \frac{r^2 S}{4Tt}$$

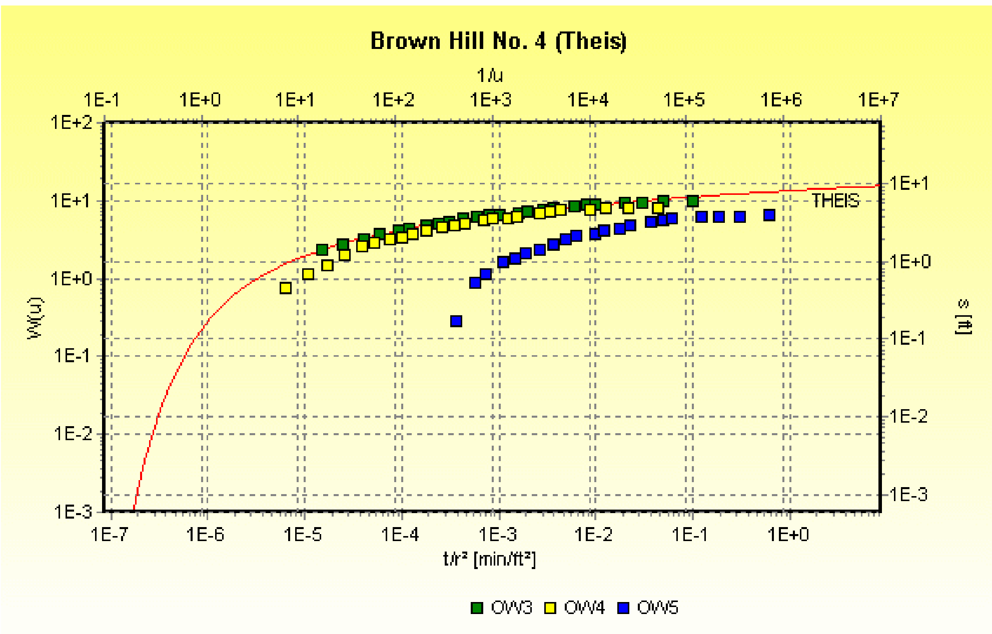
For the specific definition of u given above, the integral is known as the well function, W(u) and can be represented by an infinite Taylor series of the following form:

$$W(u) = -0.5772 - \ln(u) + u - \frac{u^2}{2 \cdot 2!} + \frac{u^3}{3 \cdot 3!} - \cdots$$

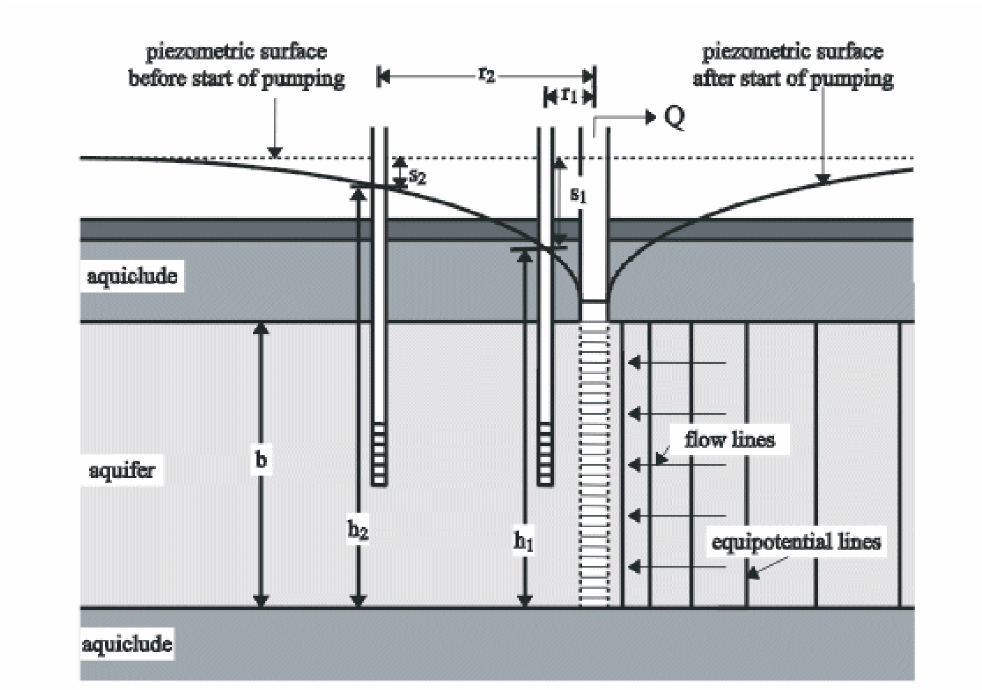
Using this function, the equation becomes:

$$s = \frac{Q}{4\pi T} W(u)$$

The line on a log-log plot with W(u) along the Y axis and 1/u along the X axis is commonly called the Theis curve. The field measurements are plotted as t or t/r^2 along the X axis and s along the Y axis. The data analysis is done by matching the line drawn through the plotted observed data to the Theis curve.



This solution is appropriate for the conditions shown in the following figure:



The Theis solution assumes the following:

- The aquifer is confined and has an "apparent" infinite extent
- The aquifer is homogeneous, isotropic, and of uniform thickness over the area influenced by pumping
- The piezometric surface was horizontal prior to pumping
- The well is fully penetrating and pumped at a constant rate
- Water removed from storage is discharged instantaneously with a decline in head
- The well diameter is small, so well storage is negligible

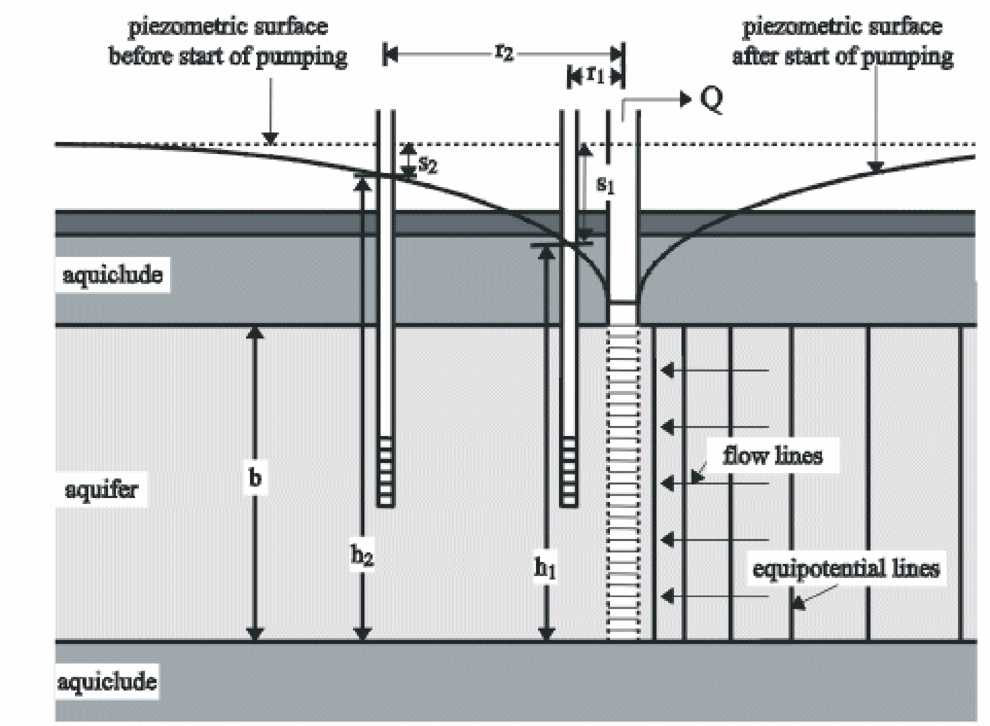
Data requirements:

- Drawdown vs. time at an observation well
- Finite distance from the pumping well to observation well
- Pumping rate (constant)

3.5 Theis Recovery Test (confined)

When the pump is shut down after a pumping test, the water levels inside the pumping and observation wells will start to rise. This rise in water level is known as residual drawdown (s'). Recovery-test measurements allow the transmissivity of the aquifer to be calculated, thereby providing an independent check on the results of the pumping test.

Residual drawdown data can be more reliable than drawdown data because the recovery occurs at a constant rate, whereas constant discharge pumping is often difficult to achieve in the field. Residual drawdown data can be collected from both the pumping and observation wells.



Strictly applied, this solution is appropriate for the conditions shown in the following figure. However, if additional limiting conditions are satisfied, the Theis recovery solution method can also be used for leaky, unconfined aquifers and aquifers with partially penetrating wells (Kruseman and de Ridder (1991), page 183).

According to Theis (1935), the residual drawdown, after pumping has ceased, is

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

$$u = \frac{r^2 S}{4Tt} \qquad u' = \frac{r^2 S'}{4Tt'}$$

where:

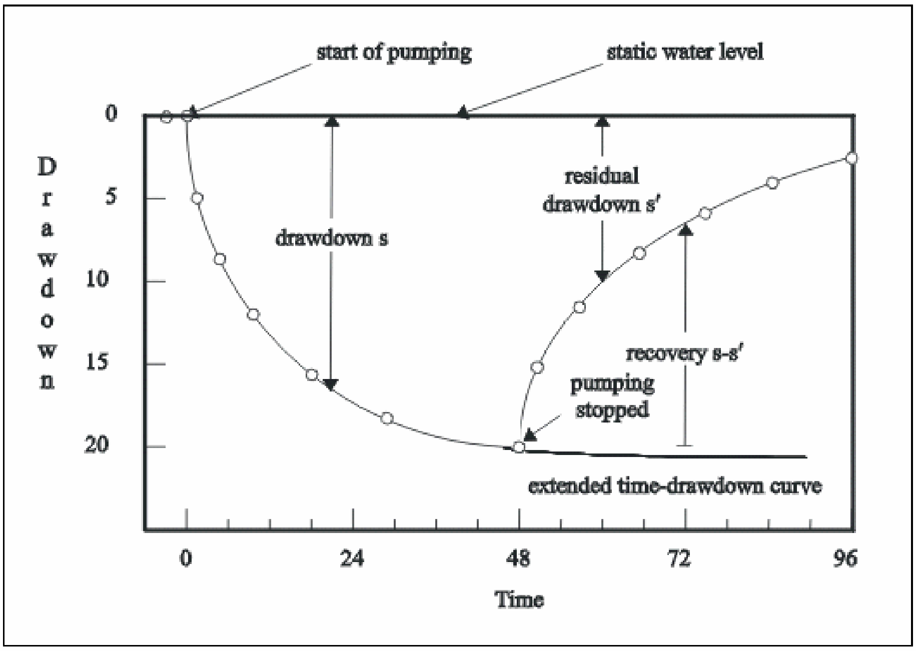
s' = residual drawdown

r = distance from well to piezometer

T= transmissivity of the aquifer (KD)

S and S' = storativity values during pumping and recovery respectively.

t and t' = elapsed times from the start and ending of pumping respectively.



Using the approximation for the well function, W(u), shown in the Cooper-Jacob method, this equation becomes:

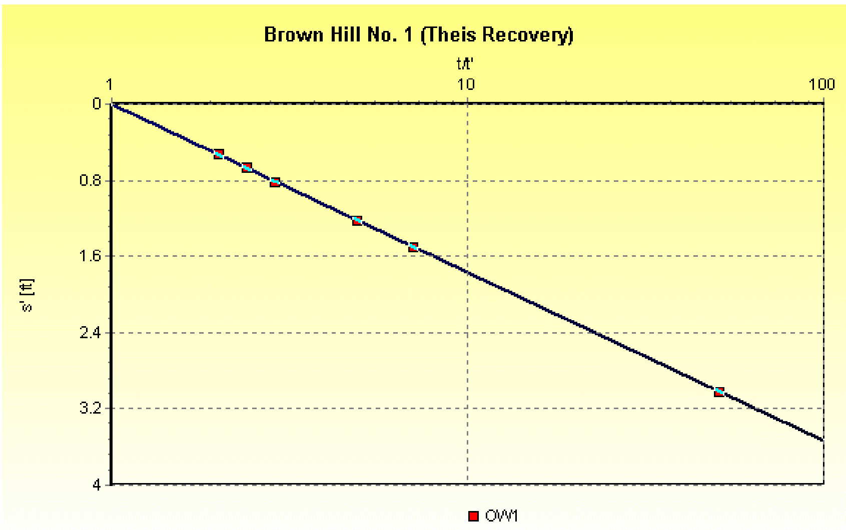
$$s' = \frac{Q}{4\pi T}\left(\ln\frac{4Tt}{r^2 S} - \ln\frac{4Tt'}{r^2 S'}\right)$$

When S and S' are constant and equal and T is constant, this equation can be reduced to:

$$s' = \frac{2.3Q}{4\pi T}\log\left(\frac{t}{t'}\right)$$

To analyze the data, s' is plotted on the logarithmic Y axis and time is plotted on the linear X axis as the ratio of t/t' (total time since pumping began divided by the time since the pumping ceased).

An example of a Theis Recovery analysis graph has been included below:



The Theis Recovery solution assumes the following:

- The aquifer is confined and has an "apparent" infinite extent
- The aquifer is homogeneous, isotropic, and of uniform thickness over the area influenced by pumping
- The piezometric surface was horizontal prior to pumping
- The well is fully penetrating and pumped at a constant rate
- Water removed from storage is discharged instantaneously with decline in head
- The well diameter is small, so well storage is negligible

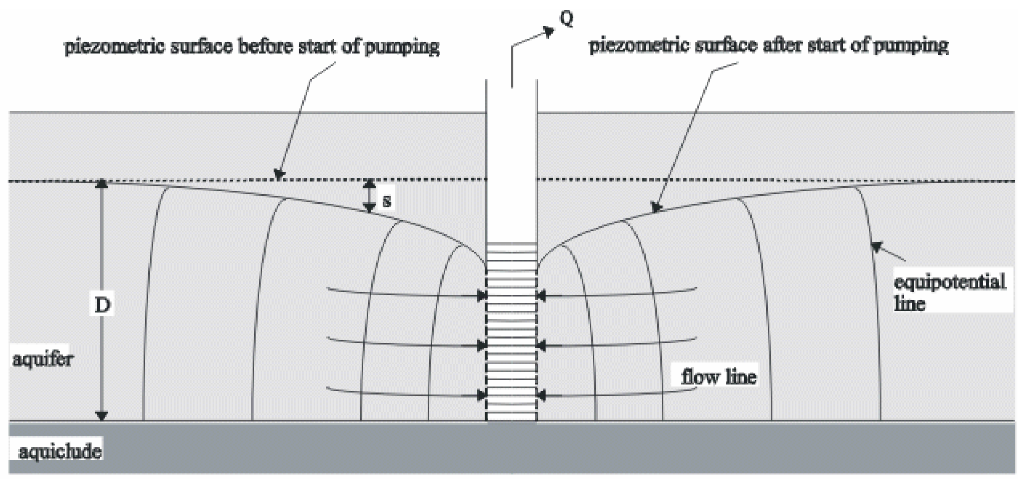
The data requirements for the Theis Recovery solution are:

- Recovery vs. time data at a pumping or observation well
- Distance from the pumping well to the observation well
- Pumping rate and duration

3.6 Neuman Method (unconfined)

Neuman (1975) developed a solution method for pumping tests performed in unconfined aquifers.

When analyzing pumping test data from unconfined aquifers, one often finds that the drawdown response fails to follow the classical Theis (1935) solution. When drawdown is plotted versus time on logarithmic paper, it tends to delineate an inflected curve consisting of (1) a steep segment at early time; (2) a flat segment at intermediate time; and (3) a somewhat steeper segment at later time.



The early segment indicates that some water is released from aquifer storage instantaneously when drawdown increases. The intermediate segment suggests an additional source of water, which is released from storage with some delay in time. When most of the water has been derived from this additional source, the time-drawdown curve becomes relatively steep again. In the groundwater literature, this phenomenon has been traditionally referred to as "delayed yield" (Neuman, 1979).

This solution is appropriate for the conditions shown in the following figure.

The equation developed by Neuman (1975) representing drawdown in an unconfined aquifer is given by:

$$s = \frac{Q}{4\pi T} W(u_A, u_B, \beta)$$

where:

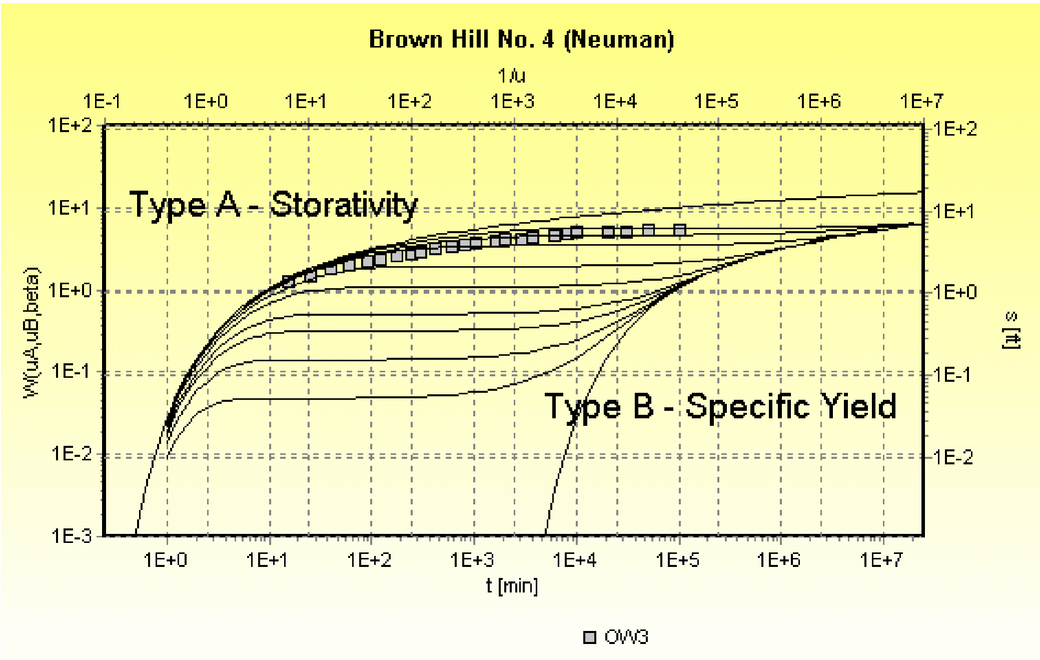
W(u_A, u_B, b) is known as the unconfined well function

$u_A = r^2S / 4Tt$ (Type A curve for early time)

$u_B = r_2Sy / 4Tt$ (Type B curve for later time)

$b = r^2Kv / D^2K_h$

Two sets of curves are used. Type-A curves are good for early drawdown data when water is released from elastic storage. Type-B curves are good for later drawdown data when the effects of gravity drainage become more significant. The two portions of the type curves are illustrated in the following figure:



The value of the horizontal hydraulic conductivity can be determined from:

$$K_h = \frac{T}{D}$$

The value of the vertical hydraulic conductivity can be determined from:

$$K_v = \frac{\beta D^2 K_h}{r^2}$$

The Neuman solution assumes the following:

- The aquifer is unconfined and has an "apparent" infinite extent
- The aquifer is homogeneous, isotropic, and of uniform thickness over the area influenced by pumping (assumes drawdown is small compared to saturated thickness)
- The piezometric surface was horizontal prior to pumping
- The well is pumped at an average rate
- Flow is unsteady

- The well diameter is small, so well storage is negligible
- The well penetrates the entire aquifer

The data requirements for the Neuman solution are:

- Drawdown vs. time data at an observation well
- Distance from the pumping well to the observation well
- Pumping rate (constant)

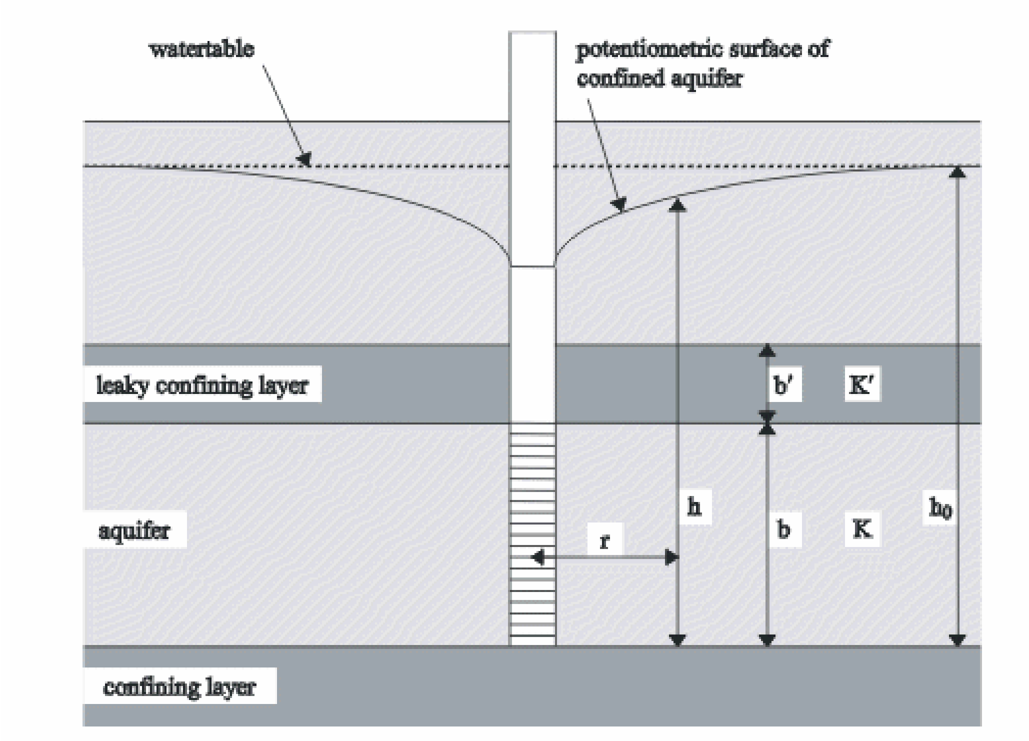
3.7 Hantush-Jacob Method (leaky, no aquitard storage)

Most confined aquifers are not totally isolated from sources of vertical recharge. Less permeable layers, either above or below the aquifer, can leak water into the aquifer under pumping conditions. Walton developed a method of solution for pumping tests (based on Hantush-Jacob, 1955) in leaky-confined aquifers with unsteady-state flow. The flow equation for a confined aquifer with leakage is:

$$\frac{\partial^2 h}{\partial r^2} + \frac{1}{r}\frac{\partial h}{\partial r} - \frac{h}{T}\frac{K'}{b'} = \frac{S}{T}\frac{\partial h}{\partial t}$$

where:

K' is the vertical hydraulic conductivity of the leaky aquitard
b' is the thickness of the leaky aquitard.



The Walton solution to the above equation is given by:

$$s = \frac{Q}{4\pi T}\int_u^\infty \frac{1}{y}\exp\left(-y - \frac{r^2}{B^2 y}\right)dy$$

where:

$$s = \frac{Q}{4\pi T} W\left(u, \frac{r}{B}\right) \qquad u = \frac{r^2 S}{4\pi T}$$

where W(u,r/B) is known as the Leaky well function (Freeze and Cherry, 1979 and Hall, 1996). The well function is a function of both u and r/B, which are defined as:

$$u = \frac{r^2 S}{4\pi T} \qquad \frac{r}{B} = r\sqrt{\frac{K'}{Kbb'}}$$

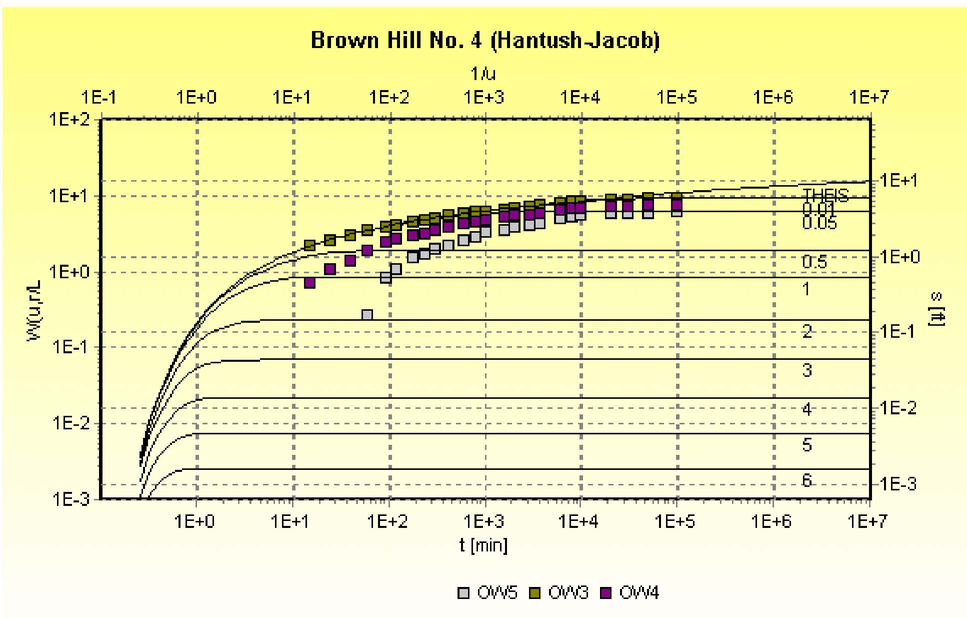
The leakage factor, B, and the hydraulic resistance, c, are defined as:

$$B = \sqrt{Kbc} \qquad c = \frac{b'}{K'}$$

If K' = 0 (non-leaky aquitard) then r/B = 0 and the solution reduces to the Theis solution for a confined system.

A log/log scale plot of the relationship W(u,r/B) along the Y axis versus 1/u along the X axis is used as the type curve as with the Theis method. The field measurements are plotted as t along the X axis and s along the Y axis. The data analysis is done by curve matching.

An example of a Hantush-Jacob analysis graph has been included below:



The Hantush-Jacob solution has the following assumptions:

- The aquifer is leaky and has an "apparent" infinite extent
- The aquifer and the confining layer are homogeneous, isotropic, and of uniform thickness over the area influenced by pumping
- The piezometric surface was horizontal prior to pumping
- The well is pumped at a constant rate
- The well is fully penetrating
- Water removed from storage is discharged instantaneously with decline in head

- The well diameter is small, so well storage is negligible
- Leakage through the confining layer is vertical and proportional to the drawdown
- The head in any un-pumped aquifer(s) remains constant
- Storage in the confining layer is negligible
- Flow is unsteady

The data requirements for the Hantush-Jacob (no aquitard storage) solution are:

- Drawdown vs. time data at an observation well
- Distance from the pumping well to the observation well
- Pumping rate (constant)

3.8 Specific Capacity

A specific capacity test is commonly used to evaluate over time the productivity of a well, which is expressed in terms of its specific capacity, Cs. Specific capacity is defined as Cs = Q/Dhw where Q is the pumping rate and Dhw is the drawdown in the well due to both aquifer drawdown and well loss. Well loss is created by the turbulent flow of water through the well screen and into the pump intake. The results of testing are useful to track changes in well yield over time, or to compare yields between different wells.

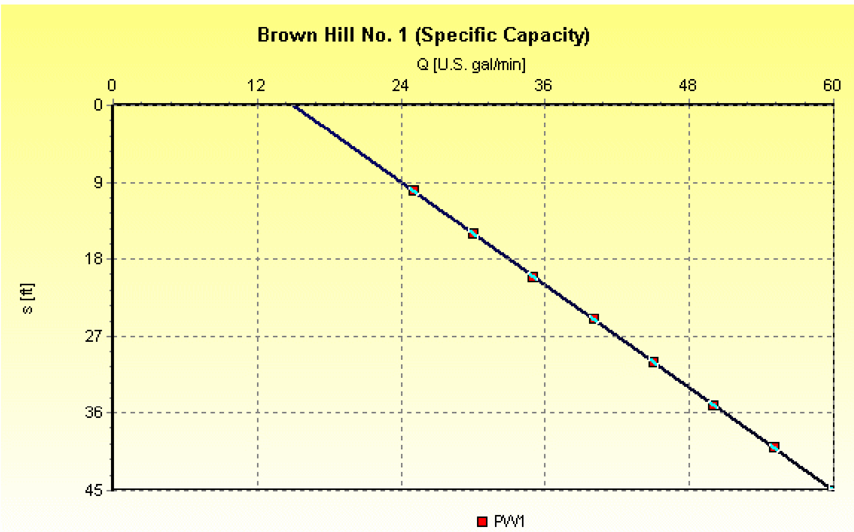
Specific capacity is estimated by plotting discharge on a linear X axis and drawdown on a linear Y axis, and measuring the slope of the straight line fit.

An example of a Specific Capacity test has been included below:

The Specify Capacity test assumes the following:

- The well is pumped at a constant rate long enough to establish an equilibrium drawdown
- Drawdown within the well is a combination of the decrease in hydraulic head (pressure) within the aquifer, and a pressure loss due to turbulent flow within the well

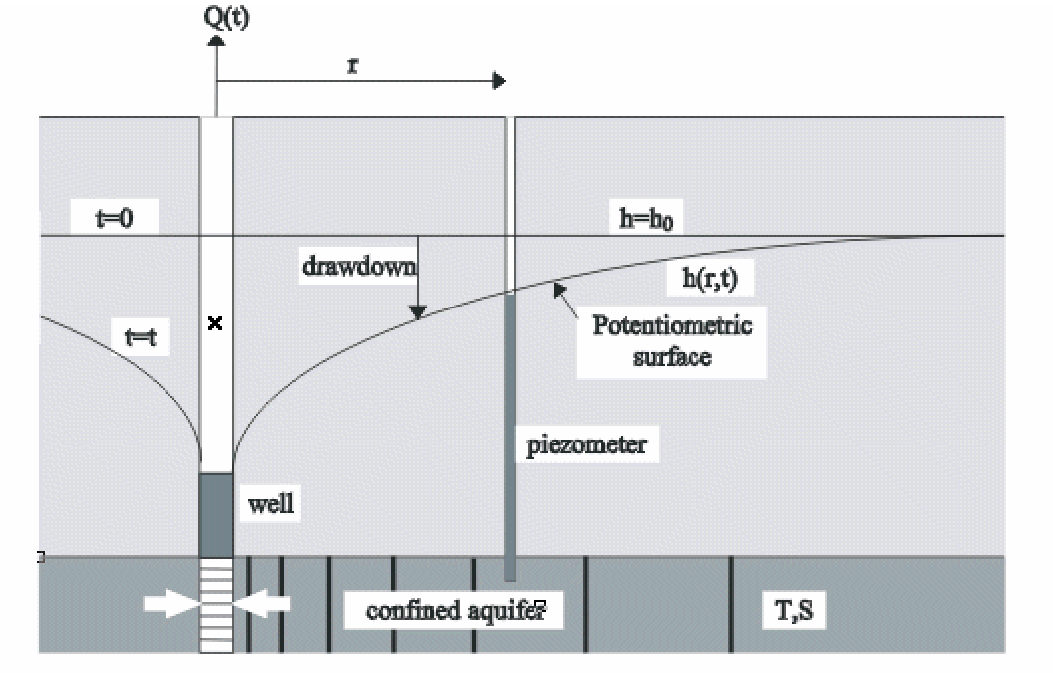
The data requirements for the Specific Capacity test are:



Drawdown vs. pumping rate data for the pumping well

3.9 Cooper-Jacob Steptest (variable discharge rate)

AquiferTest provides the ability to use water level vs. time data which were recorded during a variable rate or intermittent pumping test to determine the transmissivity and storativity. A time transformation, similar to that published by Birsoy and Summers (1980), is used to provide a congruent data set. This solution is appropriate for the conditions shown in the following figure.



The principle of superposition is applied to Cooper-Jacob's expression for non-equilibrium flow in a confined aquifer to obtain an expression for the drawdown at time t of the i th pumping period of a variable rate pumping test, as follows:

$$\frac{s}{Q_n} = \frac{2.3}{4\pi T}\log\left[\left(\frac{2.25T}{r^2 S}\right)\beta_{t(n)}\left(t-t_n\right)\right]$$

where, in general:

$$\beta_{t(n)} = \Pi_{i=1}^{n-1}\left(\frac{t-t_i}{t-t_i'}\right)^{\frac{Q_i}{Q_n}}$$

where:

- t_i = start time for the i th pumping period
- $t\text{-}t_i$ = time since the start of the i th pumping period
- t'_i = end time for the i th pumping period
- $t\text{-}t'_i$ = time since the end of the i th pumping period
- Q_i = constant pumping rate for the i th pumping period
- Q_n = sum of the intermittent pumping rates
- $\beta_{t(n)}(t\text{-}t_n)$ = adjusted time

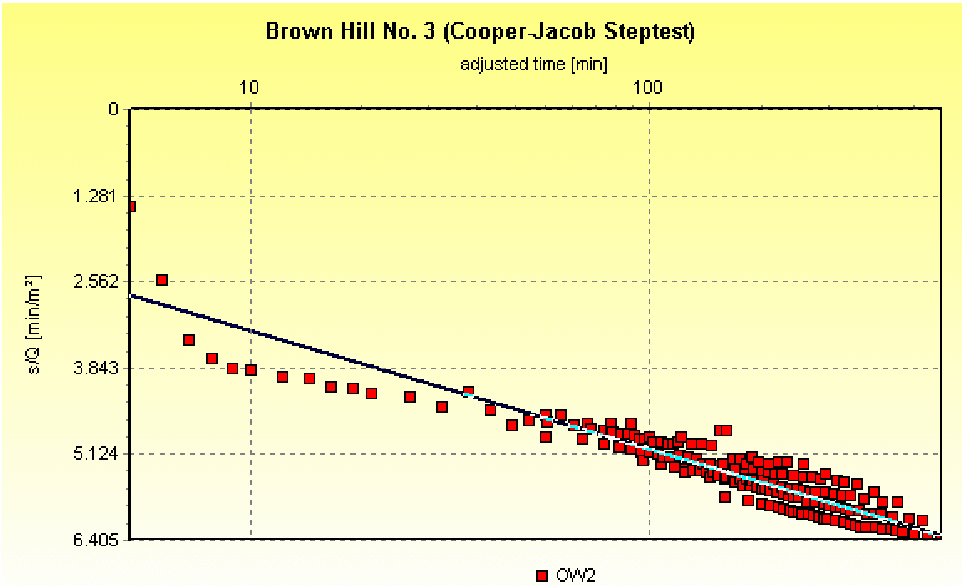
In the specific case where there is continuous pumping, but with a variable rate, the 'adjusted time' becomes:

$$\beta_{t(n)}(t - t_n) = \Pi_{i=1}^{n} (t - t_i)^{\frac{Q_i}{Q_n}}$$

In the case of pulse pumping, where the pumping rate is always the same but the pump is turned off intermittently, the 'adjusted time' becomes:

$$\beta_{t(n)}(t - t_n) = \Pi_{i=1}^{n-1} \left(\frac{t_i}{t_i^{'}} \right) t_n$$

An example of a Cooper-Jacob Steptest analysis graph has been included below:



The Cooper-Jacob Steptest solution assumes the following:

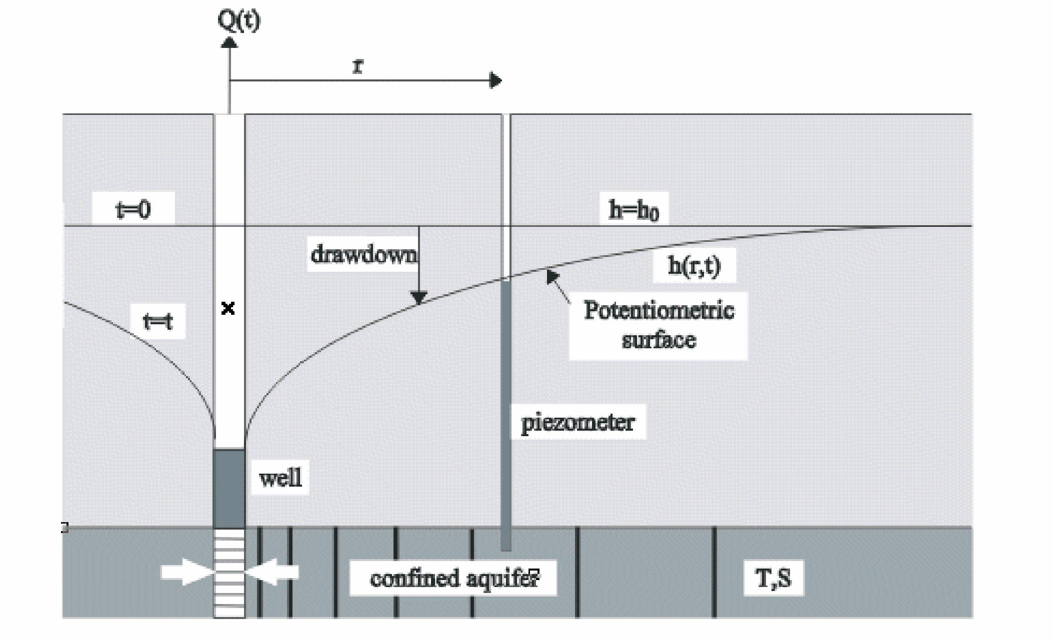
- The aquifer is confined and has an "apparent" infinite extent
- The aquifer is homogeneous, isotropic, and of uniform thickness over the area influenced by pumping
- The piezometric surface was horizontal prior to pumping
- The well is pumped step-wise or intermittently at a variable rate, or it is pumped intermittently at a constant discharge rate
- The well is fully penetrating
- Water removed from storage is discharged instantaneously with decline in head
- The well diameter is small, so well storage is negligible
- Flow toward the well is at an unsteady state
- The values of u (with the 'adjusted time') are small (rule of thumb $u < 0.01$)

The data requirements for the Cooper-Jacob Steptest solution are:

- Drawdown vs. time data at an observation well
- Distance from the pumping well to the observation well
- Variable discharge rate

3.10 Theis Steptest (Birsoy and Summers, confined)

Theis (1935) solved the unsteady-state groundwater flow equation, as noted previously. For the variable rate pumping case, you can use water level vs. time data which were recorded during a variable rate or intermittent pumping test to determinate the transmissivity and storativity. A time transformation, similar to that published by Birsoy and Summers (1980), is used to provide a congruent data set. This solution is appropriate for the conditions shown in the following figure.



The principle of superposition is applied to Theis's expression for non-equilibrium flow in a confined aquifer to obtain an expression for the drawdown at time t of the i th pumping period of a variable rate pumping test, as follows:

$$\frac{s(r,t)}{Q_n} = \frac{1}{4\pi T} \int_u^{\infty} \frac{e^{-u}\,du}{u}$$

where, in general

$$u = \frac{r^2 S}{4\,T\beta_{t(n)}\left(t-t_n\right)} = W(u)$$

$$\beta_{t(n)} = \Pi_{i=1}^{n-1}\left(\frac{t-t_i}{t-t_i{}'}\right)^{\frac{Q_i}{Q_n}}$$

t_i = start time for the i th pumping period
$t-t_i$ = time since the start of the i th pumping period
t'_i = end time for the i th pumping period
$t-t'_i$ = time since the end of the i th pumping period
Q_i = constant pumping rate for the i th pumping period
Q_n = sum of the intermittent pumping rates
$\beta_{t(n)}(t-t_n)$ = adjusted time

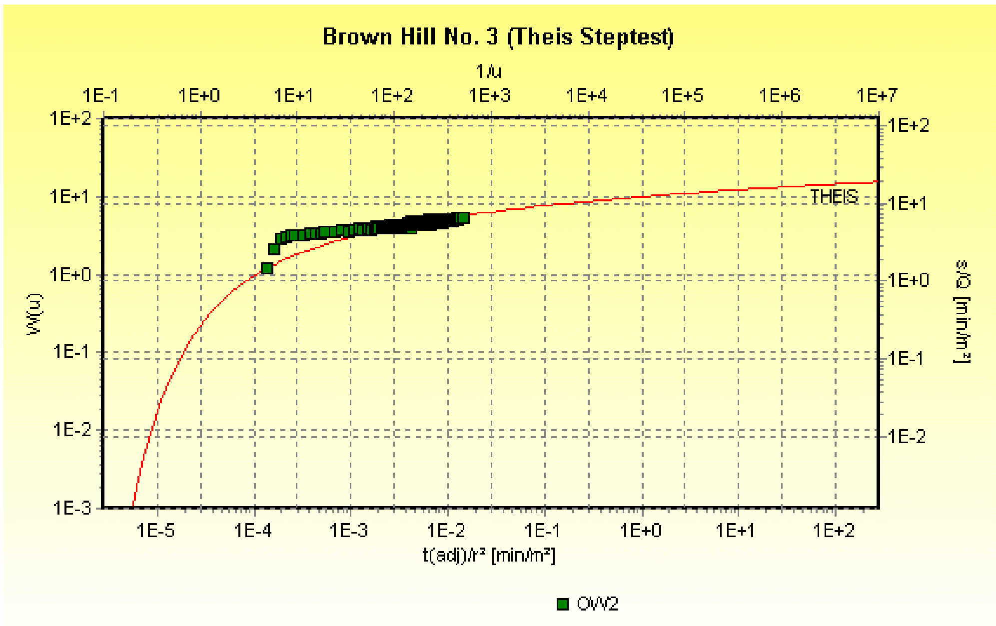
In the specific case where there is continuous pumping, but with a variable rate, the 'adjusted time' becomes:

$$\beta_{t(n)}(t - t_n) = \Pi_{i=1}^{n} (t - t_i)^{\frac{Q_i}{Q_n}}$$

In the case of pulse pumping, where the pumping rate is always the same but the pump is turned off intermittently, the 'adjusted time' becomes:

$$\beta_{t(n)}(t - t_n) = \Pi_{i=1}^{n-1} \left(\frac{t_i}{t_i'} \right) t_n$$

An example of a Theis Steptest (Birsoy and Summers) analysis graph has been included below:



The Theis Steptest (Birsoy and Summers) solution assumes the following:

- The aquifer is confined and has an "apparent" infinite extent
- The aquifer is homogeneous, isotropic, and of uniform thickness over the area influenced by pumping
- The piezometric surface was horizontal prior to pumping
- The well is pumped at a variable rate
- The well is fully penetrating
- Water removed from storage is discharged instantaneously with decline in head
- The well diameter is small, so well storage is negligible

The data necessary for the Theis Steptest (Birsoy and Summers) are:

- Water level vs. time data for an observation well a finite distance from a pumping well
- Variable rate discharge vs. time data

3.11 Jacob Correction for Unconfined Conditions

Jacob (1944) proposed the following correction to drawdown, to approximate confined conditions

$$s_{cor} = s - (s^2/2D)$$

where:

s_{cor} = the corrected drawdown

s = measured drawdown

D = original saturated aquifer thickness

This correction lets you use the Theis, Cooper-Jacob, Theis Recovery, and Steptest solutions for the analysis of pumping test data recorded for an unconfined aquifer.

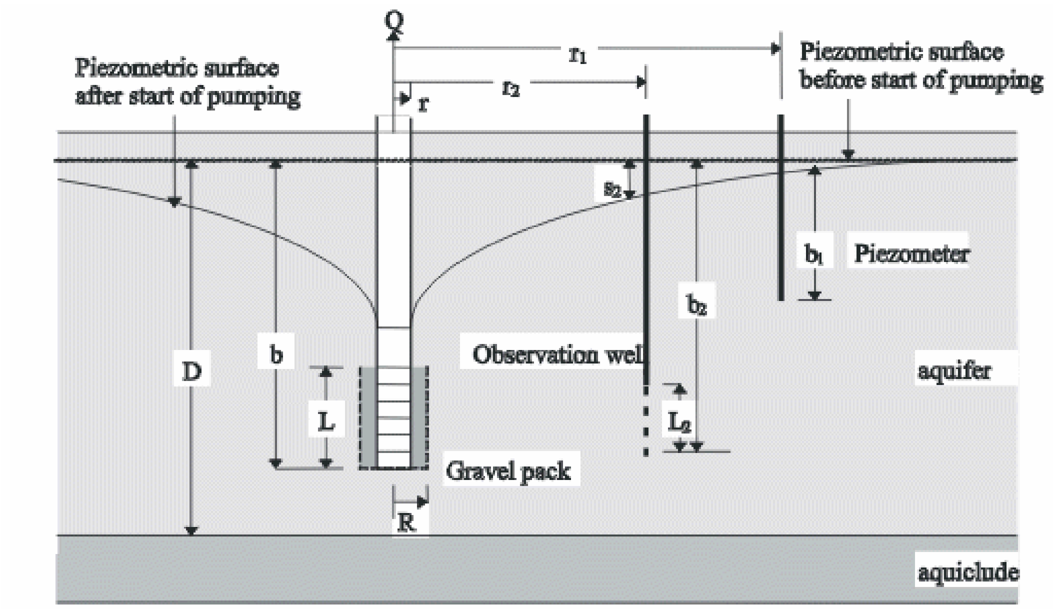
3.12 Moench Method

(partially penetrating well in confined or unconfined aquifers)

The Moench solution (Moench, 1993), is an extension of the Neuman solution (Neuman, 1972) for drawdown in a homogeneous, anisotropic, confined or unconfined aquifer, with either a fully or partially penetrating pumping well and multiple observation wells.

The Moench solution also permits analysis of delayed yield effects (as described in "Neuman Method (unconfined)" on page 24) in unconfined aquifers. The delayed yield is approximated by Boulton's convolution integral (Nwankwor et al., 1992, Boulton, 1954, 1963).

The solution is appropriate for the conditions shown in the following figure, where the aquifer can be confined or unconfined and D is the thickness of the saturated zone.



The general equation developed by Moench for dimensionless drawdown, h D, in an unconfined aquifer is

$$h_D(\gamma, \beta, \sigma, z_D, t_D) = h_{DT} + \Delta h_{DH} + \Delta h_{DN}$$

where:

$$h_d = \frac{4\pi KD}{Q}(h_0 - h_f)$$

$\gamma = \alpha\ b\ S\ y/K\ z$

$\beta = (r^2K_v)/(D^2K_h)$

$s = S/S_y$

$z_D = b/D$

$t_D = Tt/r^2S$

γ is a dimensionless fitting parameter that incorporates the effects of delayed drawdown, and α is an empirical constant. For instantaneous drawdown g is approximated at 1x10 9.

z_D is the dimensionless depth of the piezometer.

t_D is the dimensionless time.

$h_{D}T$ is the Theis (1935) solution for a well in a confined aquifer.

Δh_{DH} is the deviation from the Theis solution due to effects of partial penetration in a confined aquifer (Hantush component).

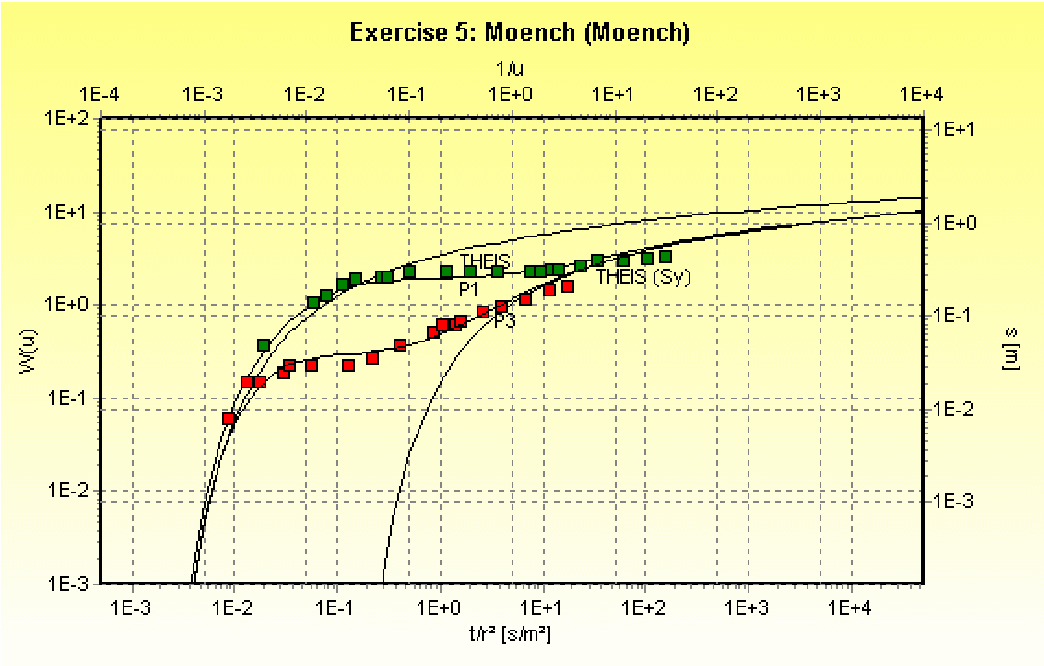
Δh_{DN} is the deviation from the Theis solution due to effects of the free surface (Neuman component).

For confined aquifers, the Moench (1993) solution uses the first two components of the above equation to account for the confined aquifer and partial penetration. Thus, for confined conditions with fully penetrating pumping and observation wells, the solution is the same as the Theis solution.

If the aquifer is unconfined and both the pumping well and the observation well are fully penetrating, the solution is the same as the Neuman solution.

The Moench solution uses dimensionless parameters for the type curves with log(t dy) plotted on the X axis and log(h d) plotted on the Y axis for the type curves. The data scales are log(t/r 2) on the X axis and log(s) on the Y axis.

An example of a Moench analysis graph has been included below:



The Moench Partially Penetrating solution assumes the following:

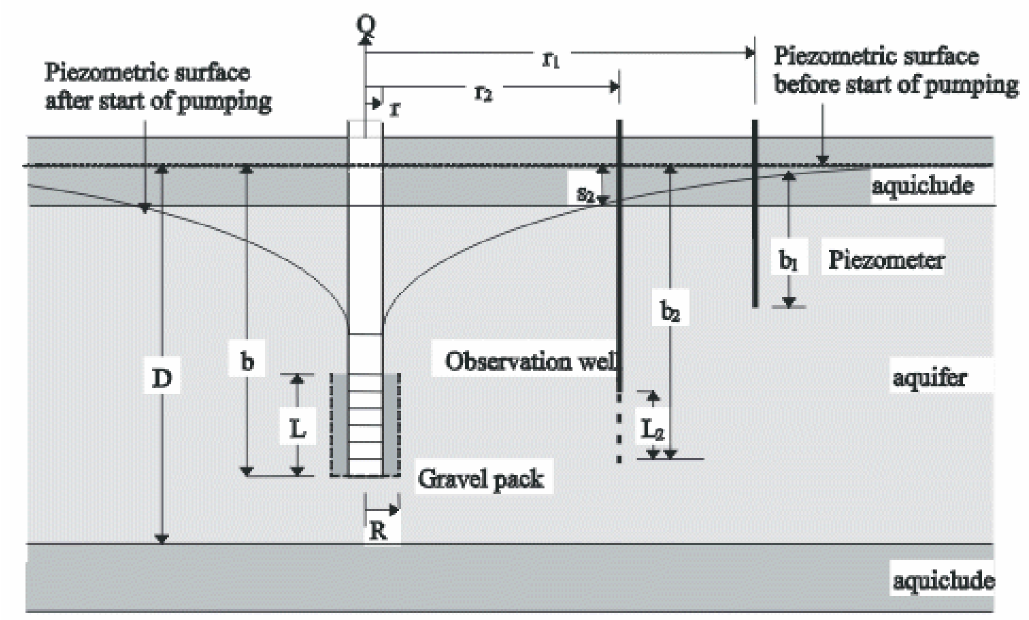
- The aquifer has an "apparent" infinite extent
- The aquifer is homogeneous and isotropic
- Drawdown is small compared to saturated thickness
- The piezometric surface was horizontal prior to pumping
- The well is pumped at an average rate
- The well diameter is small, so well storage is negligible

The Moench Partially Penetrating solution requires the following data:

- Drawdown vs. time data at one or more observation wells
- The distances from the pumping well to the observation wells
- The extraction rate at the pumping well
- The pumping well dimensions

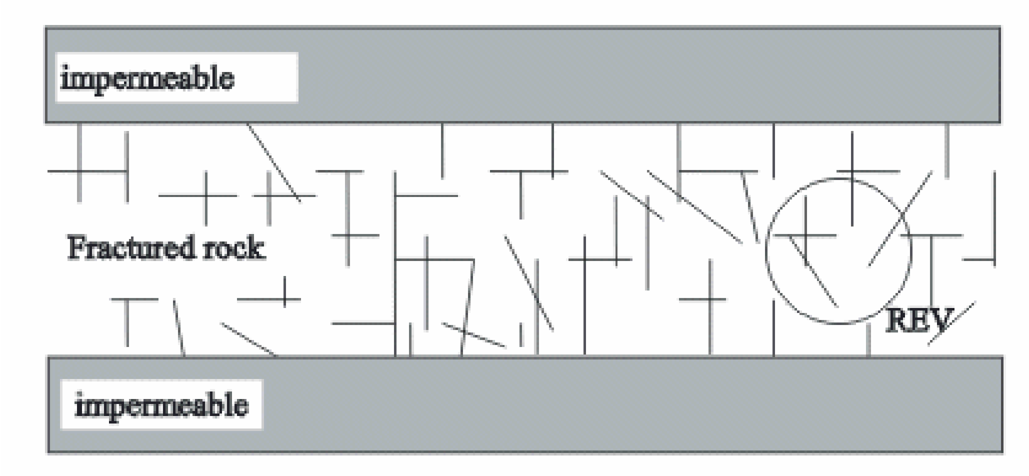
3.13 Fracture Flow (Moench)

Groundwater flow in a fractured medium can be extremely complex, therefore conventional pumping test solutions methods that require porous flow conditions are not applicable. One approach to analyze fracture flow conditions is to divide the aquifer into blocks and assume the blocks are impermeable, whereby the system can be modeled as an equivalent single-porosity porous medium. However, in the dual-porosity approach, groundwater flow is modeled as a series of porous low-permeability blocks separated by hydraulically connected fractures of high permeability. In this case, block-to-fracture flow can be either pseudo-steady-state or transient. The solutions are appropriate for the conditions shown in the following figure, where the aquifer is confined and D is the thickness of the saturated zone.



If the system is treated as an equivalent porous medium, there is no flow between blocks and fractures. Groundwater travels only in the fractures around the blocks. In this sense, the porosity is the ratio of the volume of voids to the total volume.

Where there is flow from the blocks to the fractures, the fractured rock mass is assumed to consist of two interacting and overlapping continua: a continuum of low-permeability primary porosity blocks, and a continuum of high permeability, secondary porosity fissures.



There are two double porosity models used in AquiferTest, which have been widely accepted in the literature. These are the pseudo-steady-state flow (Warren and Root, 1963) and the transient block-to-fracture flow (for example, Kazemi, 1969).

The pseudo-steady-state flow assumes that the hydraulic head distribution within the blocks is undefined. It also assumes that the fractures and blocks within a representative elemental volume (REV) each possess different average hydraulic heads. The magnitude of the induced flow is assumed to be proportional to the hydraulic head difference (Moench, 1984).

The theory for pseudo-steady-state flow is as follows (Moench, 1984, 1988):

$$h_d = \frac{4\pi KD}{Q}\left(h_0 - h_f\right) \qquad t_d = \frac{Kt}{S_s r^2}$$

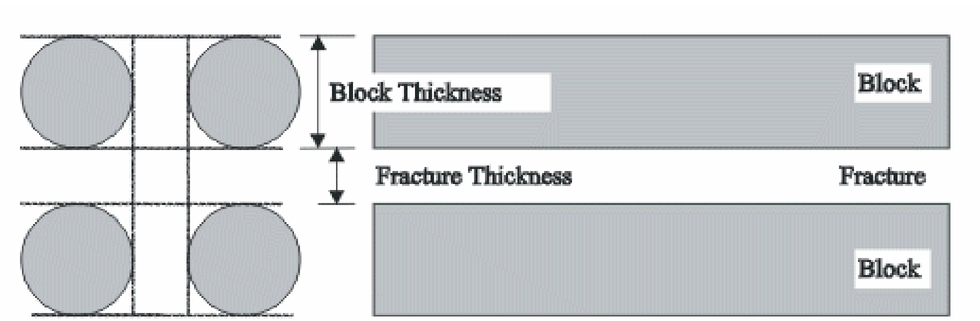
where h_d is the dimensionless drawdown, and t d is the dimensionless time.

The initial discharge from models using the pseudo-steady-state flow solution with no well-bore storage is derived primarily from storage in the fissures. Later, the fluid will be derived primarily from storage in the blocks. At early and late times, the drawdown should follow the familiar Theis curves.

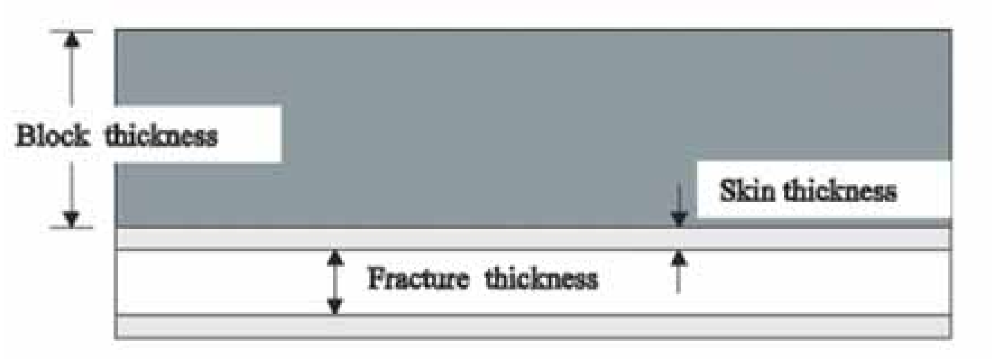
For transient block to fissure flow, the block hydraulic head distribution (within an REV) varies both temporally and spatially (perpendicular to the fracture block interface). The initial solution for slab-shaped blocks was modified by Moench (1984) to support sphere-shaped blocks. Well test data support both the pseudo-steady-state and the transient block-to-fracture flow solutions.

For transient block-to-fracture flow, the fractured rock mass is idealized as alternating layers (slabs or spheres) of blocks and fissures.

Sphere-shaped Slab-shaped



Moench (1984) uses the existence of a fracture skin to explain why well test data support both the pseudo-steady-state and transient block-to-fracture flow methods. The fracture skin is a thin skin of low permeability material deposited on the surface of the blocks, which impedes the free exchange of fluid between the blocks and the fissures.



If the fracture skin is sufficiently impermeable, most of the change in hydraulic head between the block and the fracture occurs across the fracture skin and the transient block-to-fracture flow solution reduces to the pseudo-steady-state flow solution.

The fracture skin delays the flow contributions from the blocks, which results in pressure responses similar to those predicted under the assumption of pseudo-steady state flow as follows:

$$h_{wD} = \frac{4\pi KH}{Q_T}\left(h_i - h_w\right) \qquad h'_D = \frac{4\pi KH}{Q_T}\left(h_i - h'\right)$$

where h_{wD} is the dimensionless head in the pumping well, and h'_D is the dimensionless head in the observation wells.

With both the pseudo-steady-state and transient block-to-fracture flow solutions, the type curves will move upward as the ratio of block hydraulic conductivity to fracture hydraulic conductivity is reduced, since water is drained from the blocks faster.

With the fracture flow analysis, you can also plot type curves for the pumping wells. However, for pumping wells it may be necessary to consider the effects of well bore storage and well bore skin. If the well bore skin and the well bore storage are zero, the solution is the same as the Warren and Root method (1963). The equations for well bore storage are as follows:

$$W_D = \frac{C}{2\pi r^2 S}$$

where:

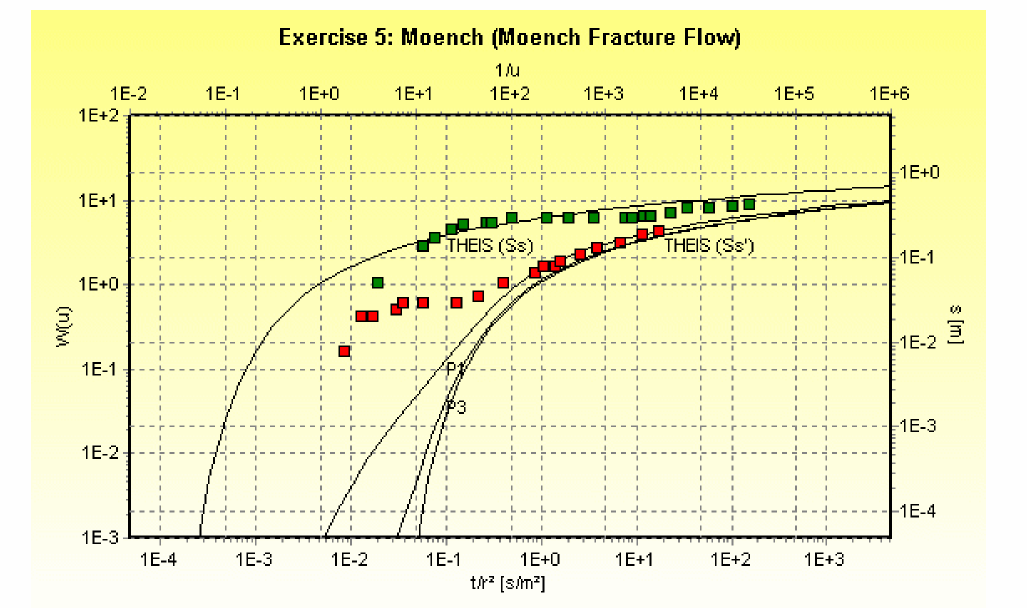
$C=\pi R^2$ (for changing liquid levels) or

$C=V_w \rho_w g C_{obs}$

where V_w is volume of liquid in the pressurized section, r_w is the density, g is the gravitational constant, C_{obs} is the observed compressibility of the combined fluid-well system, and S is the calculated storativity.

This solution, however, is iterative. If you move your data set to fit the curve, your storativity will change which in turn alters your well bore storage.

An example of a Moench Fracture Flow analysis graph has been included below:



The Moench solution for fracture flow assumes the following:

- The aquifer is anisotropic and homogeneous
- The aquifer is infinite in horizontal extent
- The aquifer is of constant thickness
- The aquifer is confined above and below by impermeable layers
- Darcy's law is valid for the flow in the fissures and blocks
- Water enters the pumped well only through the fractures
- Observation piezometers reflect the hydraulic head of the fractures in the REV
- Flow in the block is perpendicular to the block-fracture interface

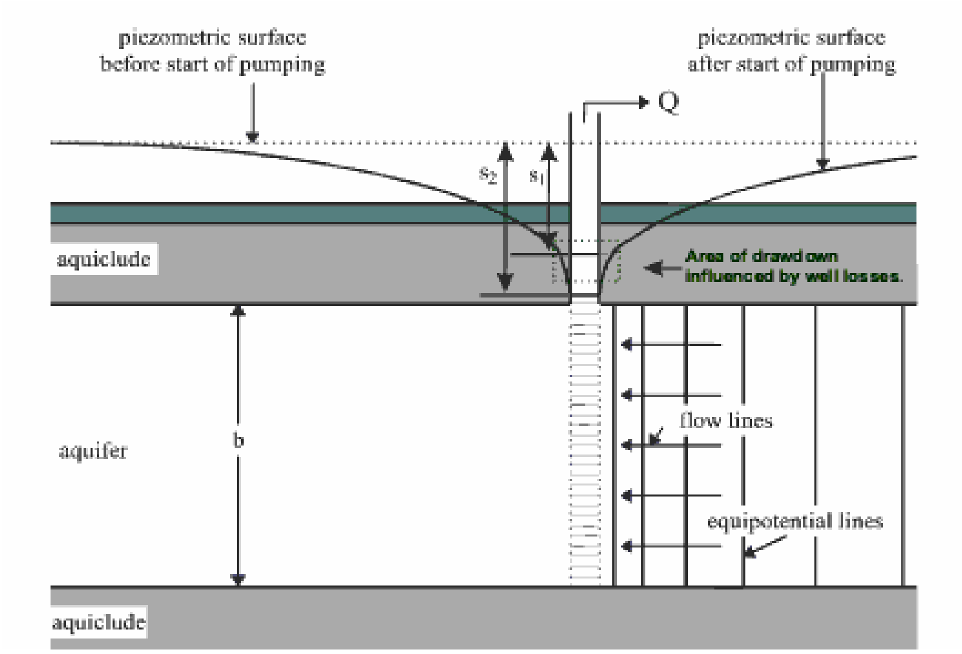
The data necessary for the Moench solution of fracture flow are:

- Water level vs. time data at one or more observation wells
- The distances from the pumping well to the observation wells
- The extraction rate at the pumping well
- The pumping well dimensions

3.14 Hantush-Bierschenk Well Loss Solution

The Hantush-Bierschenk Well Loss solution is used to analyze the results of a variable rate "step test" pumping test to determine both the linear and non-linear well loss coefficients B and C. These coefficients can be used to predict an estimate of the real water level drawdown inside a pumping well in response to pumping. Solution methods such as Theis (1935) permit an estimate of the theoretical drawdown inside a pumping well in response to pumping, but do not account for linear and non-linear well losses which result in an increase in drawdown inside the well.

The solution is appropriate for the conditions shown in the following figure, where the aquifer is confined and b is the thickness of the saturated zone.



The figure above illustrates a comparison between the theoretical drawdown in a well (S1) and the actual drawdown in the well (S2) which includes the drawdown components inherent in S1 but also includes additional drawdown from both the linear and non-linear well loss components.

The general equation for calculating drawdown inside a pumping well that includes well losses is written as:

$$s_w = BQ + CQ^p$$

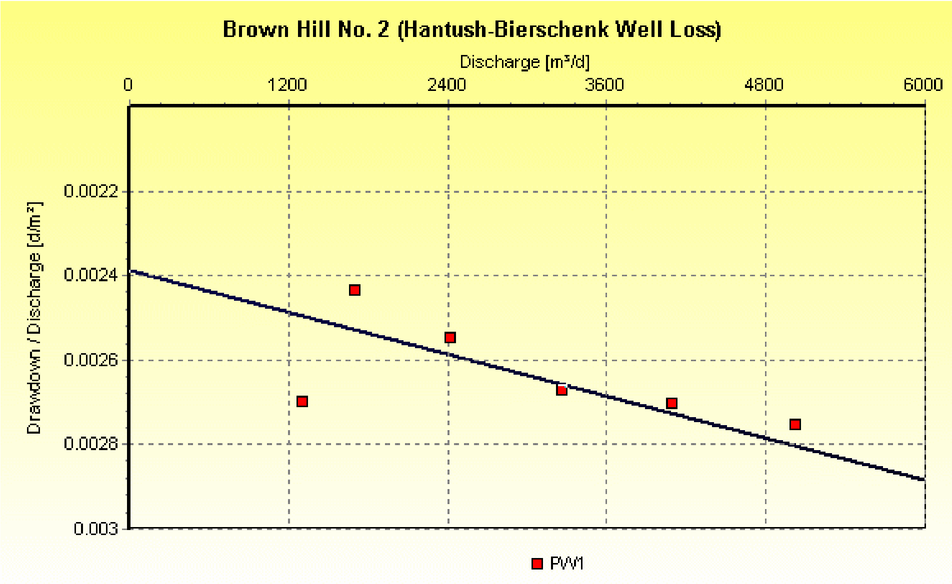
where,

s_w = drawdown inside the well= linear well-loss coefficient= non-linear well-loss coefficient= pumping rate= non-linear well loss fitting coefficient

p typically varies between 1.5 and 3.5 depending on the value of Q; Jacob proposed a value of p = 2 which is still widely used today.

AquiferTest calculates a value for the well loss coefficients B and C which you can use in the equation shown above to estimate the expected drawdown inside your pumping well for any realistic discharge Q at a certain time t (B is time dependent). You can then use the relationship between drawdown and discharge to choose, empirically, an optimum yield for the well, or to obtain information on the condition or efficiency of the well.

An example of a Hantush-Bierschenk Well Loss analysis graph has been included below:



The Hantush-Bierschenk Well Loss solution assumes the following:

- The aquifer is confined, leaky, or unconfined
- The aquifer has an apparent infinite extent
- The aquifer is homogeneous, isotropic, and of uniform thickness over the area influenced by pumping
- The piezometric surface was horizontal prior to pumping
- The aquifer is pumped step-wise at increased discharge rates
- The well is fully penetrating
- The flow to the well is in an unsteady state

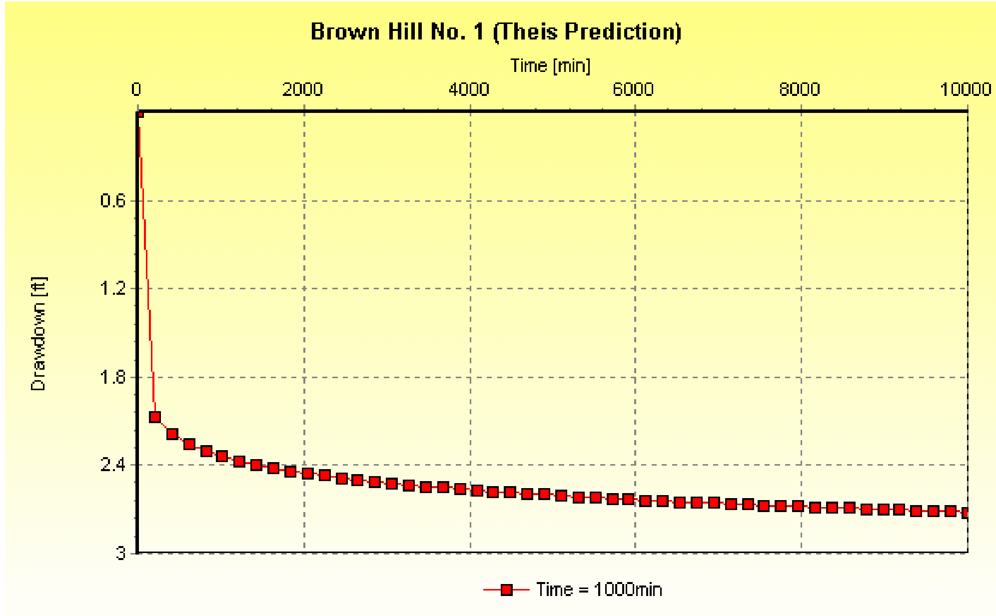
The data requirements for the Hantush-Bierschenk Well Loss solution are:

- Time-drawdown data from the pumping well
- Time-discharge data for at least three equal duration pumping sessions

3.15 Theis Prediction (Pumping Test Planning) Solution

AquiferTest includes a "forward solution" method based on the Theis solution (confined aquifer) that can be used to gain approximate answers to commonly posed questions in the test design phase.

There are a number of details that must be considered when planning a successful pumping test. Some commonly asked questions in the test design phase are:



What discharge rate should I use to ensure that a measurable water level drawdown is recorded in the observation wells and ensure that the rate of water level drawdown is not too slow to miss the early time-drawdown data from the observation well - thus making the later calculation of storativity uncertain

How large might the drawdown cone of depression be for a given discharge rate If this cone of depression reaches other wells in the area of the test (well interference), how much additional drawdown might be experienced inside the collateral pumping well

An example of a Theis Prediction graph has been included below:

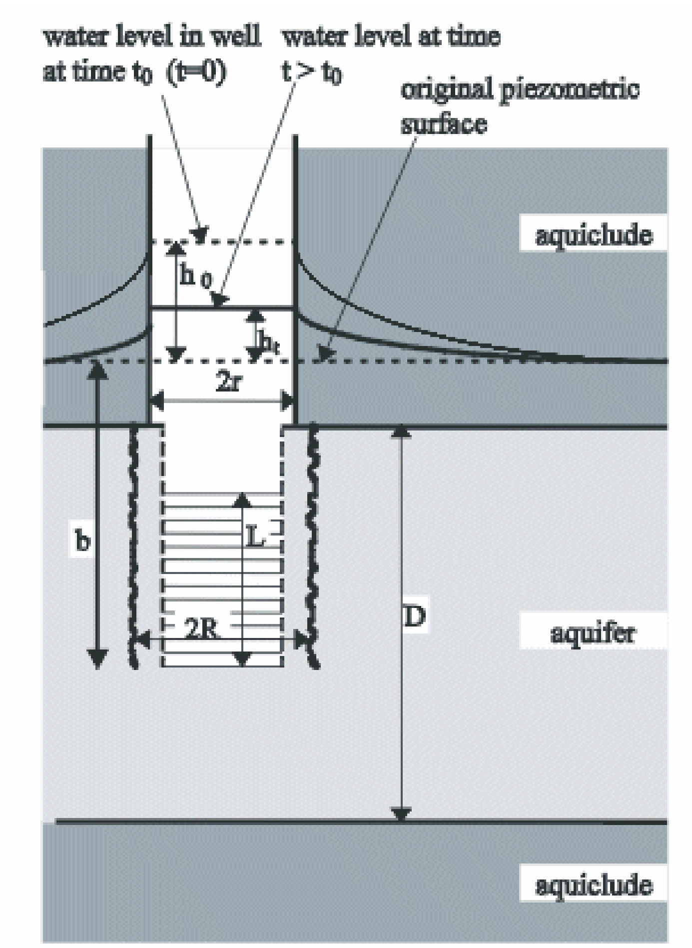
An example of how to use the "forward solution" method is given in Chapter 5 Demonstration Exercises.

3.16 Bouwer-Rice Slug Test (unconfined or leaky confined, full or partially penetrating well)

The Bouwer-Rice (1976) slug test is designed to estimate the hydraulic conductivity of an aquifer. With the slug test, the portion of the aquifer "tested" for hydraulic conductivity is small compared to a pumping test, and is limited to a cylindrical area of small radius (r) immediately around the well screen.

In a slug test, a solid "slug" is lowered into the piezometer, instantaneously raising the water level in the piezometer. The test can also be conducted in the opposite manner by instantaneously removing a "slug" or volume of water (bail test).

The solution is appropriate for the conditions shown in the figure below.



Bouwer-Rice (1976) developed an equation for hydraulic conductivity as follows:

$$K = \frac{r^2 \ln\left(\frac{R_{cont}}{R}\right)}{2L} \cdot \frac{1}{t} \cdot \ln\left(\frac{h_o}{h_t}\right)$$

where:

r = piezometer radius (or r eff if water level change is within the screened interval)

R = radius measured from centre of well to undisturbed aquifer material

R_{cont} = contributing radial distance over which the difference in head, h0, is dissipated in the aquifer

L = the length of the screen

h_t = displacement as a function of time (h t/h 0 must always be less than zero, i.e. water level must always approach the static water level as time increases)

h_0 = initial displacement

Since the contributing radius (Rcont) of the aquifer is seldom known, Bouwer-Rice developed empirical curves to account for this radius by three coefficients (A,B,C) which are all functions of the ratio of L/R. Coefficients A and B are used for partially penetrating wells, and coefficient C is used only for fully penetrating wells.

The data are plotted with time on a linear X axis and ht/ho on a logarithmic Y axis.

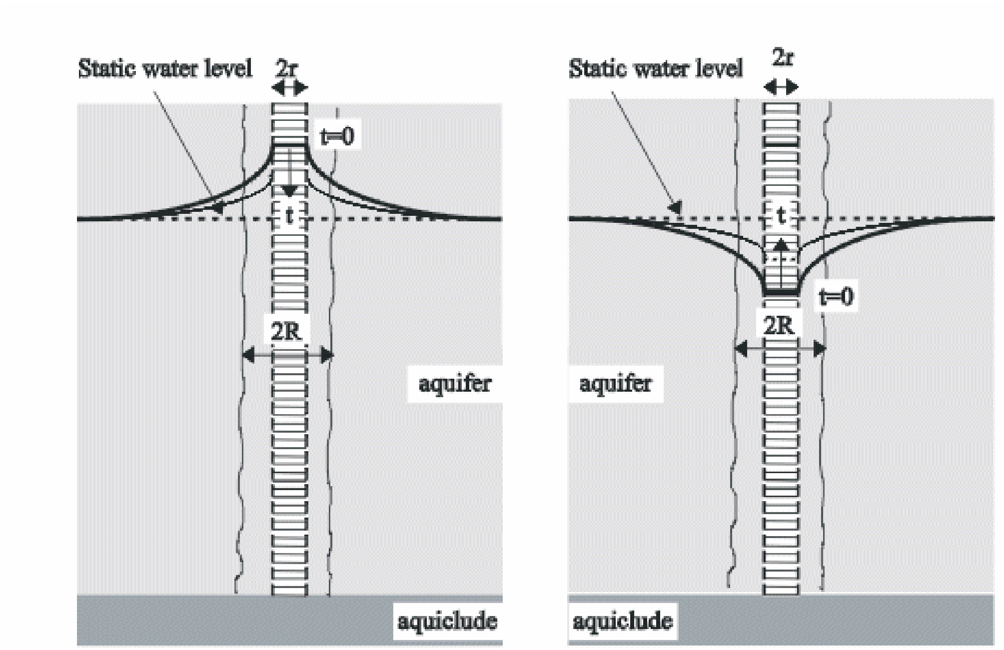
The effective piezometer radius, r, should be specified as the radius of the piezometer, unless the water level falls within the screened portion of the aquifer during the slug test.

If the water level is in the well screen, the effective radius may be calculated as follows:

$$r_{eff} = \left[r^2(1-n) + nR^2\right]^{1/2}$$

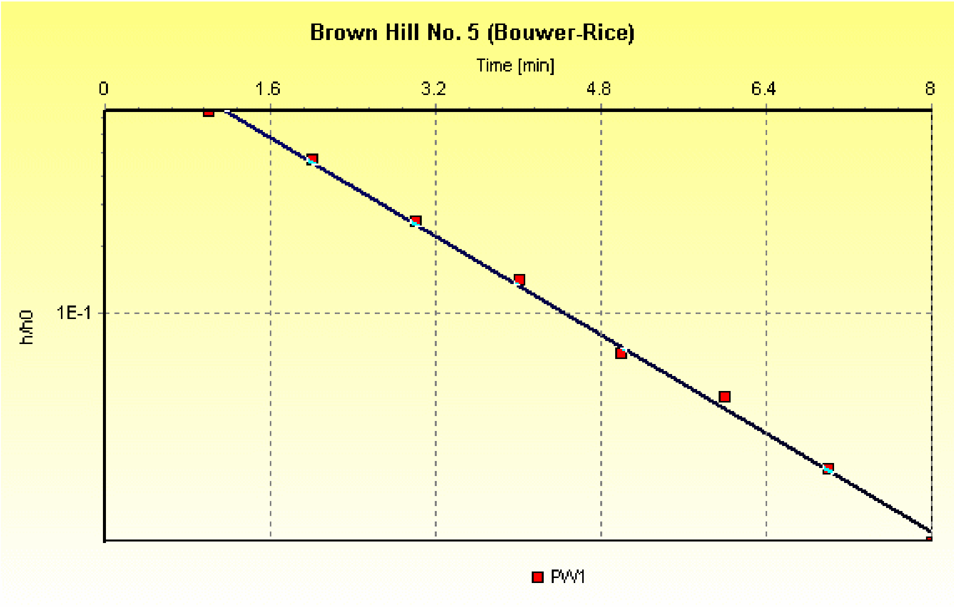
where n is the porosity of the gravel pack around the well screen.

Slug Test Bail Test



In cases where the water level drops within the screened interval, the plot of h/h0 vs. t will often have an initial slope and a shallower slope at later time. In this case, the fit should be obtained for the second straight line portion (Bouwer, 1989).

An example of a Bouwer-Rice analysis graph has been included below:



The Bouwer-Rice solution assumes the following:

- Unconfined or leaky-confined aquifer (with vertical drainage from above) of "apparently" infinite extent
- Homogeneous, isotropic aquifer of uniform thickness
- Water table is horizontal prior to the test
- Instantaneous change in head at start of test
- Inertia of water column and non-linear well losses are negligible
- Fully or partially penetrating well
- The well storage is not negligible, thus it is taken into account.
- The flow to the well is in a steady state
- There is no flow above the water table

The data requirements for the Bouwer-Rice solution are:

- Drawdown / recovery vs. time data at a pumping well
- Observations beginning from time zero onward (the value recorded at t=0 is used as the initial displacement value, H 0, by AquiferTest and thus it must be a non-zero value)

3.17 Hvorslev Slug Test

(confined or unconfined aquifer, fully or partially penetrating well)

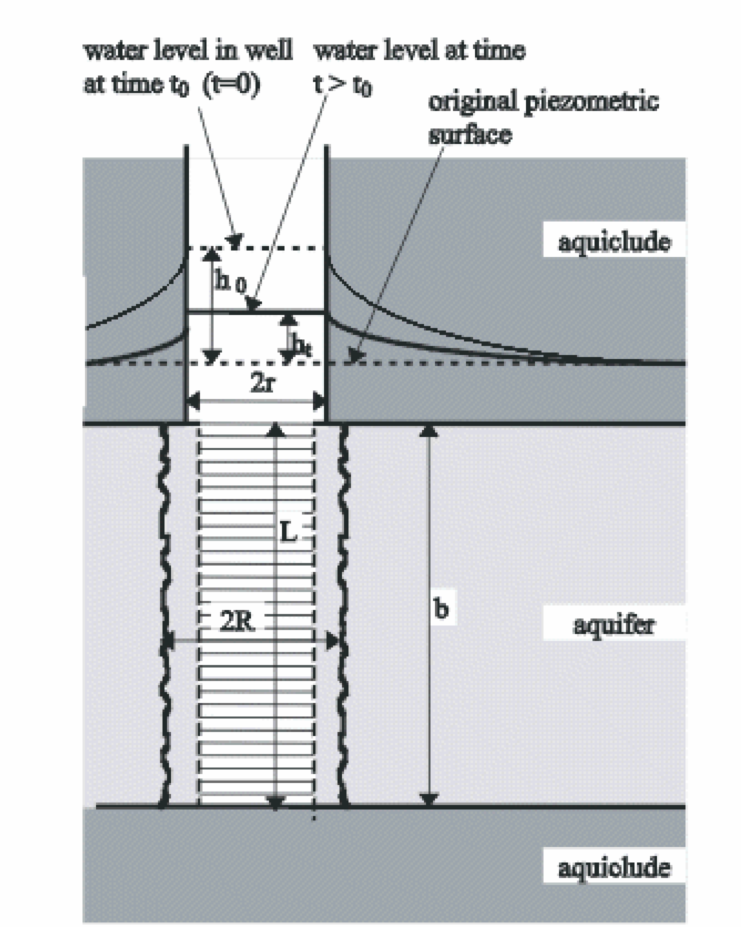
The Hvorslev (1951) slug test is designed to estimate the hydraulic conductivity of an aquifer. With the slug test, the portion of the aquifer "sampled" for hydraulic conductivity is small compared to a pumping test, and is limited to a cylindrical area of small radius (r) immediately around the well screen.

In a slug test, a solid "slug" is lowered into the piezometer, instantaneously raising the water level in the piezometer. In a bail test, water is removed, instantaneously lowering the water level in the piezometer.

The rate of inflow or outflow, q, at the piezometer tip at any time t is proportional to K of the soil and the unrecoverable head difference:

$$q(t) = \pi r^2 \frac{dh}{dt} = FK(H - h)$$

The following figure illustrates the mechanics of a slug test:



Hvorslev defined the time lag, T L (the time required for the initial pressure change induced by the injection/extraction to dissipate, assuming a constant flow rate) as:

$$T_L = \frac{\pi r^2}{FK}$$

where:

r is the effective radius of the piezometer

F is a shape factor that depends on the dimensions of the piezometer intake (see Hvorslev (1951) for an explanation of shape factors)

K is the bulk hydraulic conductivity within the radius of influence

Substituting the time lag into the initial equation results in the following solution:

$$K = \frac{\pi r^2 \left(\ln \frac{h_t}{h_0} \right)}{FT_L}$$

where:

h_t is the displacement as a function of time

h_0 is initial displacement.

The field data are plotted with log ht / ho on the Y axis and time on the X axis. The value of TL is taken as the time which corresponds to ht/ho = 0.37, and K is determined from the equation above. Hvorslev evaluated F for the most common piezometers, where the length of the intake is greater than eight times the screen radius, and produced the following general solution for K:

$$K = \frac{r^2 \ln(L / R)}{2 L T_L}$$

where:

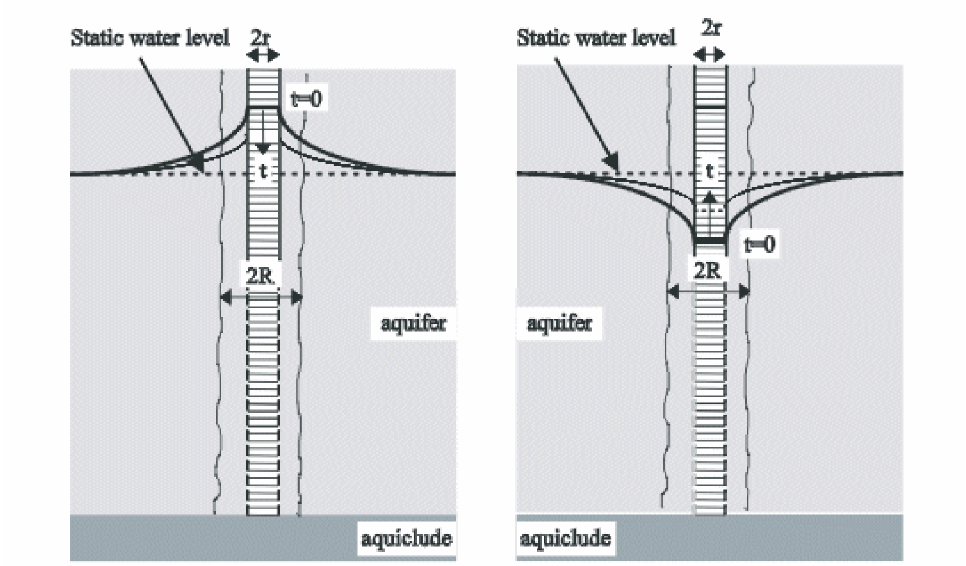
L is the screen length

R is the radius of the well including the gravel pack

T_L is the time lag when ht/h0 = 0.37

The effective piezometer radius, r, should be specified as the radius of the piezometer.

Slug Test Bail Test



In cases where the water level drops within the screened interval, the plot of ht/h0 vs. t will often have an initial slope and a smaller slope at later time (known in the literature as the "double straight line effect"). In this case, you should manually fit the line to the second straight-line portion of the data (Bouwer, 1989). It is not necessary for the line to go through (0,0).

An example of a Hvorslev analysis graph has been included below:

The Hvorslev solution assumes the following:

- Non-leaky confined aquifer of "apparently" infinite extent
- Homogeneous, isotropic aquifer of uniform thickness
- Water table is horizontal prior to the test
- Instantaneous injection/withdrawal of a volume of water results in an instantaneous change in water level
- Inertia of water column and non-linear well losses are negligible
- Fully or partially penetrating well
- The well is considered to be of an infinitesimal width
- Flow is horizontal toward or away from the well

The data requirements for the Hvorslev solution are:

- Drawdown / recovery vs. time data at a pumping well

Observations beginning from time zero onward (the observation at t=0 is taken as the initial displacement value, H 0, and thus it must be a non-zero value)

3.18 Cooper-Bredehoeft-Papadopulos Slug Test(confined, large well diameter, well storage)

The Cooper-Bredehoeft-Papadopulos (1967) slug test applies to the instantaneous injection or withdrawal of a volume of water from a large diameter well cased in a confined aquifer. If water is injected into the well, then the initial head is above the equilibrium level and the solution method predicts the buildup. On the other hand if water is withdrawn from the well casing, then the initial head is below the equilibrium level and the method calculates the drawdown. The drawdown or buildup s is given by the following equation:

$$s = \frac{2H_0}{\pi}\int_0^{\infty} \exp\left(-\frac{\beta u^2}{\alpha}\right)\left(J_0\left(\frac{ur}{r_c}\right)[u\,Y_0(u) - 2\alpha Y_1(u)] - Y_0\left(\frac{ur}{r_c}\right)[uJ_0(u) - 2\alpha J_1(u)]\right)\left(\frac{1}{\Delta(u)}\right)du$$

where

$$\Delta(u) = [uJ_0(u) - 2\alpha J_1(u)]^2 + [uY_0(u) - 2\alpha Y_1(u)]^2$$

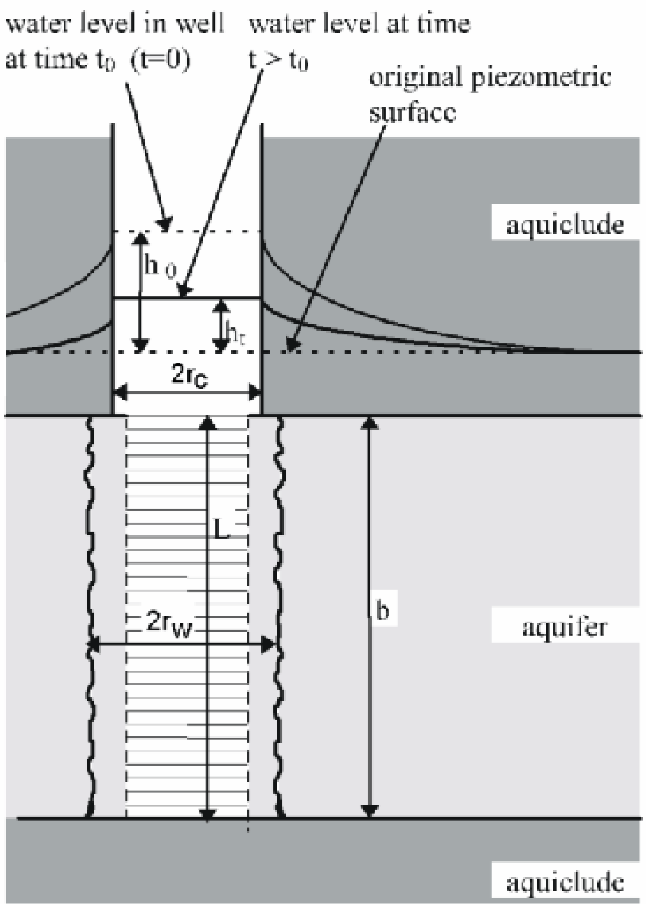
$$\alpha = (r_w^2 S)/r_c^2$$

$$\beta = (Tt)/r_c^2$$

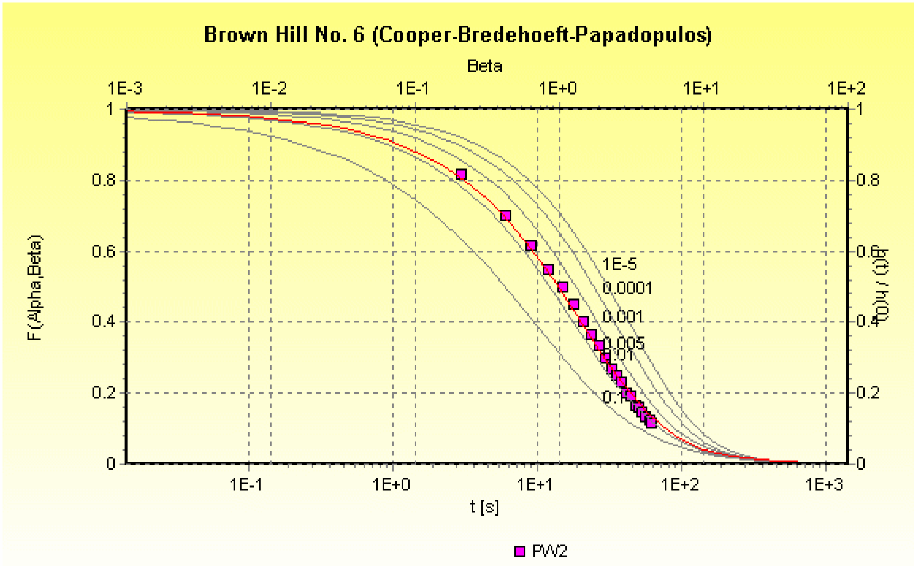
and

H_0 = initial change in head in the well casing due to the injection or withdrawal
r = radial distance from the injection well to a point on the radial cone of depression
r_c = effective radius of the well casing
r_w = effective radius of the well open interval
T = Transmissivity of the aquifer
S = Storativity of the aquifer
t = time since the injection or withdrawal
J_0 = Zero Order Bessel function of the first kind
J_1 = First Order Bessel function of the first kind
Y_0 = Zero Order Bessel function of the second kind
Y_1 = First Order Bessel function of the second kind

The following diagram illustrates the mechanics for the Cooper-Bredehoeft-Papadopulos solution method:



An example of a Cooper-Bredehoeft-Papadopulos analysis graph has been included below:



The Cooper-Bredehoeft-Papadopulos method assumes the following:

- the aquifer is isotropic, homogenous, compressible and elastic
- the layers are horizontal and extend infinitely in the radial direction
- the initial piezometric surface (before injection) is horizontal and extends infinitely in the radial direction
- the aquifer is bounded above and below by aquicludes
- Darcy's law is valid for the flow domain
- the injection well is screened over the entire saturated thickness of the aquifer
- the volume of water is injected or withdrawn instantaneously at time t = 0

The data requirements for the Cooper-Bredehoeft-Papadopulos solution are:

- Time vs. depth to water level at a pumping well
- Pumping well geometry

3.19 References

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4. Using AquiferTest

4.1 General Overview

AquiferTest is designed to automate the most common tasks that hydrogeologists and other water supply professionals typically encounter when planning and analyzing the results of an aquifer test. The program design allows you to efficiently manage all information from your aquifer test and perform more analyses in less time. For example, you need to enter information about your testing wells (e.g. X and Y coordinates, elevation, screen length, etc.) only once in AquiferTest.

Each well and related information is stored in the project database separately from imported data and test analyses. After you create a well, you can see it in a navigator (project tree) view.

When you import data or create an analysis, you specify which wells to include from the list of available wells in the project. If you decide to perform additional analyses, you can again specify from the available wells without re-creating them in AquiferTest.

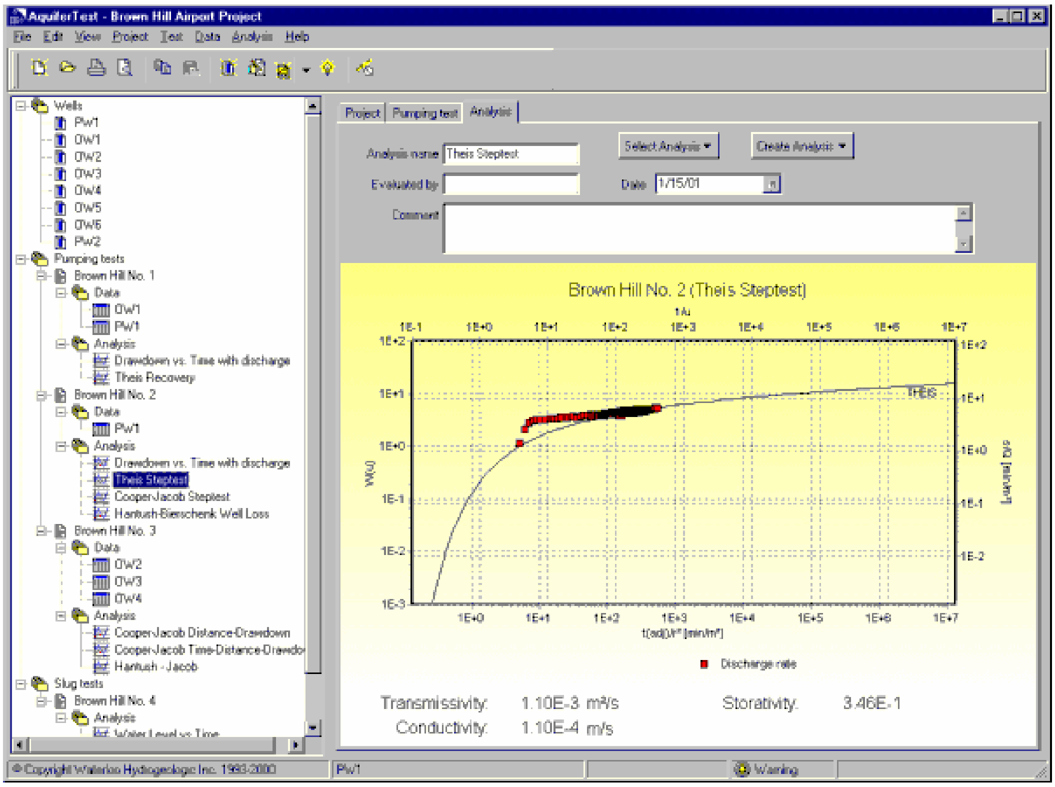
You can also change your solution method interactively while in analysis view by simply right-clicking the mouse and selecting one of the methods supplied with AquiferTest. There is no need to re-enter your data or create a new project. Your analysis graph is refreshed, and the data re-analyzed using the selected solution method. This is useful for quickly comparing the results of data analysis using slightly different solution methods. If you need solution-specific information for the re-analysis, AquiferTest prompts you for the required data.

In the following sections, the features available in AquiferTest are described in detail.

4.2 Window Layout

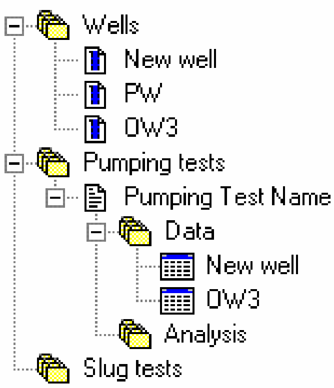
4.2.1 Window Layout

A typical AquiferTest window is shown above. The different sections of the window are described below.



4.2.2 Navigator Tree

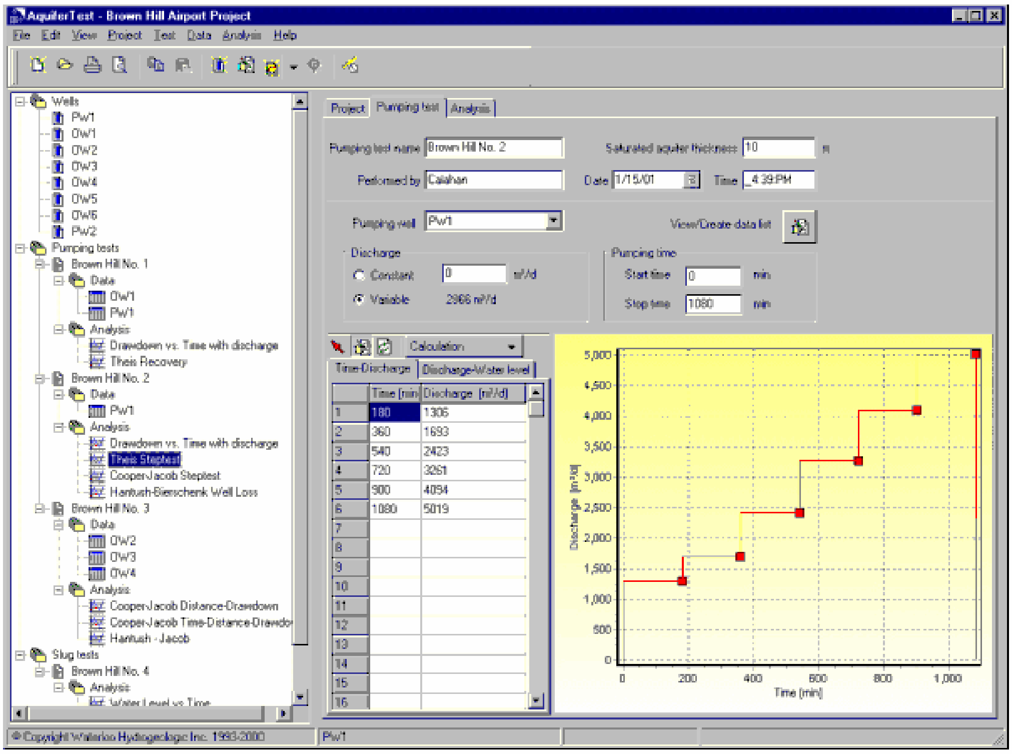
The navigator section shows the wells, tests, and analyses for the current project in a standard tree view. As with other Windows applications, you can use the + or - icon to expand or collapse an element in the tree.



Creating and deleting elements contained within the tree, including wells, data lists, pumping tests, slug tests, and associated analyses is discussed later in this chapter.

4.2.3 Properties Notebook

In AquiferTest, the data you enter is displayed in a standard Windows properties notebook. You can freely move from one page to another by using the tabs at the top of each page.

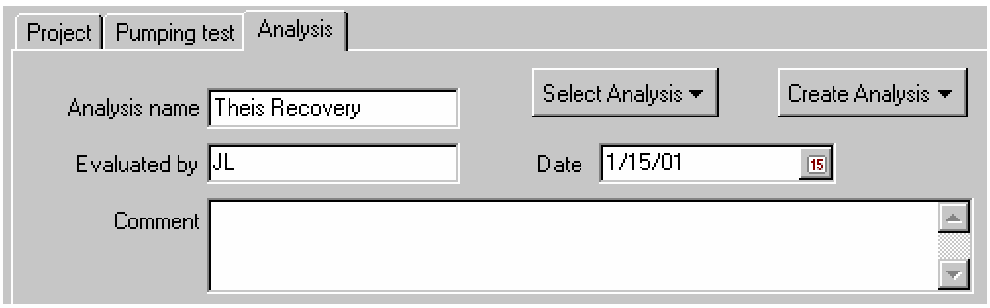


A variety of different pages, or tabs, are encountered when using AquiferTest, including:

- Project tab - contains project description and map
- Well tab - contains selected well location and dimensions
- Data tab - contains data for selected well
- Pumping test tab - contains pumping test details
- Slug test tab - contains slug test details
- Analysis tab - contains selected analysis and associated options
- Summary tab - contains a summary of analyses for selected test

The available tabs in the Properties Notebook vary depending on which well, data list, or test is highlighted in the Navigator tree.

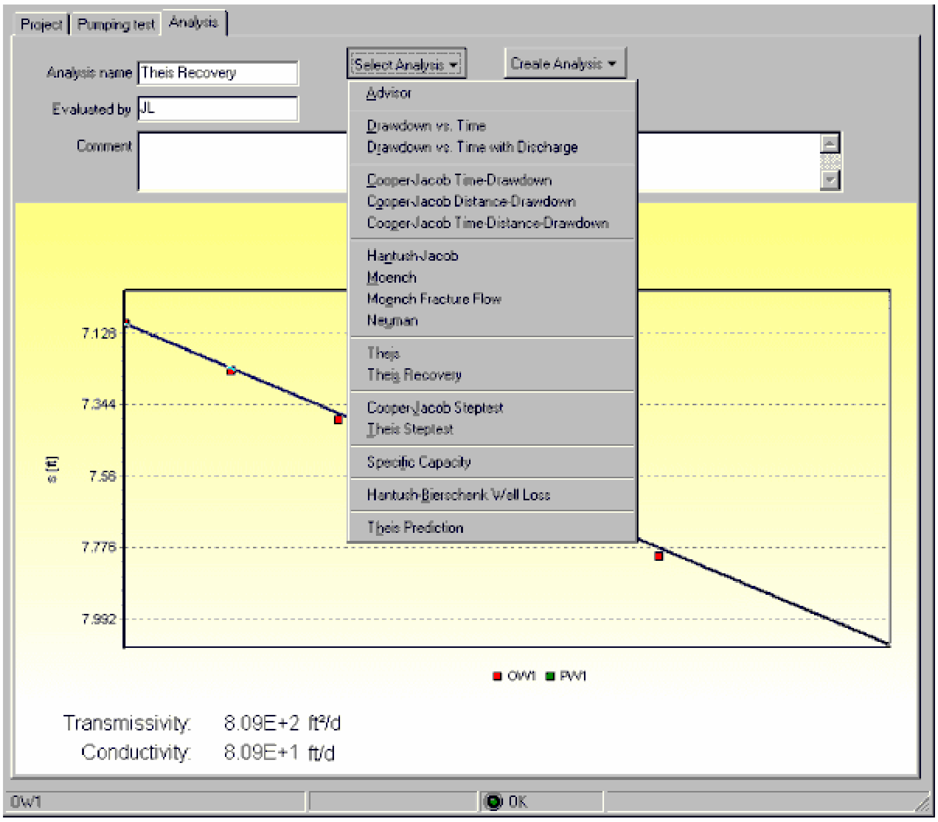
For example, when conducting a pumping test there are three available tabs:



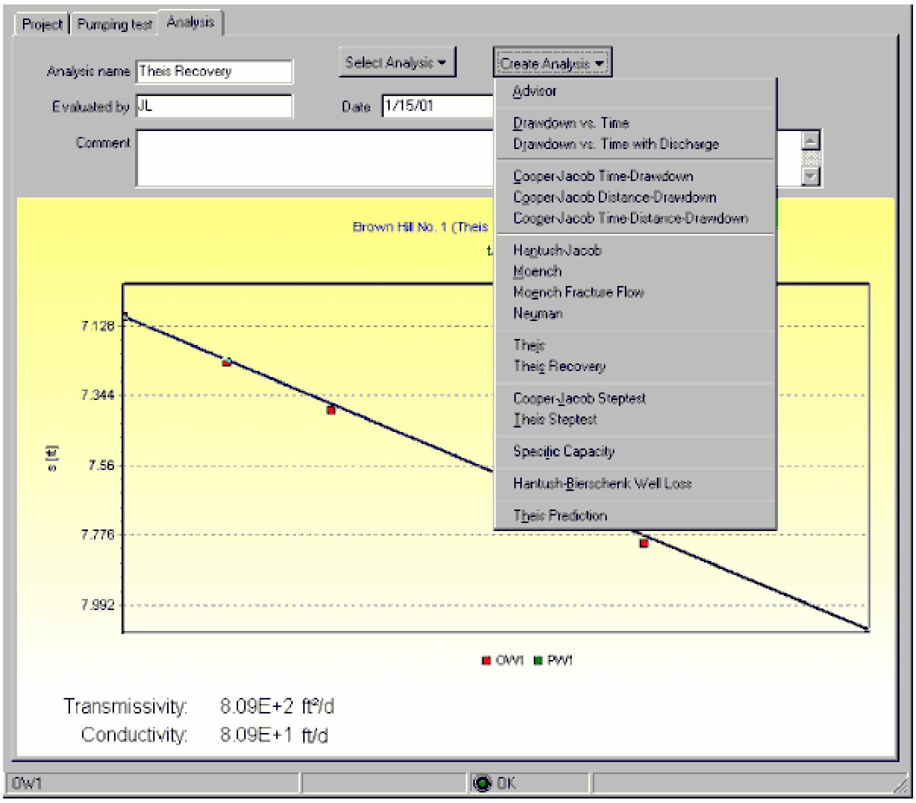
Project
Pumping test
Analysis

In the Analysis notebook page for both the Pumping and Slug tests, there are two pull-down menu buttons entitled, Select Analysis and Create Analysis.

By clicking on Select Analysis, a pull-down menu will appear that allows you to change the CURRENT analysis type, as shown in the figure below:



Conversely, by selecting Create Analysis you can create a NEW analysis of your choice for the current data set. If you select this option, the test will be displayed and added to the navigator tree automatically.

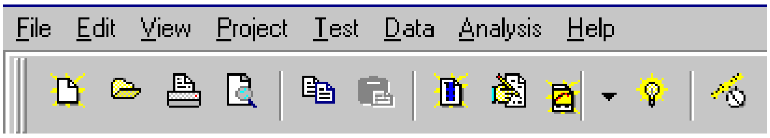


4.3 Database Management

AquiferTest saves all of its input and analysis data in a database file. In the following section, several basic database management techniques are described in detail. Mastering these activities will make managing your data easier and increase the speed of the program.

4.4 Menu Bar and Icons

The following sections describe each of the items on the menu bar, and the equivalent icons. For a short description of an icon, move the mouse pointer over the icon without clicking either mouse button.



4.5 File Menu

File Menu

The File menu contains the following items:

Create database

- New Project
- Open Project
- Import

- Export
- Preferences...
- Maps...
- Report editor
- Print Preview
- Print
- Exit

Create database

Create a new AquiferTest database.

New Project

Create a new project. To return to the existing project, select Open Project.

Open Project

Open an existing AquiferTest project from the list of projects in your database.

You can also use this option to delete a project, as follows:
[1] Select Open Project.
[2] Select the project that you want to delete.
[3] Select Delete.
This is the easiest way to delete an entire project.

Import

Import one of the following:
A project that you have previously exported
A test that you have previously exported
Well locations and geometry (from an .ASC or .TXT file)
An AquiferTest version 2.x file (extension .HYT)

Export

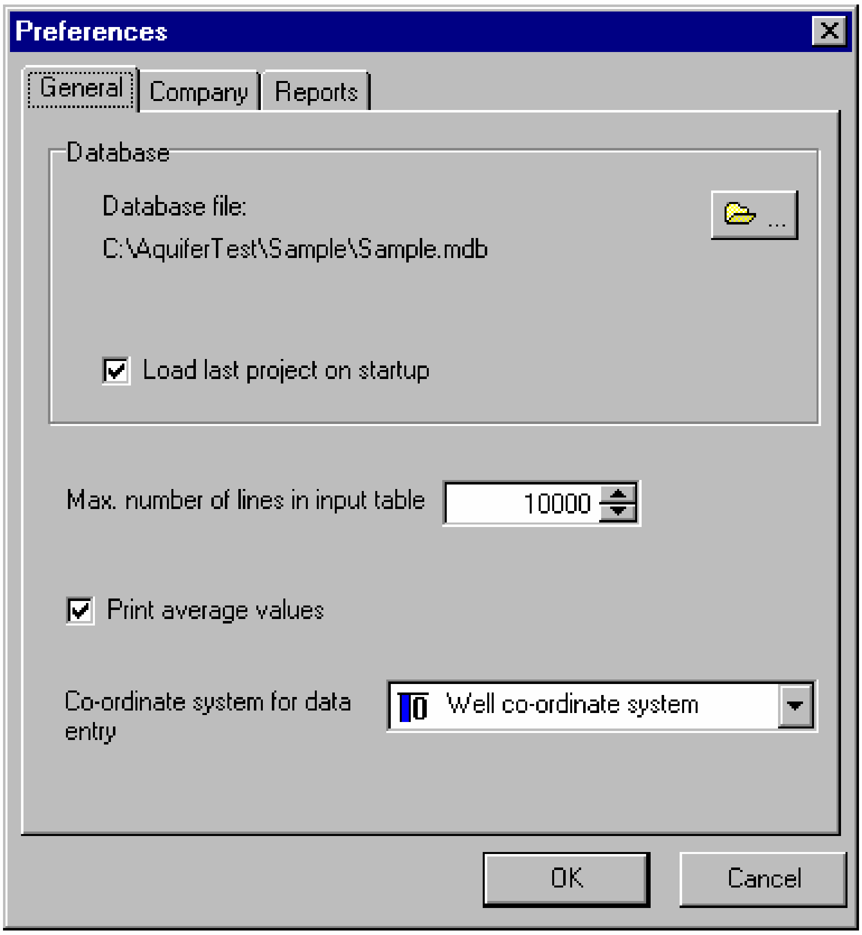
AquiferTest provides several different options for exporting data and analysis results. The Export option allows you to export one of the following:

- the current project to an exchange file format (extension .aex)
- the selected test to an exchange file format (extension .aex)
- the selected analysis to a graphics file (extension .bmp, .jpg, .wmf or .emf)

The exchange files can be imported at a later date into AquiferTest on this computer or another computer. This is a useful feature when exchanging data between colleagues or with a client.

Preferences...

Specify default settings for various program options.



Maps...

View, add, or delete maps in the Map database.

Report Editor

AquiferTest includes six pre-designed report templates:
Site Plan with background (.bmp) map
Well report
Pumping Test Data report
Slug Test Data report
Analysis report
Analysis Summary report
With the report designer, you can make many changes to the report templates including:
Changing the report layout
Adding graphics
Changing the text that appears in various fields
Changing the color, font, and size of text fields
Moving text fields and graphics
Adding static text labels for more descriptions

The Report Designer is a separate component, with its own extensive help system. To assist you in becoming familiar with the Report Editor, we have included several sections below that detail the major features.

Print Preview

View a copy of the output that will appear if you select Print.

Print

Print a report for the object that is currently selected in the navigator (project tree) panel. For example, if you have a well selected, the Well report is printed.

Exit

Exit the program. All changes are automatically saved.

4.6 Edit Menu

Edit Menu

The Edit menu contains the following items:
Copy
Paste
Delete...

Copy

opy the selected item from AquiferTest to the Windows clipboard. Depending on your Windows System setup, the decimal sign used for the data will either be a period (.) or a comma (,). You can change this within Windows by selecting Start, then Settings, then Control Panel, then Regional Settings.

Paste

aste data from the Windows clipboard into AquiferTest. With this command, only the first two columns are transferred. Therefore, you have to make sure that the first two columns of the information on the clipboard are the desired columns of data. When importing data from a spreadsheet, the data must be in adjacent columns with the time data on the left and the water level data on the right. When importing data from a text editor, the columns of data must be separated by tabs (tab delimited).

NOTE: There are different formats available for data pairs in Windows; the one used in AquiferTest is the "text" (*.txt) format. To select this format, enter the Clipboard Viewer (Start, Programs, Accessories, Clipboard Viewer) and select Display, then Text.

Delete

Delete an AquiferTest well, test, or analysis.

4.7 View Menu

View Menu

The View menu contains the following items:

- Results
- Symbol list
- Small Toolbuttons
- Units Converter
- Enlarge Graph

Results

When this item is selected, the calculated results from your analysis are shown beneath the graph. In most cases, this is what you will want.

When this item is unselected, your calculated results are not shown beneath the analysis graph. Use this mode when you want to view only the graph, without seeing the calculated results.

Symbol List

Display or hide tool bar icons.

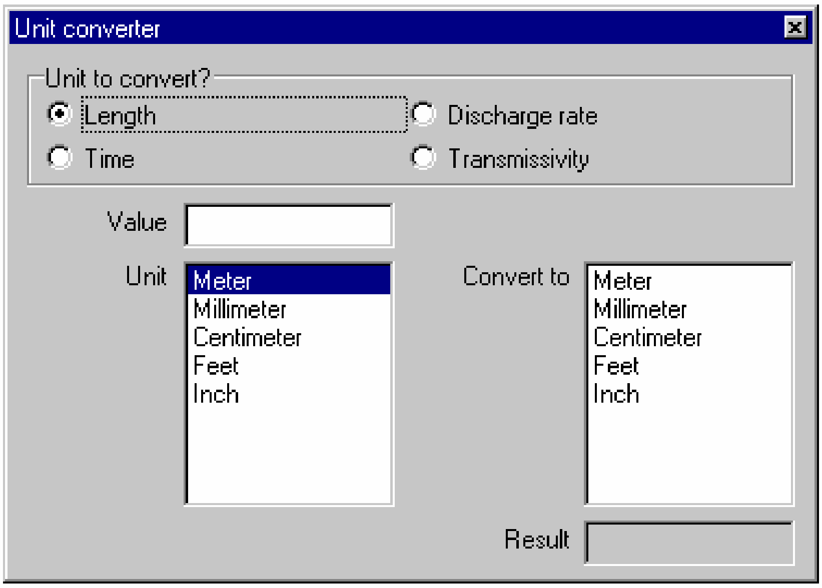
Small Tool Buttons

When this item is selected, the tool icons are displayed under the menu bar without any text. This saves space on the window.

When this item is unselected, the name is displayed under each icon.

Units Converter

Displays a useful utility for converting commonly encountered units of measure. Simply enter the measurement value, and choose which units to convert from and to, and view the result.



Enlarge Graph

When this item is selected, the analysis graph expands to fill the entire window. The navigator section and the rest of the properties notebook are not visible. Use this option when you want to visualize your data more closely.

When this item is unselected, the graph appears in its normal position at the bottom of a page of the properties notebook.

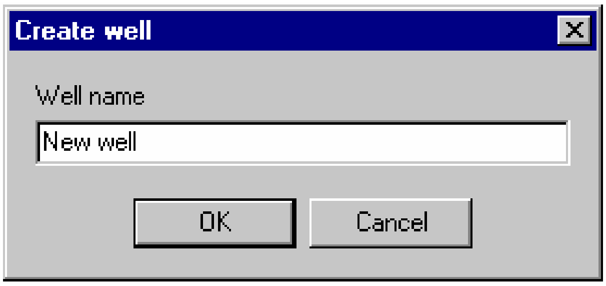
4.8 Project Menu

Project Menu

The Project menu contains the following items:
Create Well...
Map...
Units...

Create Well...

Define a new observation well or test well. Another way to create a well is: click the right mouse button with the pointer in the navigator (project tree) panel, then select New Well.

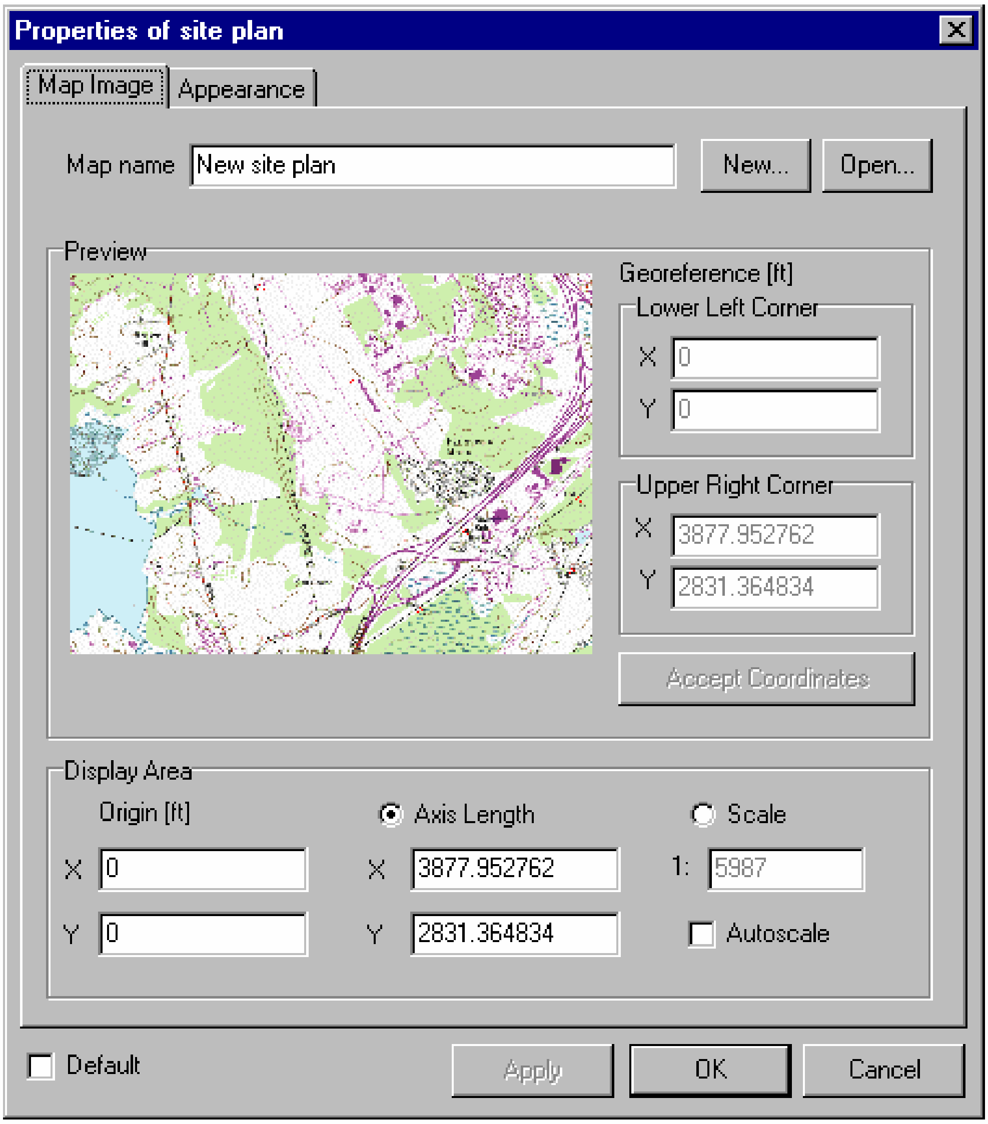


Map

Display a map of the wells that are defined for this project. This map appears at the bottom of the

Project page of the properties notebook.

If you have a map of the test site, you can display this map as a background picture. The well locations are shown as dots on this picture.

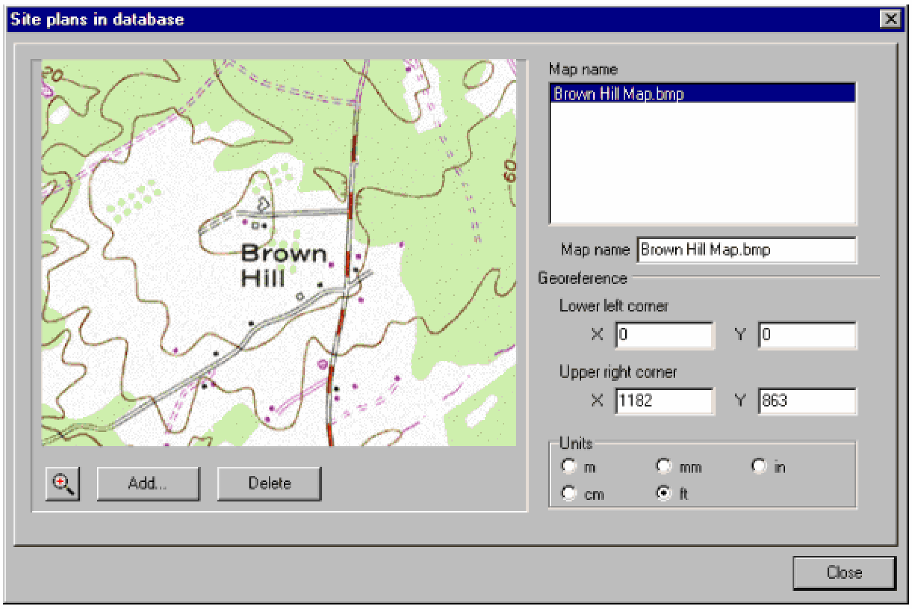


If you do not have a map picture, the wells are mapped with no background. The map shows the locations of wells relative to each other.

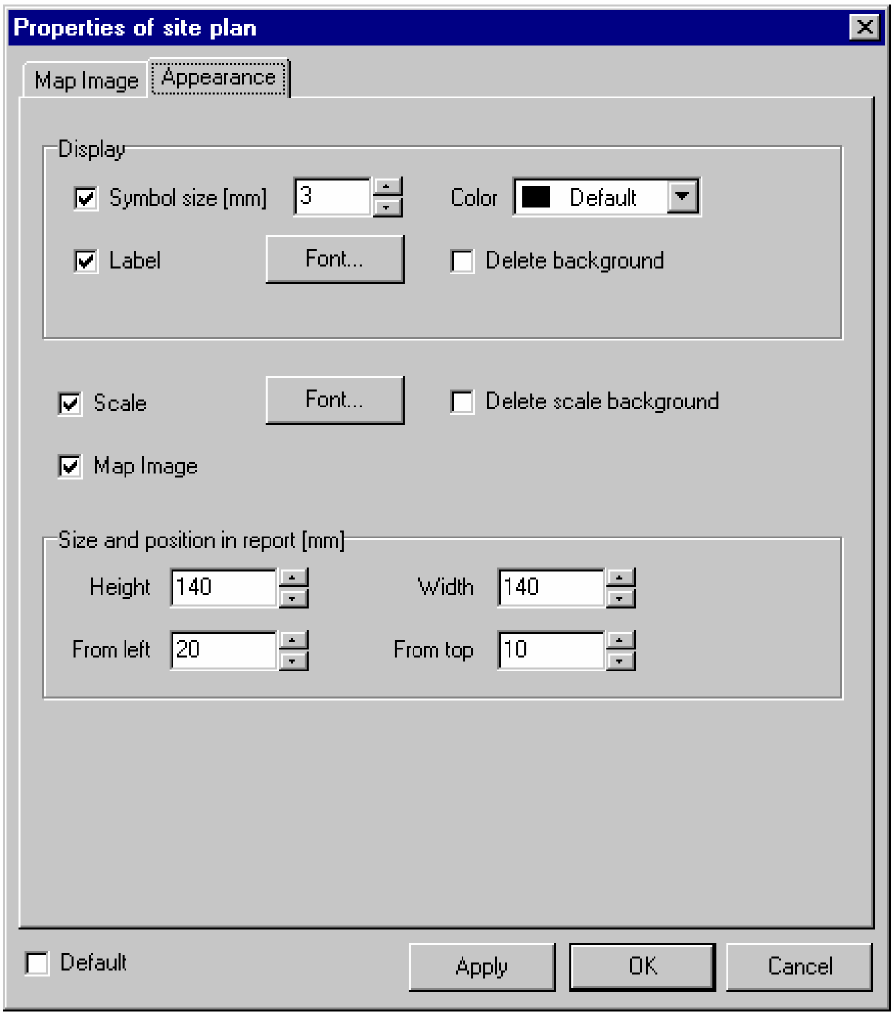
In a future version of AquiferTest, you will also be able to plot water level data as a contour map.

On the Map Image page, you can specify how large the map should be when it is displayed, the position of the top left corner of the map, the scale, and the origin position.

By clicking [Open...] on the Map Image tab, you can view a list of map images available in the AquiferTest map database shown below. To add a map file to the database, click [Open...] and navigate to where is file is located. AquiferTest supports the following map file formats: .jpeg, .jpg, .bmp, .emf, .wmf, and .dxf.



On the Appearance page, you can specify the size and color of the well marker, whether a background picture is displayed, and whether a scale is displayed. You can also specify the size of the map image that appears when you print a Site Plan report.



Units.

Changing units in AquiferTest can be done on two levels, the project and the test level.

Select the units for the current project. These units will be used for all new data and analyses that you add to the current project. Changing units at the project level has no effect on existing test data or analyses.

You can also change units at the test level, as described on page 91. A test-level change allows you to analyze the results of a pumping test with units different from the project units.

By checking the Default option, the units specified will be used for all new projects.

4.9 Test Menu

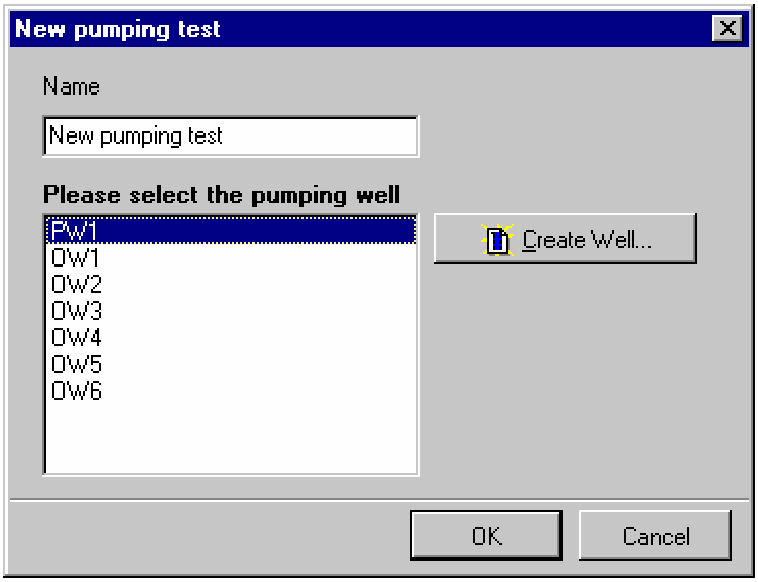
Test Menu

The Test menu contains the following items:

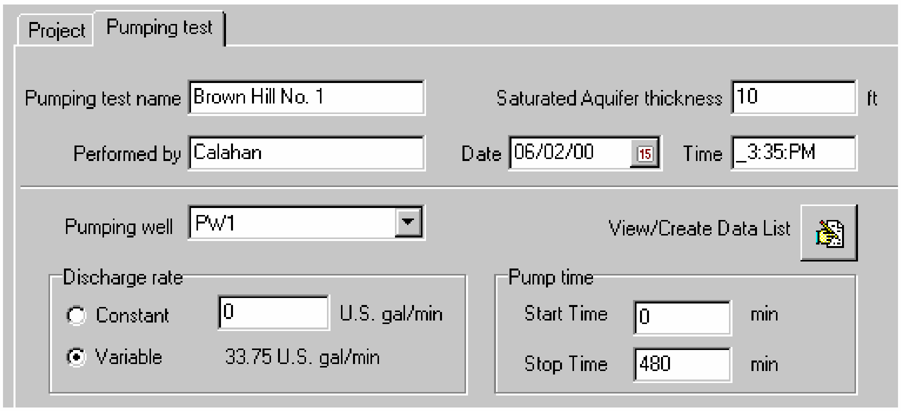
- Create pumping test...
- Create slug test...
- Units...

Create pumping test..

Selecting this menu option will create a new pumping test. Another way to create a pumping test is: highlight the Pumping Test folder in the navigator (project tree) panel with the pointer, and click the right mouse button. Select New pumping test, and the following dialogue will appear:



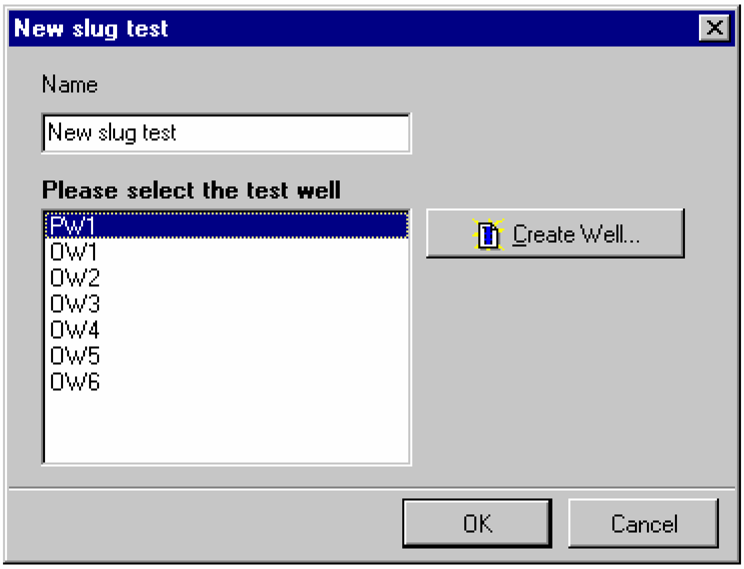
The New pumping test window will prompt you to enter a name for the pumping test, and to select the pumping well from a list of all wells at the project site. If the well(s) you are interested in do not appear in this list, you can click the [Create Well...] button to add the new well(s). After you have selected the pumping well for this pumping test, click the [OK] button.



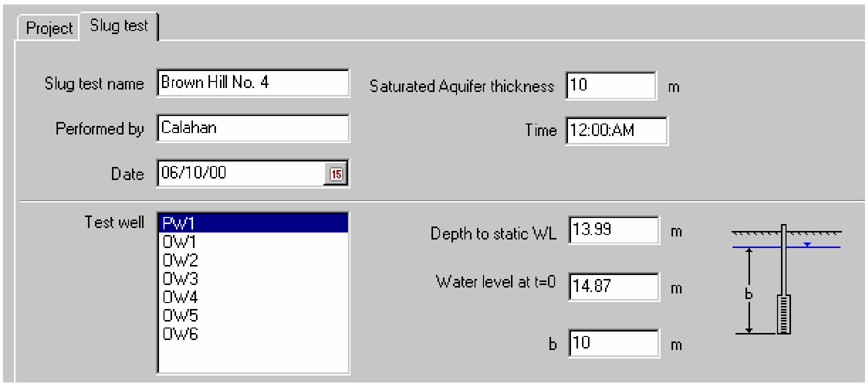
In the Pumping test notebook page, you can enter the details of the pumping test including the Saturated Aquifer thickness, discharge rate(s), pumping time(s), etc.

Create slug test

Selecting this menu option will create a new slug test. Another way to create a slug test is: select the Slug Tests folder in the navigator (project tree) panel with the pointer, and click the right mouse button. Select New slug test.



The New pumping test window will prompt you to enter a name for the slug test, and to select the test well from a list of all wells at the project site. If the well(s) you are interested in do not appear in this list, you can click the [Create Well...] button to add the new well(s). After you have selected the test well for this slug test, click the [OK] button.

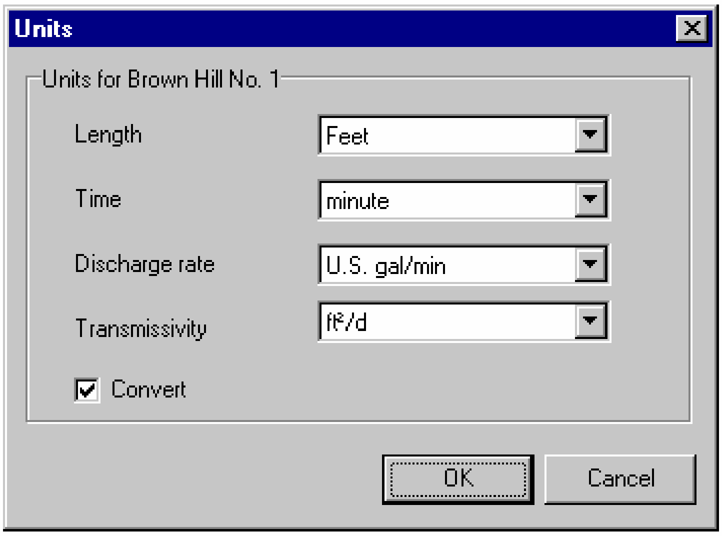


In the Slug test notebook page, you may enter the test details as seen in the figure above.

Units

Specify units for the currently selected test - other tests are not affected. Use this option when you need to analyze an aquifer test that was documented in units different from your project-level units.

If you select the convert check box, any existing data are converted from the old units to the new units. If you do not select this check box, the existing numbers are not changed. In other words, this check box determines whether a value of 2 minutes should be converted to 120 (or remain as 2) when you change the time unit from "minute" to "second".



For information about setting units at the project level, see the Units section discussed on page 88.

4.10 Data Menu

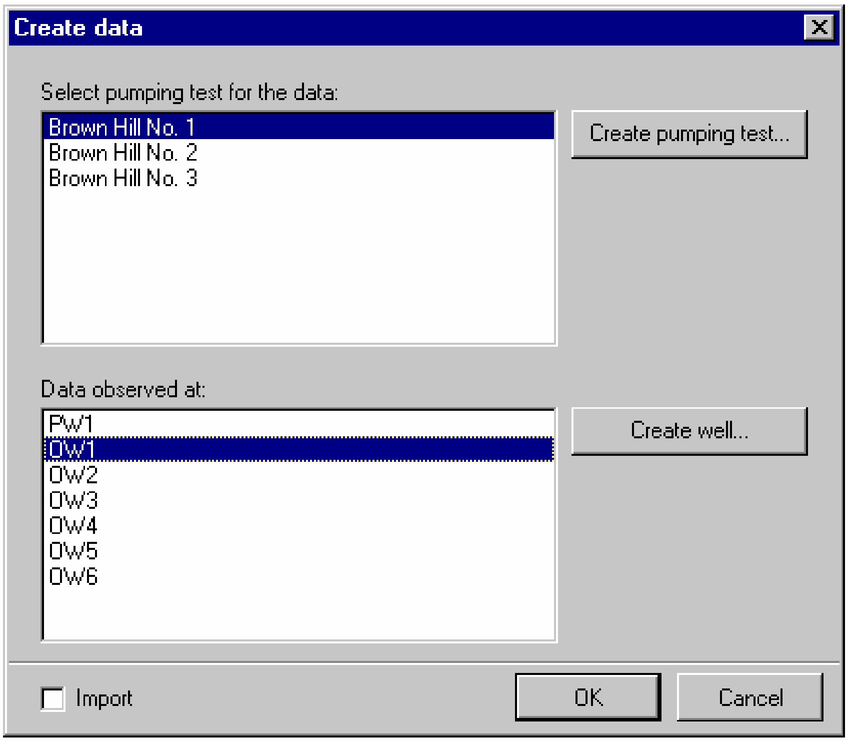
Data Menu

The Data menu contains the following items:

- New...
- Import...
- Data logger file...

New

Add data for the currently selected pumping test. Another way to create pumping test data is: click the right mouse button with the pointer in the navigator (project tree) panel with the Data folder highlighted, then select Create datalist... Finally, a third way, and perhaps the simplest, is to select the View/Create Data List icon located on the Pumping Test notebook page.



All three of the options listed above will display the Create data dialogue box (shown below).

Using this dialogue box, you can create a new or select an existing pumping test, create a new or select an existing observation well, and import observation well data by clicking the Import option located at the bottom of the dialogue box (text file only). Then, click [OK] to add the new data to the selected pumping test.

Import.

Imports aquifer test data from an ASCII text file or Excel spreadsheet.

Choosing this option will display a dialogue in which you can use the mouse to graphically select the data you want to import. For example, if your file contains column headings, you can exclude those from being imported.

AquiferTest supports the direct import of data from Excel versions 4.0, 5.0 and 7.0.

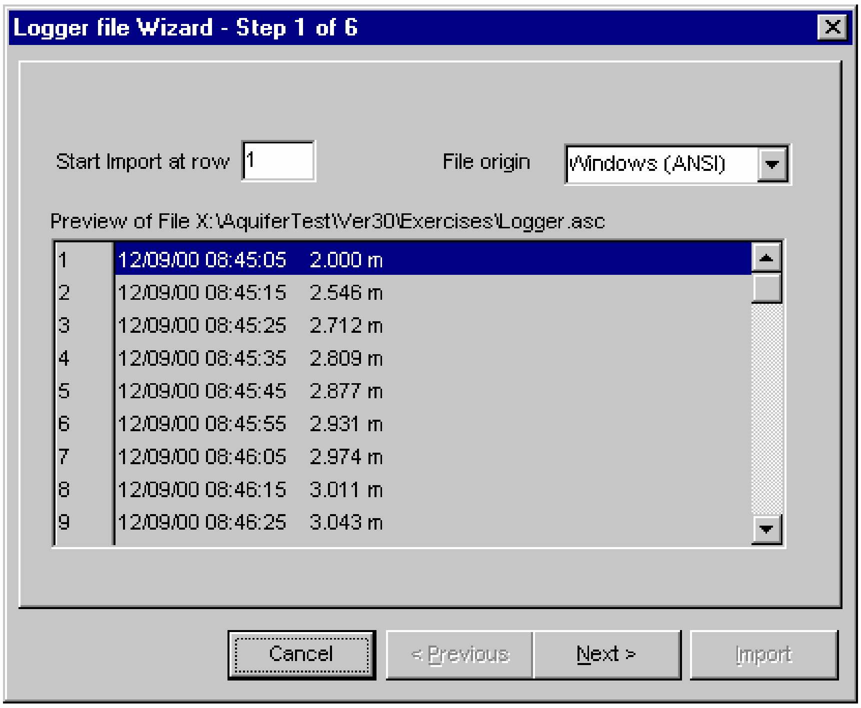
NOTE: AquiferTest is not compatible with Excel 97. Please use the Save as option in Excel, and select a lower version of Excel to save your data (ex. file type 95/5.0 spreadsheet). Alternatively, you can simply copy-and-paste the data from the Excel spreadsheet to the AquiferTest data table using the Windows clipboard.

Data logger file.

Imports free format ASCII text files created by most data loggers using the Logger File Wizard, which is a six-step process as described below.

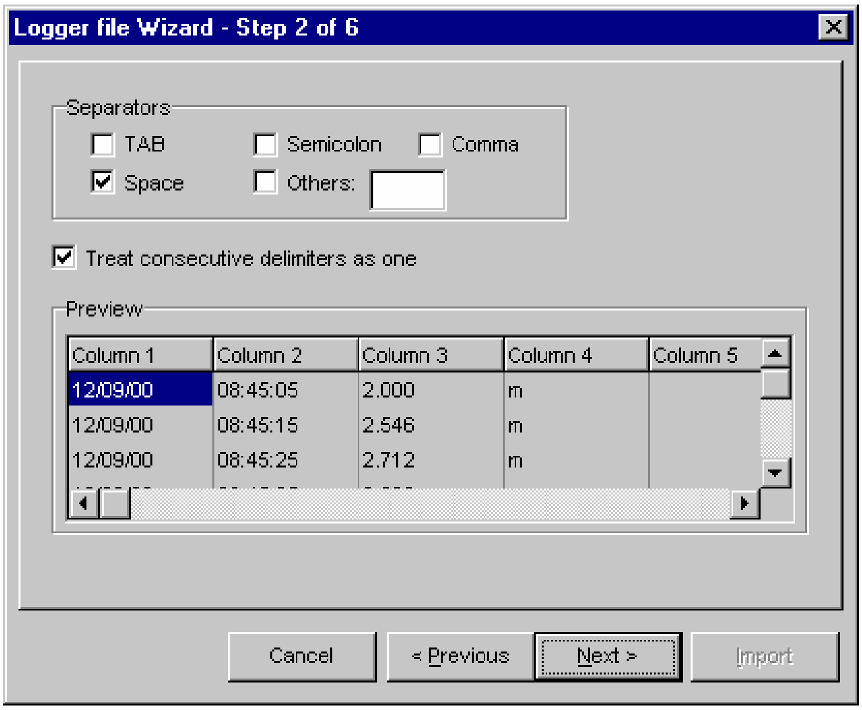
Logger File Wizard - Step 1:

In the first step, you specify the row number where you want to start importing. This is useful if, for example, row 1 of your logger file contains a column header, which you should not import, and allows you to start importing at row 2.



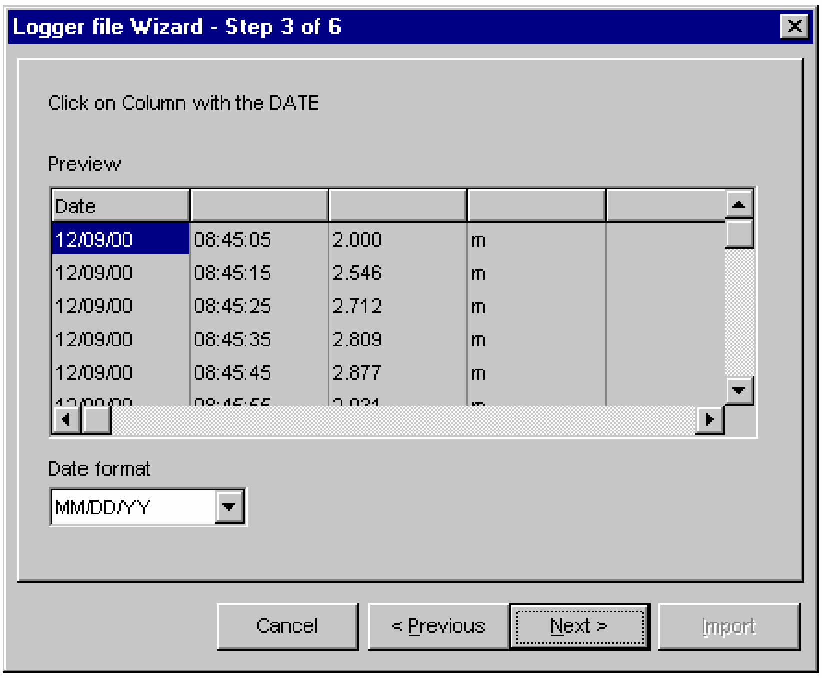
Logger File Wizard - Step 2:

In the second step, you specify the data delimiter. Knowledge of which data delimiter is used by your data logger is not required. Under Separators, simply click to choose the delimiter options until the data become separated into columns of time and water level. The correct delimiter when chosen will separate the data columns automatically.



Logger File Wizard - Step 3:

In the third step, you need to click the mouse pointer on the column header representing the Date when the data was collected. The word Date appears in the column header title box. The Date format also needs to be selected; the Logger File Wizard supports the following formats:

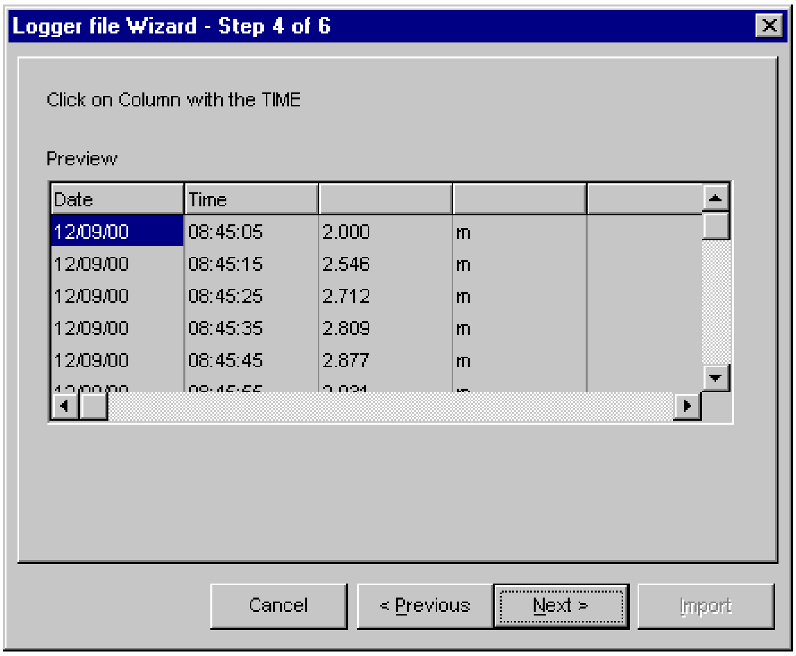


- DD/MM/YY
- DD/MM/YYYY
- MM/DD/YY
- MM/DD/YYYY
- DD.MM.YY

- MM.DD.YY
- M/D/yy

Logger File Wizard - Step 4:

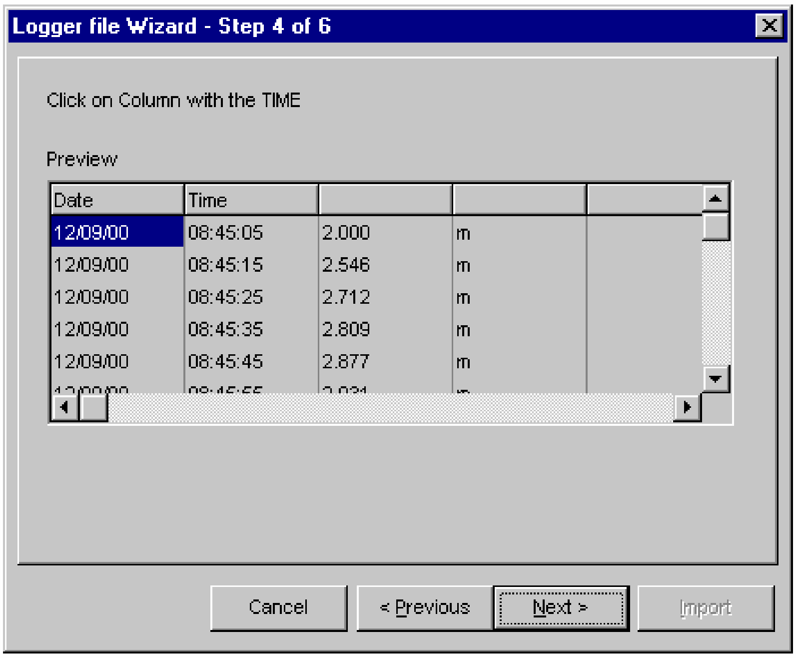
In the fourth step, you need to click the mouse pointer on the column header representing the Time when the data was collected. The word Time appears in the column header title box.



Logger File Wizard - Step 5:

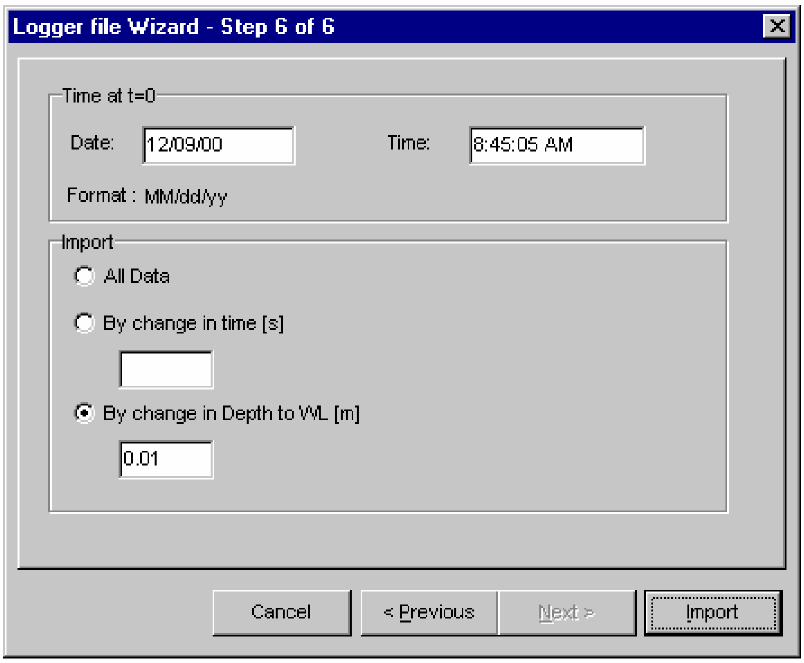
In the fifth step, you need to click the mouse pointer on the column header representing the Depth to WL data. The title Depth to WL appears in the column header title box. The Unit for the water level data also needs to be selected; the Logger File Wizard supports the following formats:

m
mm
cm
ft
inch



Logger File Wizard - Step 6:

In the sixth step, you specify information that determines which data values are imported. If the file contains many records with essentially the same data value (which is typical for a logger file), you will probably want to filter the data as shown below. You can filter the data by either change in time or change in water level.



The number of datapoints that can be imported by AquiferTest is limited by available system resources - typically many thousand datapoints could could be imported.

NOTE: The maximum number of data points is controlled in the File/Preferences dialogue.

However, from a practical point of view importing so many datapoints would likely not be useful in a conventional aquifer analysis. You should try to minimize the number of datapoints imported for each analysis as the import speed will be reduced when the number of datapoints imported exceeds 200. Applying one of the import filter options under Import will allow you to reduce the number of datapoints imported.

To finish the import process, click [Import] and the datapoints will be imported into your project.

4.11 Analysis Menu

Analysis Menu

The Analysis menu contains the following items:
Create
Data...
Settings
Properties...
Method
State

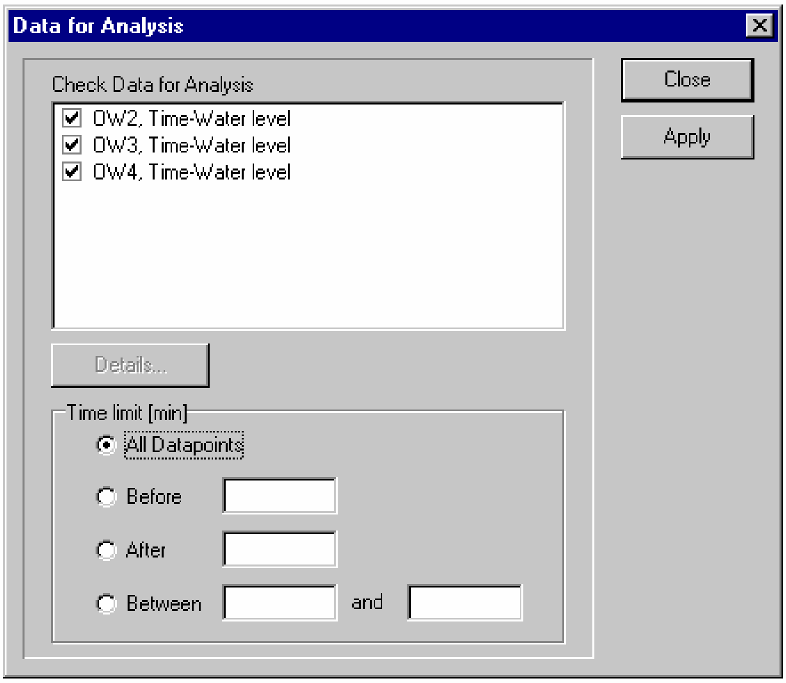
Create

Create an analysis for the currently selected pumping test. Another way to create an analysis is: click the right mouse button with the pointer in the navigator (project tree) panel, then select Create analysis, followed by the analysis of choice from the list that appears.

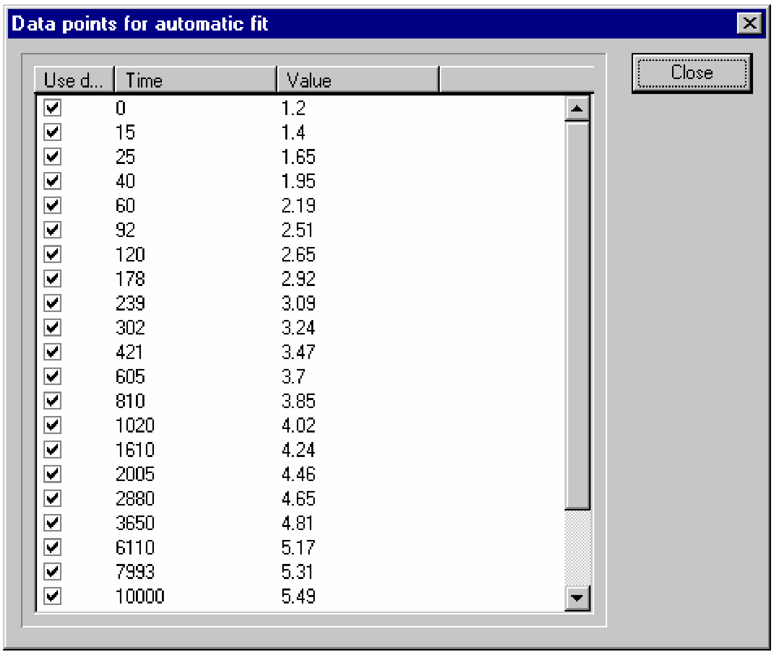
A third option, and perhaps the simplest, is to select the Create Analysis button located on the Pumping Test notebook page.

Data

Change the data for the currently selected analysis.



To exclude certain DATA SERIES from the current analysis, remove the check-mark beside the desired data series (for example, OW2 from the above figure). As a result, the analysis graph will display only those data sets that are selected (as indicated by the check-mark).



To exclude certain DATA POINTS from the regression analysis, select [Details]. On the window that appears, remove the check-mark beside each data point that should be excluded.

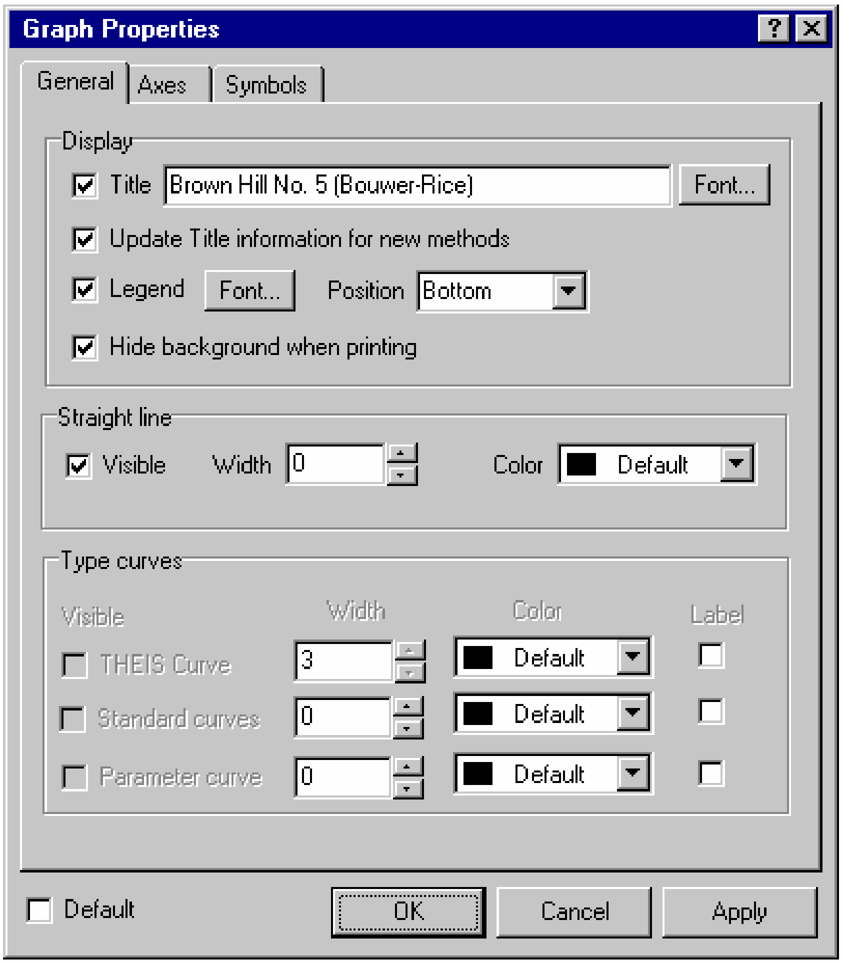
NOTE: The excluded points will be removed from the regression analysis, but will remain on the graph. To remove data points from the graph, use the Time Limit option which allows you to limit the data Before, After, or Between specified time(s).

Settings

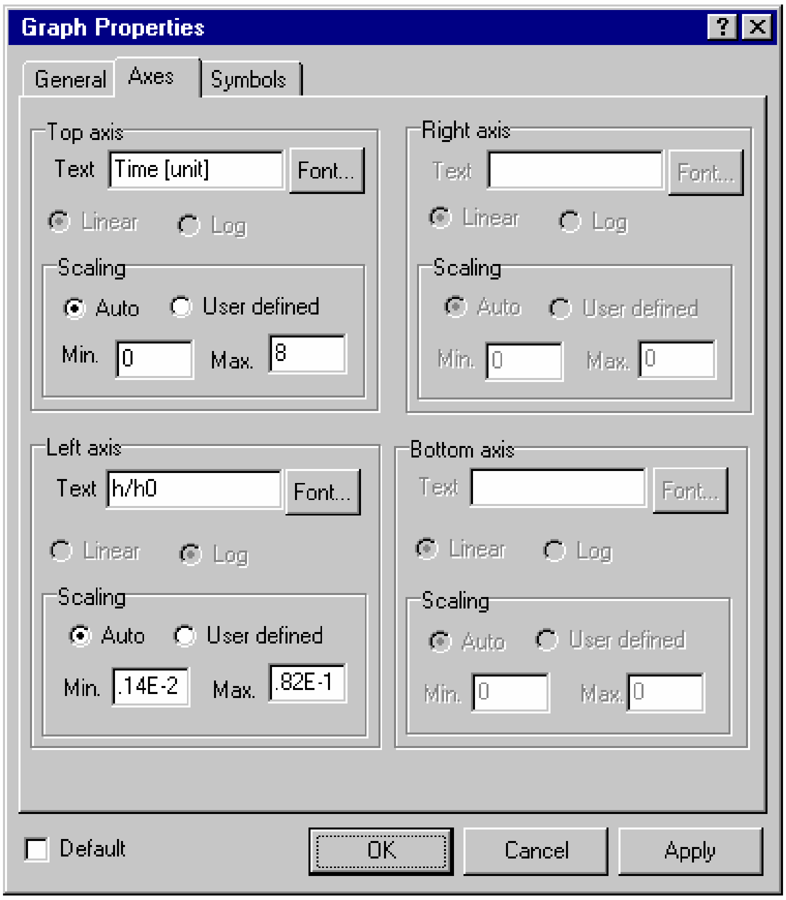
Specify values for various analysis parameters. For information about the analysis methods and their parameters, see the description of each method discussed later in this chapter.

Properties.

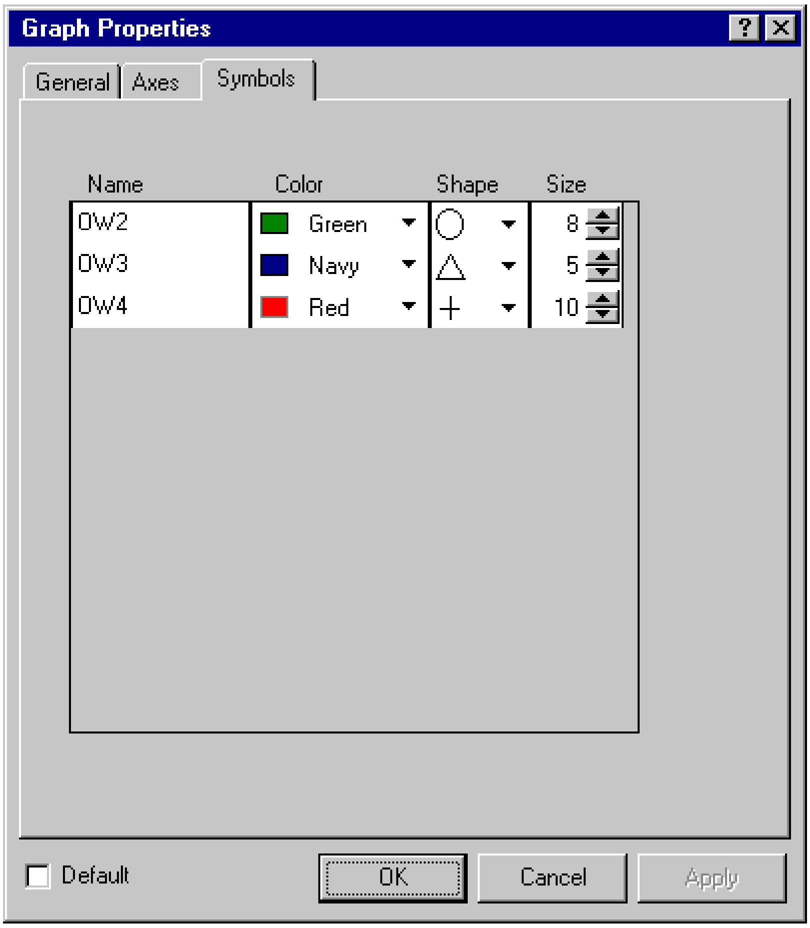
Specify how you want the graph to be displayed. The options vary slightly from one analysis method to another. The figures that follow apply to the Bouwer-Rice method.



On the General tab, you can specify the title and legend settings (font and color) as well as other options that affect the appearance of the graph, including line thickness and color for the various analysis curves.



On the Axes tab, you can specify how the axes will appear (font and color) and whether the scaling is set to automatic or user-defined.



On the Symbols tab, you can specify the shape, size and color of each data set symbol.

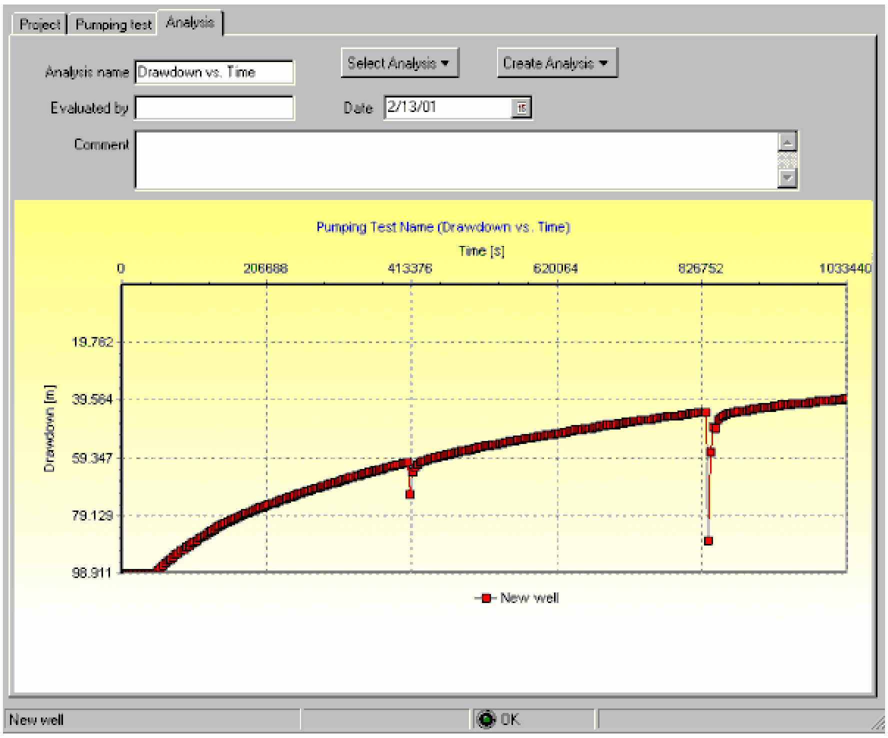
Method

Displays a list of solution methods that are available in AquiferTest. For information about analysis methods and their settings, see the description of each method discussed later in this chapter.

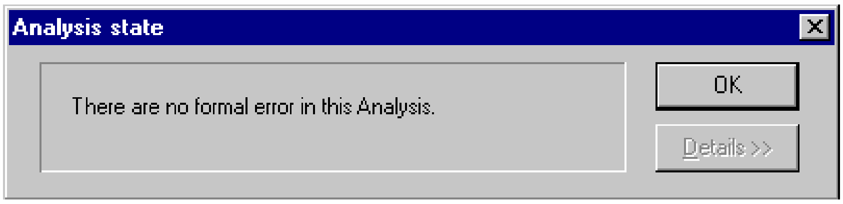
Analysis state

Receive information about your AquiferTest analysis. The information may be advisory in nature, or may report the specifics of an error in the analysis. Errors are usually caused by the absence of required data for a chosen analysis. The Analysis State advisor is visible on the bottom toolbar of the graph display, and may be either:

Red: Error
Yellow: Warning
Green: Message
Dark Green: O.K.



By clicking on the Analysis State symbol from the bottom toolbar, an Analysis State window appears.



The figure above illustrates an analysis with no formal errors; however, if there was an error or message, the Details button can be used to access the description of the problem.

4.12 Help Menu

Help Menu

The Help menu contains the following items:
Contents
About

Contents

See the Table of Contents for this book (the same information is shipped to you in two forms: as a printed book, and as an online help file.)

About

See copyright and version information about AquiferTest.

4.13 Analysis Methods and Settings

Analysis Methods and Settings

For pumping tests, the following solution methods are available:

Theis
Cooper-Jacob Time-Drawdown
Cooper-Jacob Distance-Drawdown
Cooper-Jacob Time-Distance-Drawdown
Walton (Hantush-Jacob)
Neuman
Moench
Moench Fracture Flow
Theis Steptest
Cooper-Jacob Steptest
Theis Recovery
Hantush-Bierschenk Well Loss
Specific Capacity
Theis Prediction

For slug tests, the following solution methods are available:

Hvorslev
Bouwer-Rice
Cooper-Bredehoeft-Papadopulos

Each analysis produces a graph displaying the data points, which is subsequently overlaid by a specific type curve that varies depending on the analysis method. At this point you have two options; automatic or manual curve fitting.

Using the Automatic Curve Fit

To fit a type curve to your data using the Automatic Fit option, use your left mouse button to select a data set, and then click the Automatic fit icon (light bulb) from the top menu bar. AquiferTest uses a least squares regression to match the type curve to your data, which minimizes the total squared error of the residuals. In other words, it usually favours the late time data, as drawdown values for a particular data set tend to get larger over time.

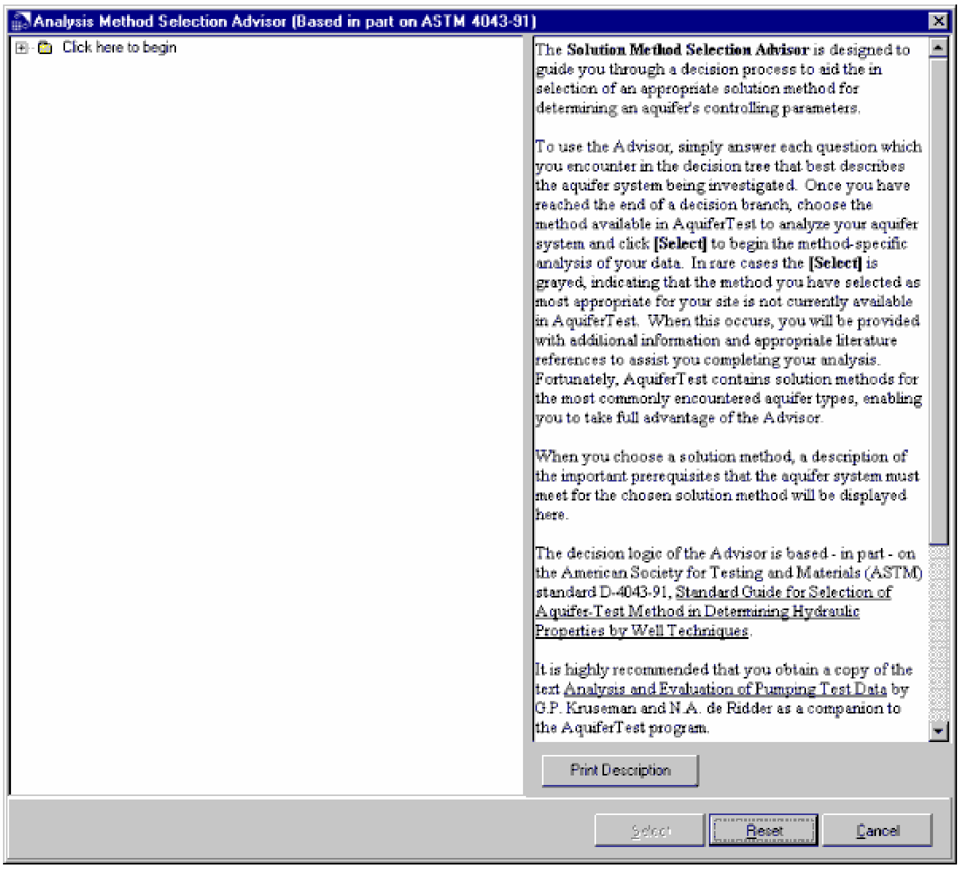
Automatic curve fitting can be performed for all graphical solution methods in AquiferTest. However, the least squares fit is not always the most appropriate curve match, as professional judgement is essential for the proper assessment of AquiferTest data. You are encouraged to use your knowledge of the geologic and hydrogeologic settings of the test to manually fit the data to a type curve, simply by pressing the arrow keys on your keyboard.

Solution Method Advisor

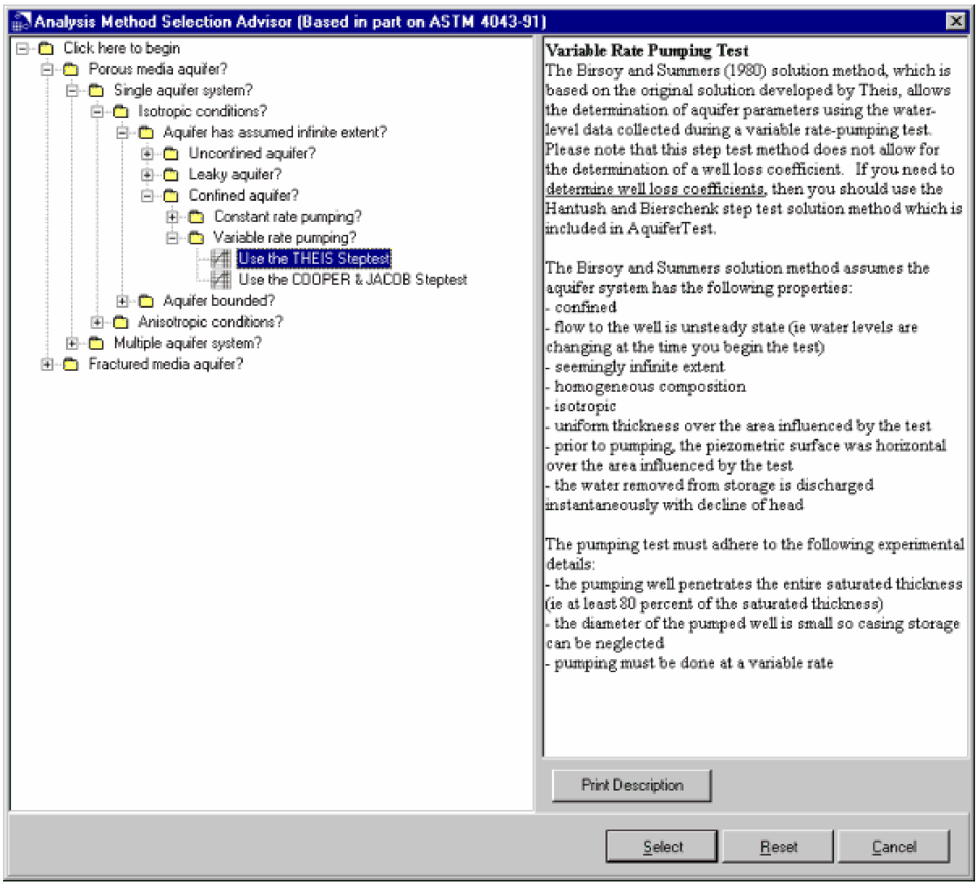
AquiferTest includes a unique utility that can assist you in selecting an appropriate solution method for your site. The Advisor presents a "decision tree" which you navigate through by answering simple yes or no questions about the geologic, hydrogeologic and test-specific details of your site. Once you have reached the end of a "logic branch", the Advisor will present you with a list of potential solution methods based on answers you have provided.

The decision logic of the Advisor is based - in part - on the American Society for Testing and Materials (ASTM) standard D-4043-91, Standard Guide for Selection of Aquifer-Test Method in Determining Hydraulic Properties by Well Techniques.

To start the Advisor, select Analysis, Method, and the choose Advisor. The following Advisor dialogue will be displayed.



As shown in the figure on the following page, when you reach the end of a "logic branch" you have the option of selecting from a list of available solution methods in AquiferTest to analyze your data. A brief description of the solution method will appear on the right.



You will encounter two kinds of solution method icons used in the Advisor. Each of these is explained below.

When you see this icon next to a solution method, it means that that method is available for use in AquiferTest.

When you see this icon next to a solution method, it means that the method is not yet available in AquiferTest. When a solution method is not available for use in AquiferTest, you will be provide with some guidance in the right window of the Advisor dialogue box on how best to proceed.

After you have selected one of the available solution methods on the end of a "logic branch", choose [Select] from the bottom of the dialogue box and an analysis plot of your test data will be displayed using the solution method you have chosen.

Disclaimer on the Use of the Advisor

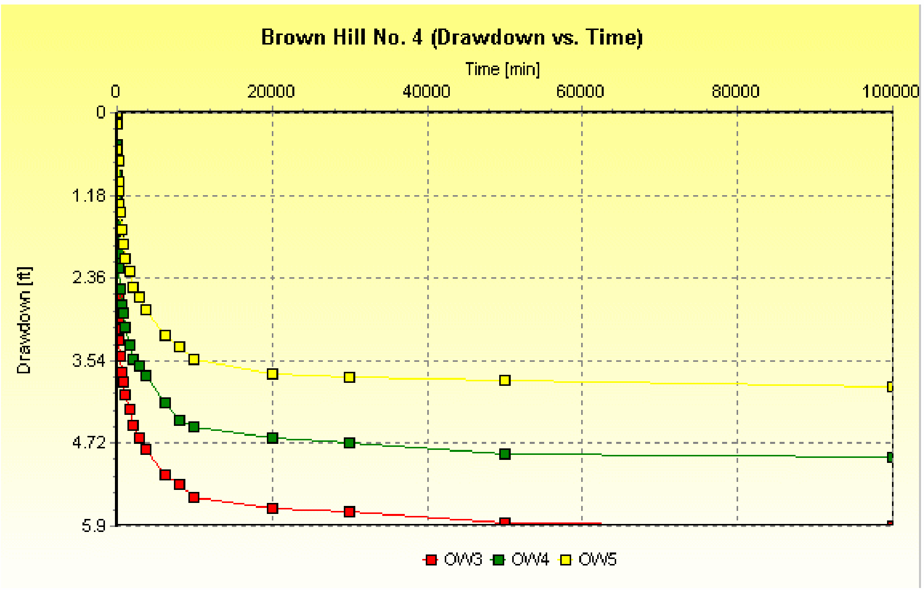
The information provided in the Advisor has been collected from published sources deemed reliable. As with any aquifer test analysis, the final decision on which solution method will provide scientifically defensible results is left to the professional conducting the analysis.

Although deemed reliable, the information in the Advisor is provided to aid in the selection of a correct solution method - the final selection of a solution method is up to the discretion of the groundwater professional. WHI is not responsible for any loss or damage resulting from the use of the Advisor.

Drawdown vs. Time

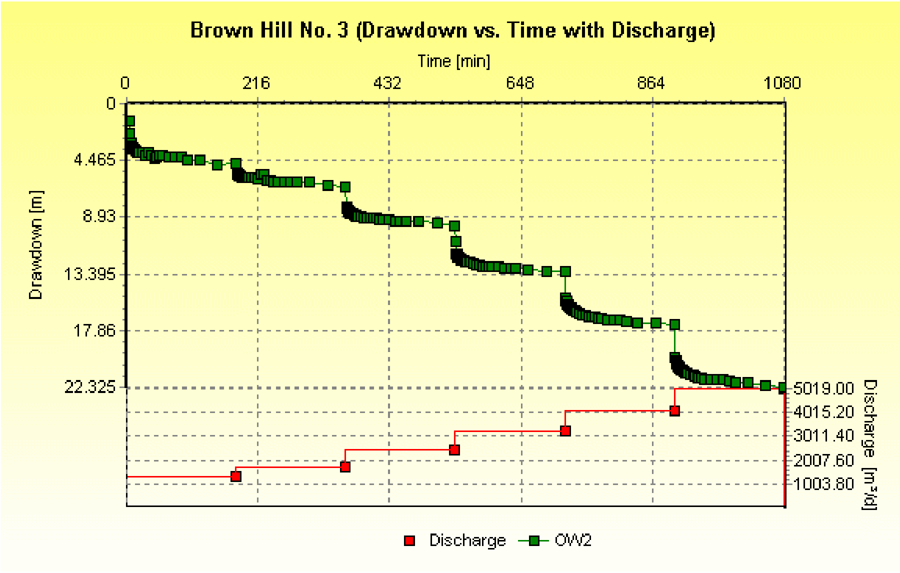
A preliminary graph that displays your drawdown versus time data. To apply a specific analysis method, right-click on the graph and select the appropriate method.

Or simply use of the buttons located above the graph to either create a new analysis, or change the current analysis.



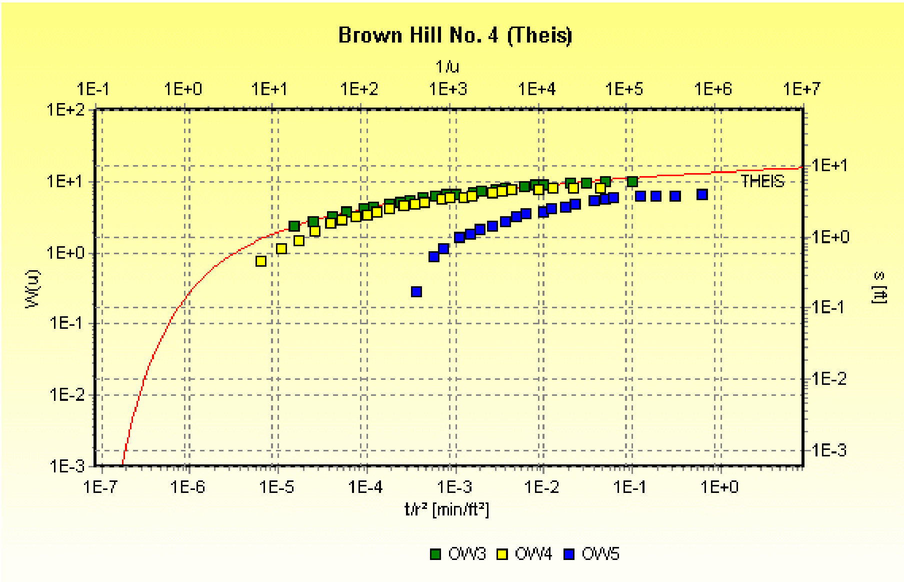
Drawdown vs. Time with Discharge

You can also view your data in a drawdown vs. time with discharge graph. This graph can be useful for visualizing changes in drawdown which result from changes to the discharge rate.



Theis

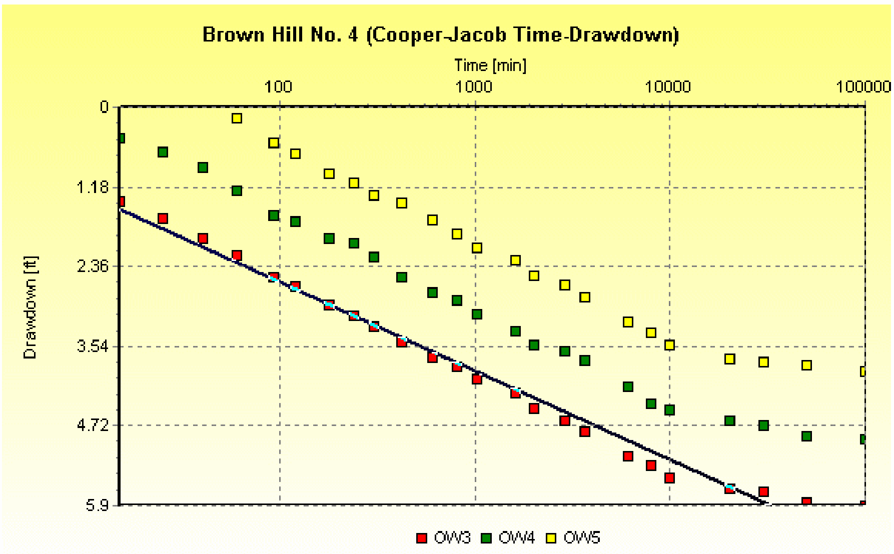
If you select the Theis solution method from the list of available methods, the following graph is displayed in analysis view:



Each solution method has a Settings dialogue, where you can edit the method-specific parameters for your test. The settings dialogue for the Theis solution is shown below:

Cooper-Jacob Time-Drawdown

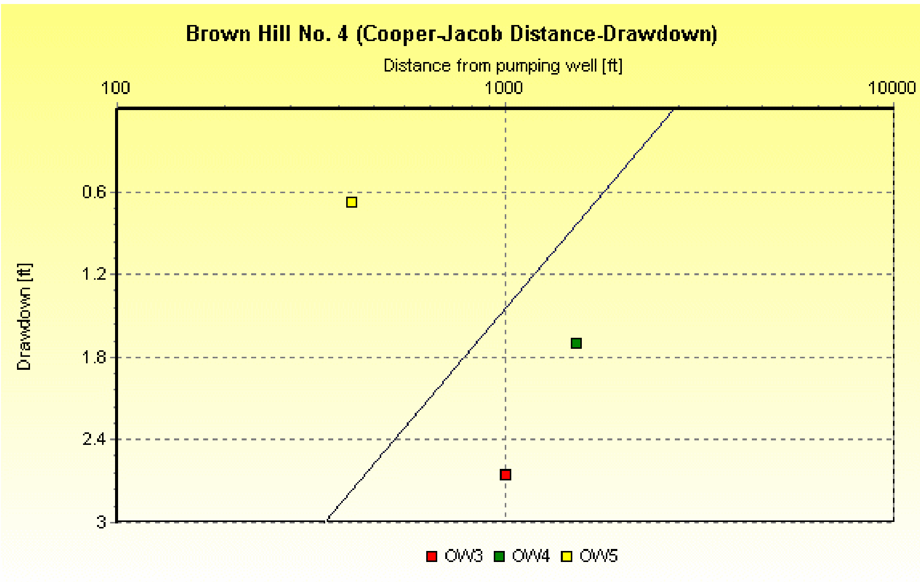
If you select the Cooper-Jacob Time-Drawdown solution method from the list of available methods, the following graph is displayed:



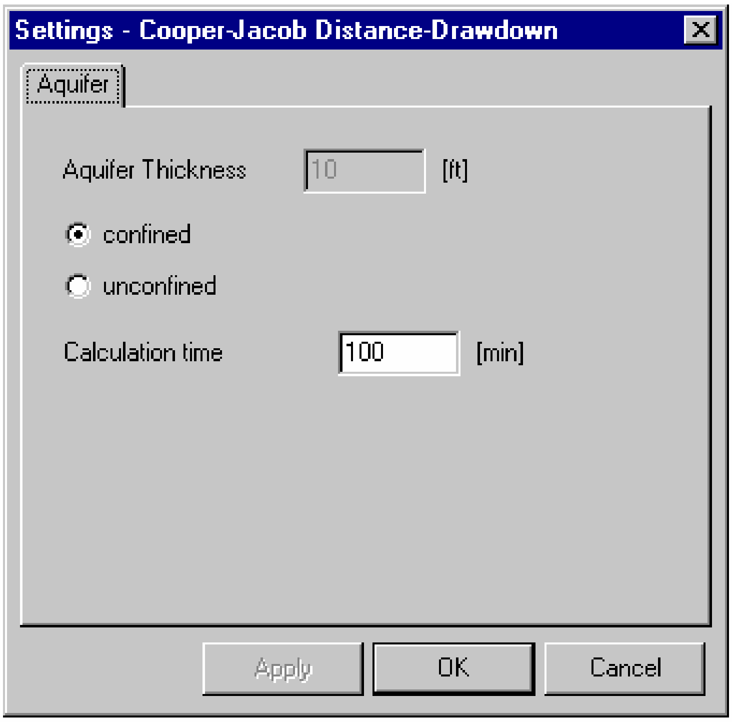
Each solution method has a Settings dialogue, where you can specify the method-specific parameters for your test. The settings dialogue for the Cooper-Jacob Time Drawdown solution is shown below:

Cooper-Jacob Distance-Drawdown

If you select the Cooper-Jacob Distance-Drawdown solution method from the list of available methods, the following graph is displayed:

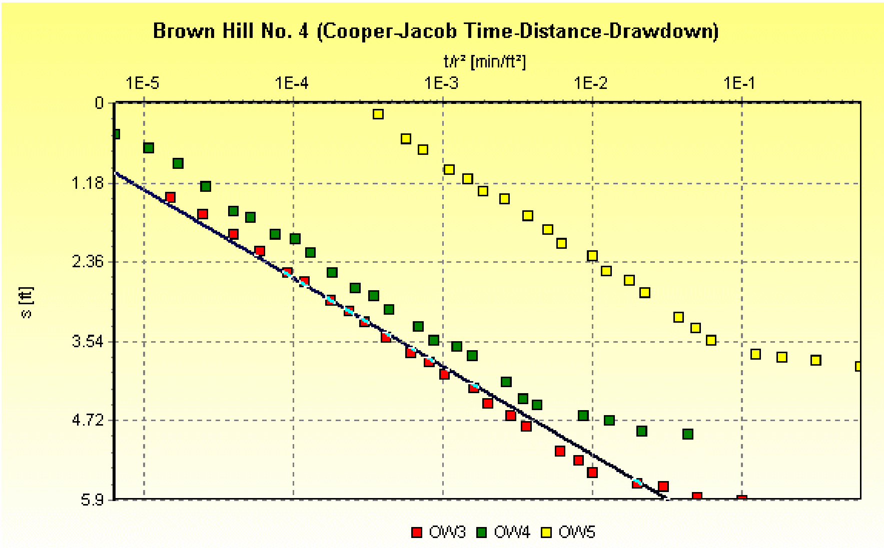


Each solution method has a Settings dialogue, where you can specify the method-specific parameters for your test. The settings dialogue for the Cooper-Jacob Distance-Drawdown solution is shown below:

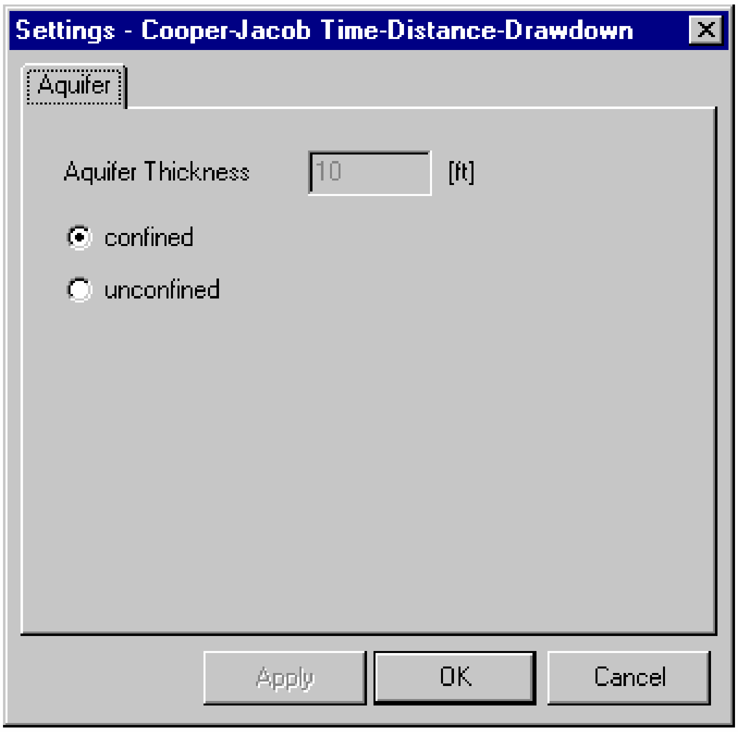


Cooper-Jacob Time-Distance-Drawdown

If you select the Cooper-Jacob Time-Distance-Drawdown solution method from the list of available methods, the following graph is displayed:

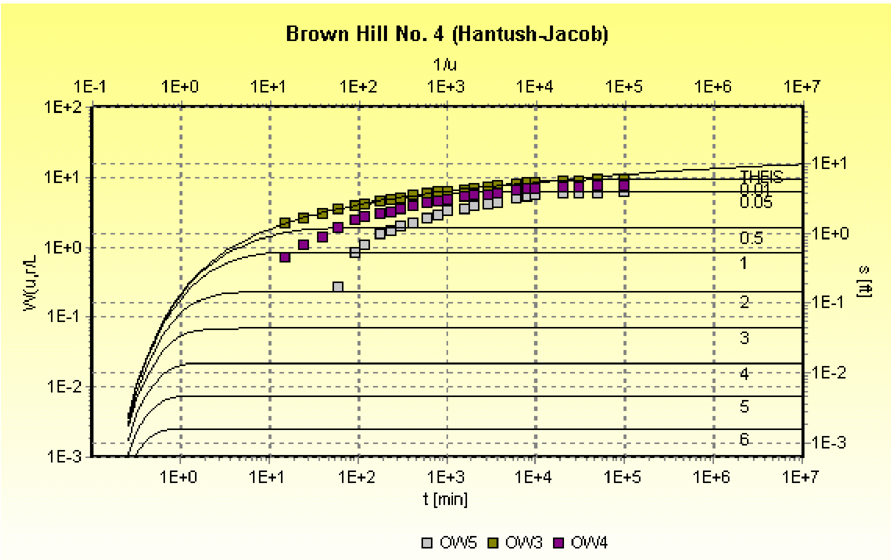


Each solution method has a Settings dialogue, where you can specify the method-specific parameters for your test. The settings dialogue for the Cooper-Jacob Time-Distance-Drawdown solution is shown below:

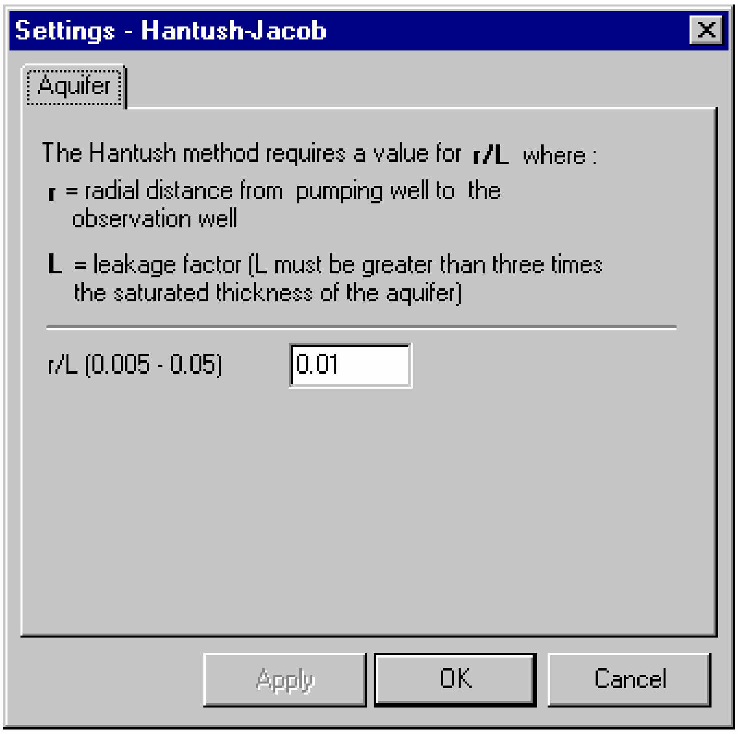


Hantush-Jacob

If you select the Hantush-Jacob solution method from the list of available methods, the following graph is displayed:



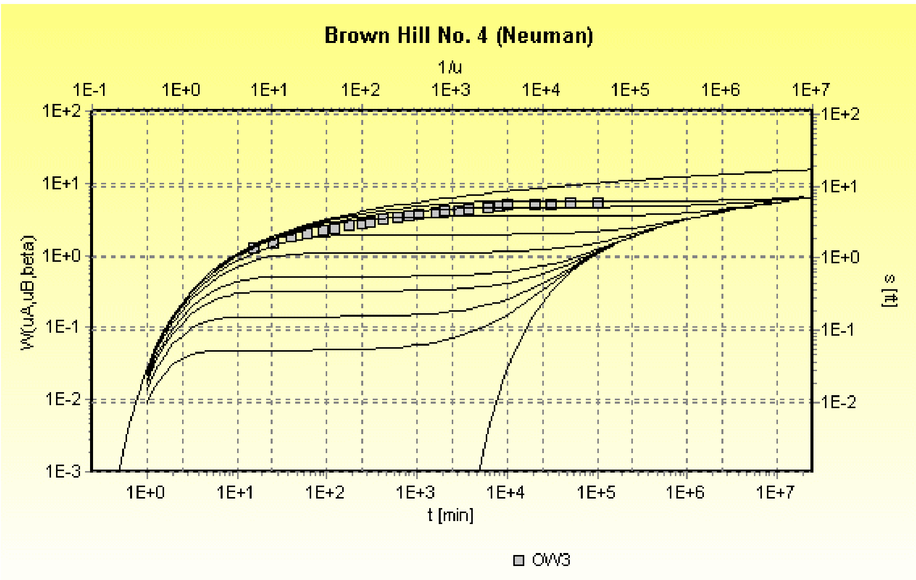
Each solution method has a Settings dialogue, where you can specify the method-specific parameters for your test. The settings dialogue for the Hantush-Jacob solution is shown below:



Using this dialogue, you can specify an r/L value.

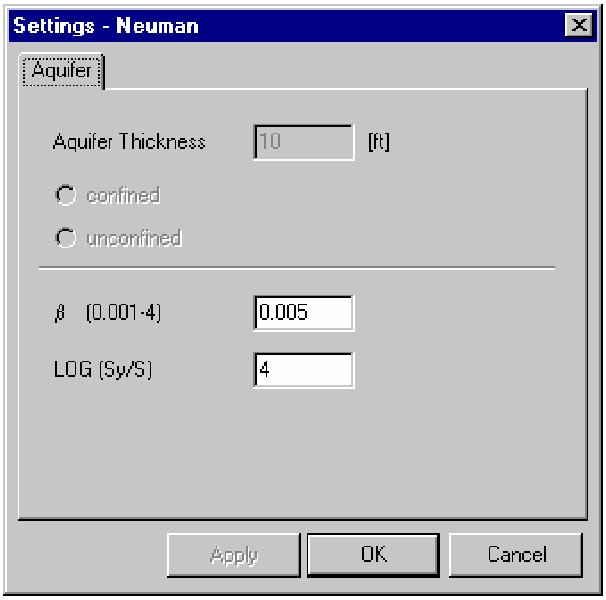
Neuman

If you select the Neuman solution method from the list of available methods, the following graph is displayed:



Both the W(u a, b) and the W(u b, b) are displayed at the same time for early and late time data respectively. If the data are matched to the early time, the value of storativity should be used. If the data are matched to the late time, the specific yield should be used.

Each solution method has a Settings dialogue, where you can specify the method-specific parameters for your test. The settings dialogue for the Neuman solution is shown below:



If the Aquifer Thickness is specified, AquiferTest will also compute the K 2 value from the fitted b curve as follows:

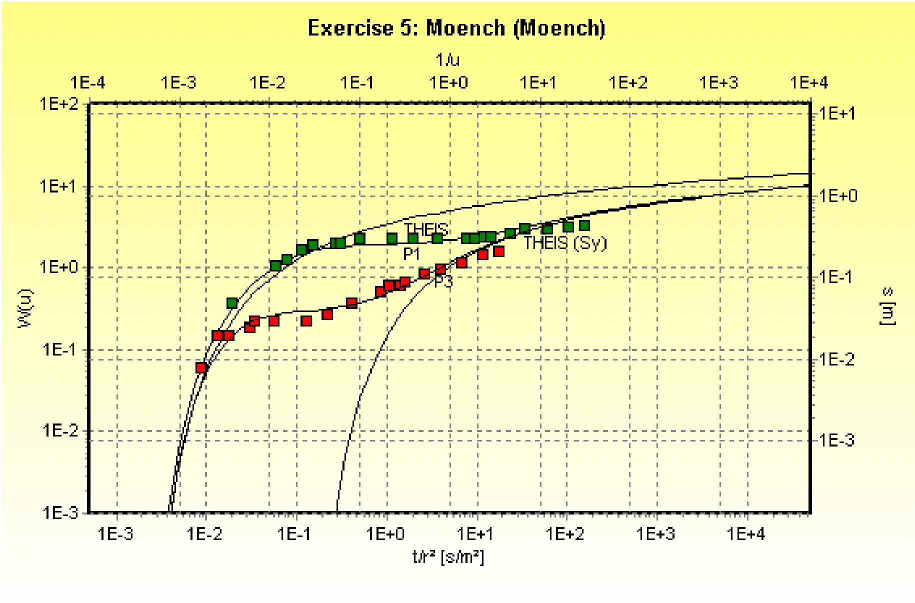
$$K_2 = \frac{\beta K_H b}{r^2}$$

When using the Neuman method, you should always use the same type curve for a single pumping test. For this reason, you can set the separation of the Theis curves by specifying a value of log (Sy/S). Pumping test data can then be matched to the early and late time type curves at the same time. Adjusting the value of log (Sy/S) is an iterative process to best match the data to the type curve.

You can also plot any additional b curves within the practical range, β= 0.001 to 4.0.

Moench

If you select the Moench solution method from the list of available methods, the following graph is displayed:



Each solution method has a Settings dialogue, where you can specify the method-specific parameters for your test. The settings dialogue for the Moench solution is shown below.

For the Moench method, you must enter all values for the Aquifer thickness, S/Sy, Kv/ Kh, and gamma. The aquifer thickness must be greater than the depth of a partially penetrating well or equal to the depth of a fully penetrating well. The solution method assumes that the aquifer is of uniform thickness, so all fully penetrating wells must all have the same value, b, or the depth from the water level to the bottom of the well screen.

S/Sy is the ratio of the storativity to the specific yield. This will plot the two Theis curves. The Moench curve will be plotted between the two Theis curves.

The ratio of the vertical hydraulic conductivity to the horizontal conductivity can be specified in the Kv/Kh entry.

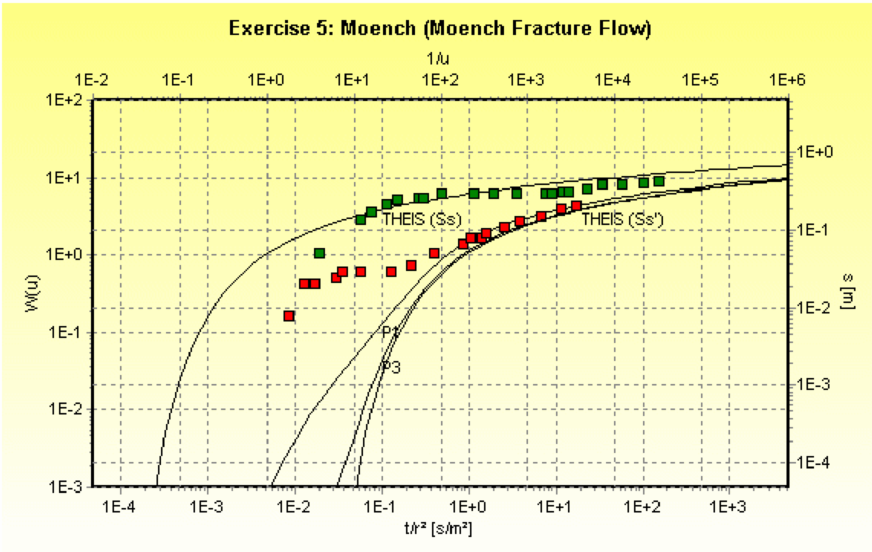
Gamma is the dimensionless drawdown parameter. It is based on the empirical constant alpha, vertical hydraulic conductivity, saturated thickness, and specific yield (Moench, 1995). A large Gamma value implies instantaneous drawdown, and a low value implies delayed drawdown.

On the Calculation tab, you can set the accuracy parameters for the numerical solution. The default settings should be acceptable for most scenarios. For more information about the accuracy settings, see Moench (1993).

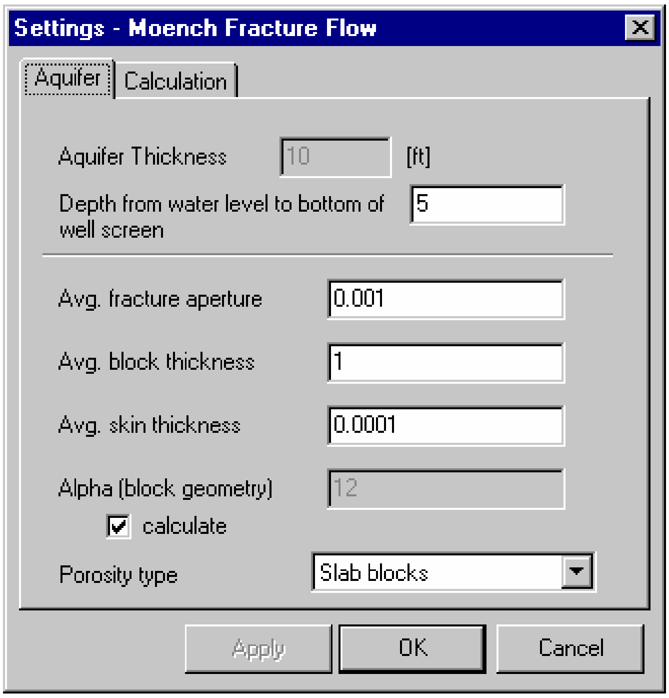
To restore the default accuracy settings for the Moench analysis, click [Reset].

Moench Fracture Flow

If you select the Moench Fracture Flow solution method from the list of available methods AND enter all the required variables, the following graph is displayed:



Each solution method has a Settings dialogue, where you can specify the method-specific parameters for your test. The settings dialogue for the Moench Fracture Flow solution is shown below:



The aquifer thickness must be greater than the depth of a partially penetrating well or equal to the depth of a fully penetrating well.

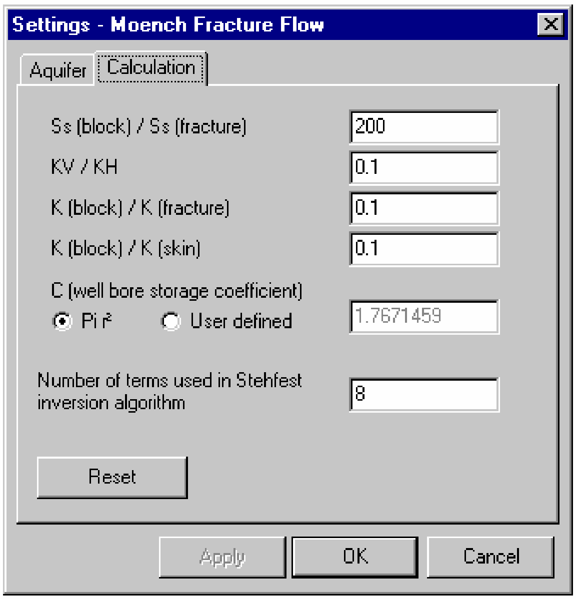
The fracture aperture and block thickness must be greater than zero. The skin thickness must be greater than or equal to zero.

The alpha (block geometry) value is by default calculated as 3/(b'/2) 2, where b' is the block thickness (Moench, 1984). The alpha parameter is used only in pseudo-steady state flow solutions.

The porosity type is one of the following:

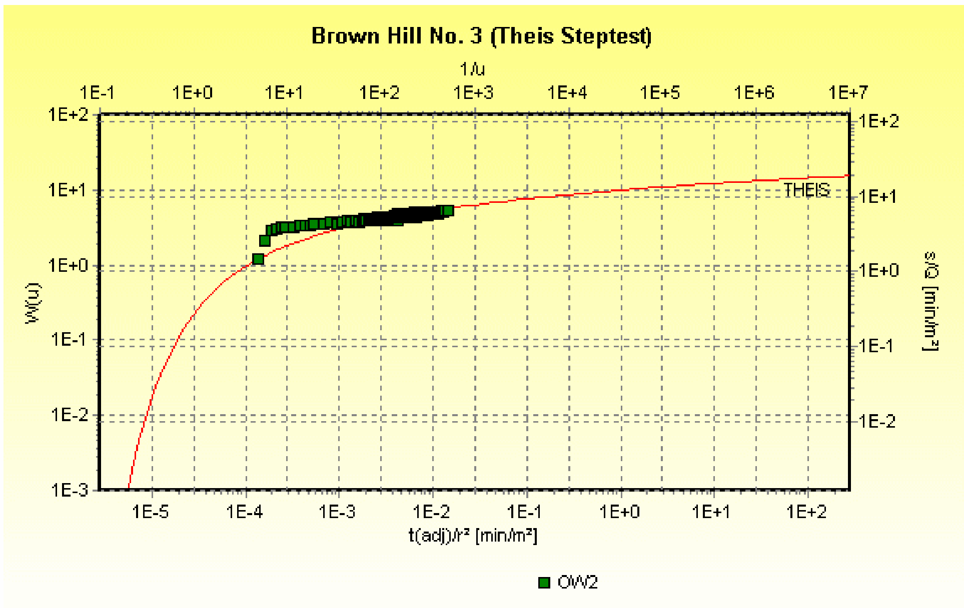
- Single porosity
- Pseudo-steady flow
- Slab blocks (transient block to fracture)
- Spherical blocks (transient block to fracture)

For the Fracture Flow method, you must enter all values for the Ss (block)/Ss (fracture), Kv/ Kh (ratio of the vertical hydraulic conductivity to the horizontal conductivity), K (block)/K (fracture), K (block)/K (skin), C (well bore storage coefficient), and the number of terms used in the Stehfest inversion algorithm. The default values were obtained from the examples published by Moench (1984).



Theis Steptest

If you select the Theis Steptest solution method from the list of available methods, the following graph is displayed:



Each solution method has a Settings dialogue, where you can specify the method-specific parameters for your test. The settings dialogue for the Theis Steptest solution is shown below:

Ensure you have the time-discharge data formatted correctly when using a step test analysis. The table below illustrates the pumping time and discharge rates for a pumping test included in the sample database.

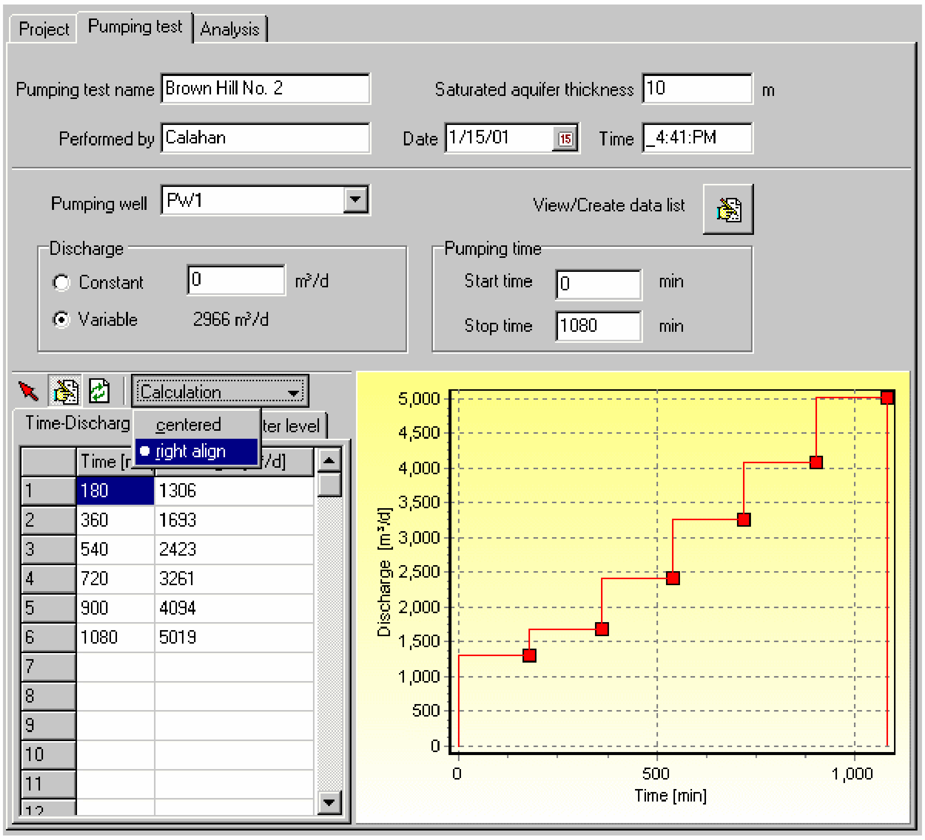
Note: To access the sample database, click File/Open Project from the top menu bar. Then, navigate to the Sample directory and open the enclosed database file.

Time (min.)	Discharge (m3/d)
180	1306
360	1693
540	2423
720	3261
900	4094
1080	5019

When you enter your time-discharge data in AquiferTest, your first entry is the initial pumping rate. Using the table above as an example, the pumping rate from 0-180 minutes was 1306 m 3/day. The second pumping rate from 180-360 minutes was 1693 m 3/day, and so on.

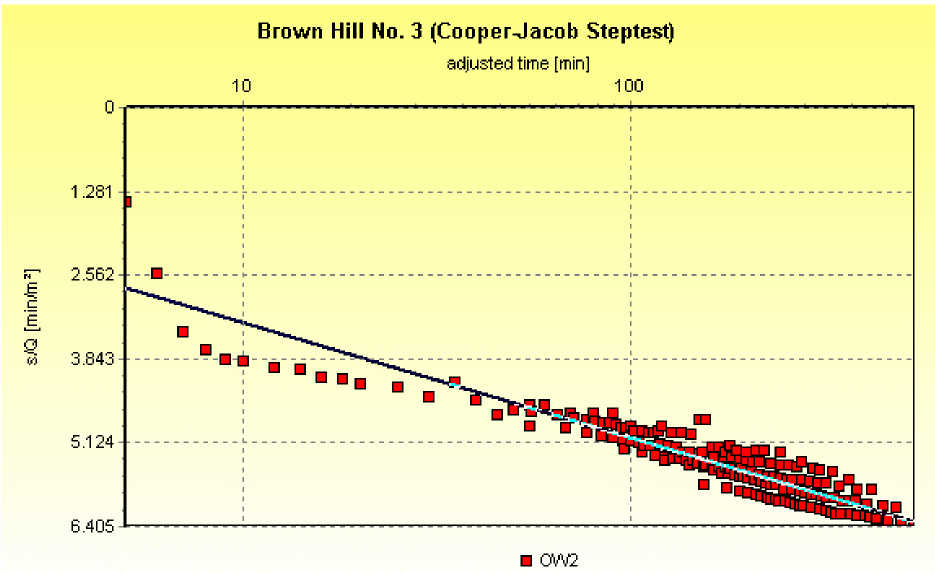
Once you have entered the pumping test data, click the Calculation button located above the data table. From the drop-down window that appears, select right align to set the correct format for the time-drawdown data.

For your convenience, the figure below has been included to demonstrate the correct data format for the pumping test notebook page.



Cooper-Jacob Steptest

If you select the Cooper-Jacob Steptest solution method from the list of available methods, the following graph is displayed:

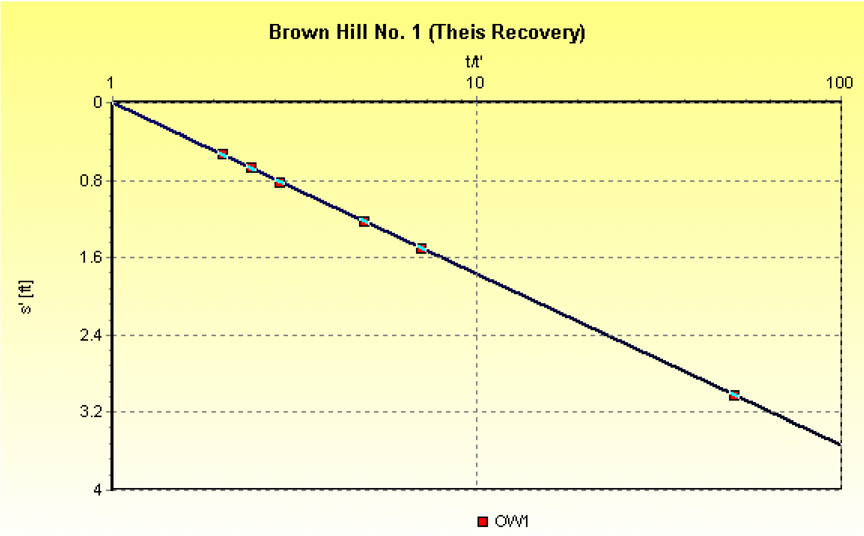


Each solution method has a Settings dialogue, where you can specify the method-specific parameters for your test. The settings dialogue for the Cooper-Jacob Steptest solution is shown below:

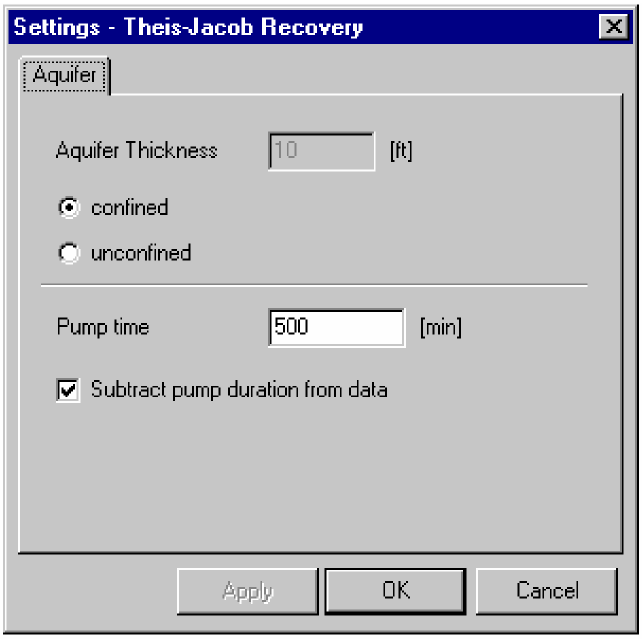
For information relating to the format of time-discharge data, please see the previous Theis Steptest section.

Theis Recovery

If you select the Theis Recovery solution method from the list of available methods, the following graph is displayed:



Each solution method has a settings dialogue, where you can specify the method-specific parameters for your test. The settings dialogue for the Theis Recovery solution is shown below:



You must enter the pumping duration. If you entered measurements since the beginning of pumping, select Subtract pump time from data so that only the values measured after pumping was stopped will be used.

Hantush-Bierschenk Well Loss

Using the Hantush-Bierschenk Well Loss solution is simply a matter of formatting the data correctly. The table below illustrates the pumping time and discharge rates for a pumping test included in the sample database.

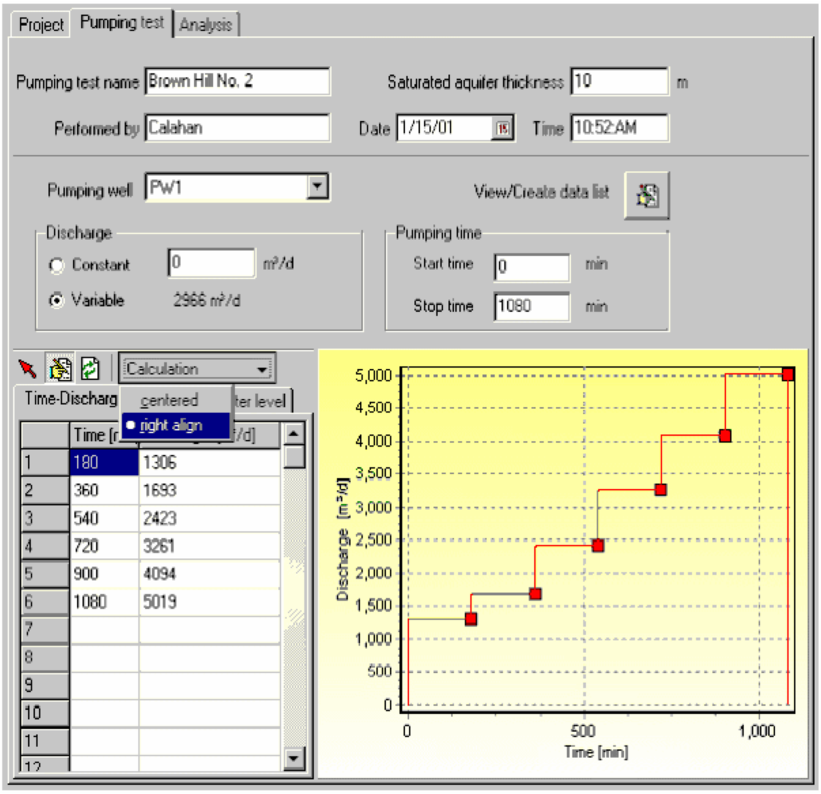
Note: To access the sample database, click File/Open Project from the main menu bar. Then, navigate to the Sample directory and open the enclosed database file.

Time (min.)	Discharge (m3/d)
180	1306
360	1693
540	2423
720	3261
900	4094
1080	5019

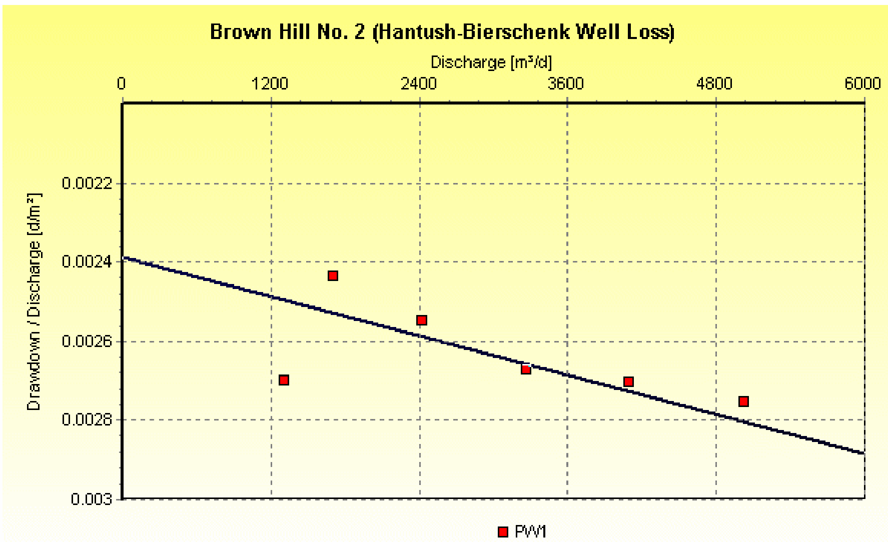
When you enter your time-discharge data in AquiferTest, your first entry is the initial pumping rate. Using the table above as an example, the pumping rate from 0-180 minutes was 1306 m 3/day. The second pumping rate from 180-360 minutes was 1693 m 3/day, and so on.

Once you have entered the pumping test data, click the Calculation button located above the data table. From the drop-down window that appears, select right align to set the correct format for the time-drawdown data.

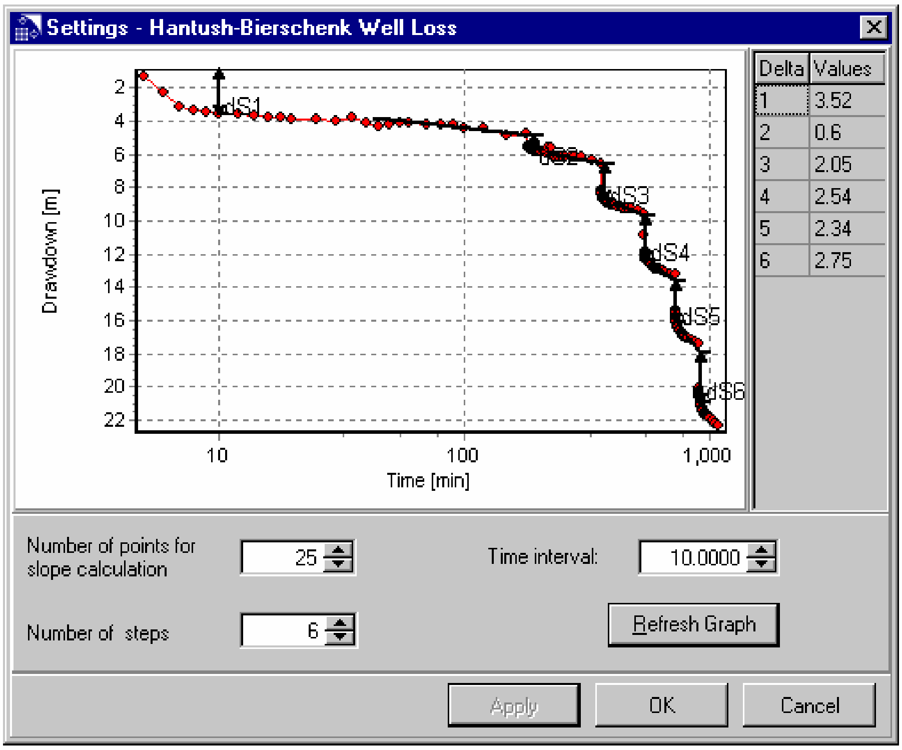
For your convenience, the figure on the following page has been included to demonstrate the correct data format for the pumping test notebook page.



Now, create a new data list and enter the time-drawdown data for the pumping well. Once completed, select the Hantush-Bierschenk well loss method from the list of available methods to display the graph below:

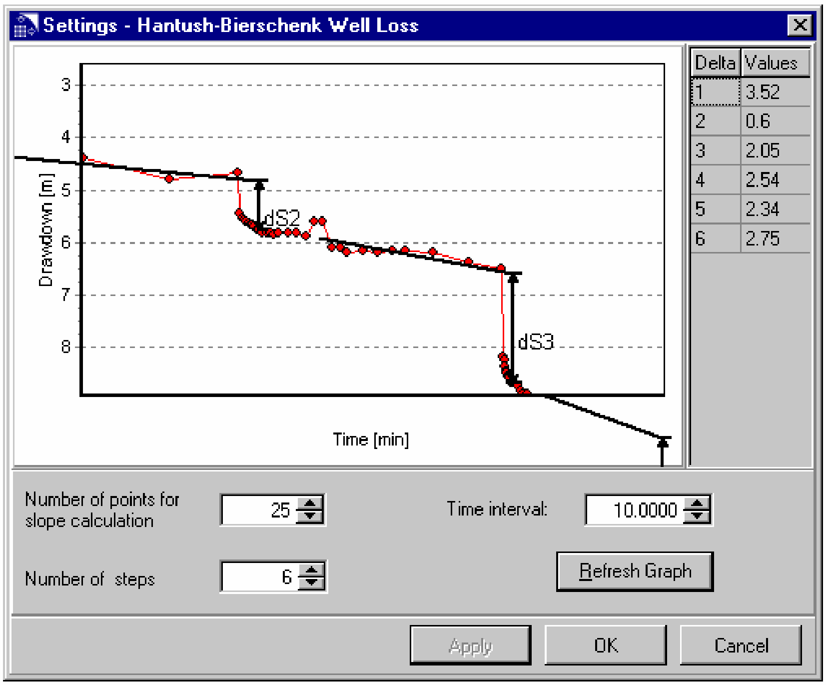


When you right-click on the analysis graph and select Settings..., the Settings: Hantush-Bierschenk Well Loss dialogue box is displayed:



This dialogue allows you to edit the number of steps to include in the analysis, as well as the line-fitting parameters for each step.

You can zoom in on the step plot by left-clicking and dragging open a box down and to the right around the data you wish to examine more closely. To zoom out, simply drag open a box up and to the left.



Each step in the analysis corresponds to a pumping rate entered in the pumping test notebook page. In the example above, there are six pumping rates in the test which therefore allows a maximum of six steps in the analysis.

The time-drawdown data is plotted on a semi-log graph, and the slope of each line is determined based on the Number of points for slope calculation you specify. Selection of data points begins at the end of the step and progresses backward in time as you add more points for the line slope calculation. For example, if the number of points is equal to five then AquiferTest will use the last five data points in each step to calculate the slope.

The Time interval is the time from the beginning of each step at which the change in drawdown (Ds) for each step is measured. For example, in the figure above Ds is measured 100 minutes from the beginning of each step. The point of time for calculating Ds is calculated as follows:

$$t_i + \Delta t = t_{ds}$$

where:

ti = starting time of step
Dt = the specified time interval
tds = calculation point for Ds

This measurement point is essential as the difference in drawdown is calculated between each step and displayed as dS1-dS6. The selection of the time interval is left to the discretion of the user.

AquiferTest then uses the drawdown differences and the specified time interval to produce two coefficients: B (linear well loss coefficient) and C (non-linear well loss coefficient). These coefficients can be used to estimate the expected drawdown inside your pumping well for a realistic discharge (Q) at a certain time (t). This relationship can allow you to select an optimum yield for the well, or to obtain information on the condition or efficiency of the well.

Finally, the Number of steps allows you to edit the number of steps (i.e. changes in the discharge rate) to use in the discharge versus drawdown plot. You should have a minimum of three steps specified to assist in obtaining a good fit of the line to the analysis plot.

For more information on the Hantush-Bierschenk Well Loss solution, please refer to a pumping test reference such as Kruseman and deRidder (1990).

Theis Prediction (Pumping Test Planning Forward Solution)

If you select the Theis Prediction solution method from the list of available methods, the following graph is displayed:

The pumping test planning solution is used by varying the input parameters in the Settings dialogue for the method. To view this dialogue, right-click on the analysis graph and select Settings...

The following Settings dialogue will be displayed. The components of this dialogue window are explained below.

Under Test Conditions, you can edit the following parameters:
Storativity - the estimated storativity of the confined aquifer you are planning to test.
Transmissivity - the product of the aquifer thickness (D) times the hydraulic conductivity (K).
Discharge - the rate at which water is removed from the pumping well.
Under Calculation, you can edit the following parameters:
Number of Datapoints - allows you to choose the number of points to plot on the planning graph.
You have two ways to view the planning graph: Time vs. Drawdown or Distance vs. Drawdown.
For Time vs. Drawdown plots, you have the following options. Note that this plot is distance dependent.
The Distance is the distance from the pumping well (located at 0,0) to the observation point where the plot of time versus drawdown is based.
End of Time is the maximum time which will be plotted on the time axis on the time versus drawdown graph.

For Distance vs. Drawdown plots, you have the following options. Note that this plot is time dependent.

Min. and Max. Distance allows you to specify the distance to be used on the distance axis of the distance versus drawdown plot.

The Time specified indicates at what point in time after pumping began (t=0) the distance versus drawdown plot should be based.

For a tutorial on how to use the Theis Prediction solution, see Chapter 5: Demonstration Exercises .

Specific Capacity

If you select the Specific Capacity solution method from the list of available methods, the following graph is displayed:

Hvorslev

If you select the Hvorslev solution method from the list of available methods, the following graph is displayed:

For the Hvorslev analysis method, you must enter all values for the piezometer geometry.

The effective piezometer radius (r) should be entered as the inside radius of the piezometer / well casing if the water level in the piezometer is always above the screen, or as calculated by reff=[r2(1-n) + nR2]1/2
if the water level falls within the screened interval during the slug test (where r = the inside

radius of the well, R = the outside radius of the filter material or developed zone, and n = porosity).

The radius of the developed zone (R) should be entered as the radius of the bore hole, including the gravel/sand pack. The Length of the screened interval (L), should be entered as the length of screen within the saturated zone under static conditions.

Bouwer-Rice

If you select the Bouwer-Rice solution method from the list of available methods, the following graph is displayed:

Each solution method has a Settings dialogue window, where you can specify the method-specific parameters for your test. The settings dialogue for the Bouwer-Rice solution is shown below:

For the Bouwer-Rice slug test method, you must enter all values for the piezometer geometry.

The effective piezometer radius (r) should be entered as the inside radius of the piezometer / well casing if the water level in the piezometer is always above the screen, or as calculated by reff=[r2(1-n) + nR2]1/2, where n = porosity, if the water level falls within the screened interval during the slug test (where r = the inside radius of the well, R = the outside radius of the filter material or developed zone, and n = porosity).

The radius of the developed zone (R) should be entered as the radius of the bore hole, including the gravel/sand pack.

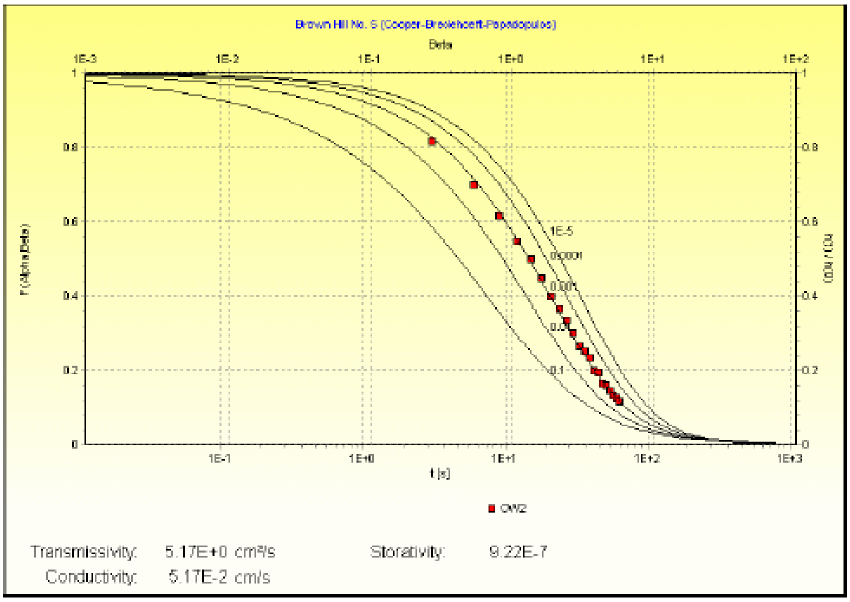
The Length of the screened interval (L), should be entered as the length of screen within the saturated zone under static conditions.

The height of the stagnant water column (b), should be entered as the distance from the static piezometric surface to the bottom of the screen.

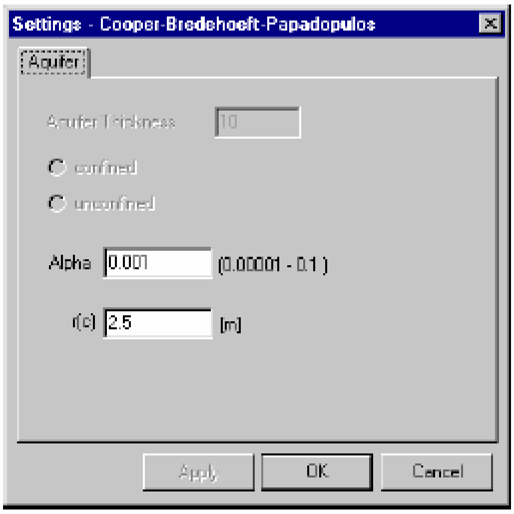
The saturated thickness of the aquifer (D), should be entered as the saturated thickness under static conditions.

Cooper-Bredehoeft-Papadopulos

If you select the Cooper-Bredehoeft-Papadopulos solution method from the list of available methods, the following graph is displayed:



Each solution method has a Settings dialogue window, where you can specify the method-specific parameters for your test. The settings dialogue for the Cooper-Bredehoeft-Papadopulos solution is shown below:



Using this dialogue, you can enter a user-specified Alpha value ranging from 0.1 - 0.00001.

In addition you can enter an r(c) value, which is the radius of the well casing and is used to calculate the storativity for your slug test analysis.

5. Demonstration Exercises

This chapter will explore many features of AquiferTest including various pumping test solution methods, importing data from a datalogger file (*.ASC), importing well locations and geometry from a text file (*.TXT) and planning a pumping test. The functionality of each feature is explained in detail in the following six exercises:

- "Exercise 1: Theis Analysis - Confined Aquifer Pumping Test"

- "Exercise 2: Cooper-Jacob Analysis Confined Aquifer Pumping Test"
- "Exercise 3: Theis Recovery Analysis with Data Logger Data"
- "Exercise 4: Hvorslev and Bouwer-Rice Slug Test Analyses"
- "Exercise 5: Moench Analysis - Unconfined Aquifer Pumping Test"
- "Exercise 6: Theis Prediction - Planning a Pumping Test"

The sequence of a typical AquiferTest session is:

[1] Open or create a project
[2] Enter or import data
[3] Select the analysis method
[4] Fit the type curve
[5] Print the output

If AquiferTest is not already installed, follow the instructions found in Chapter 2 - Getting Started.

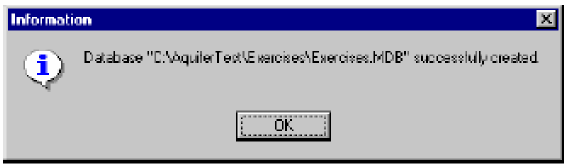
To move from one data entry box to the next, use the Tab key.

5.1 Exercise 1: Theis Analysis - Confined Aquifer Pumping Test

Exercise 1: Theis Analysis - Confined Aquifer Pumping Test

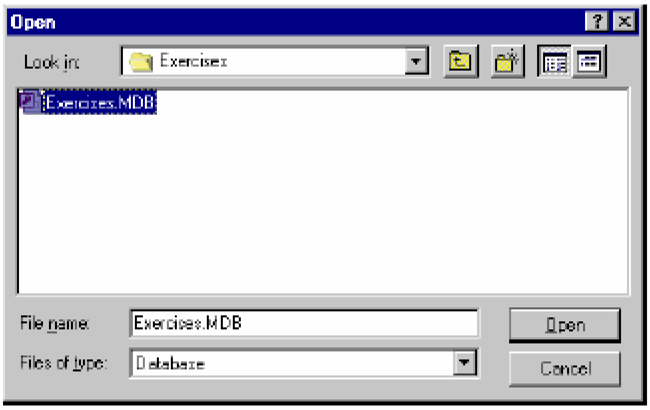
[1] If you have not already done so, double-click the AquiferTest icon to start an AquiferTest session.
[2] From the Main menu bar, click File followed by Create database...
[3] In the Save As window that appears, navigate to the Exercises folder that has been provided with AquiferTest. Then type Exercises in the File name field, and click Save.

[4] A window will appear confirming the creation of a new database. Click [OK].



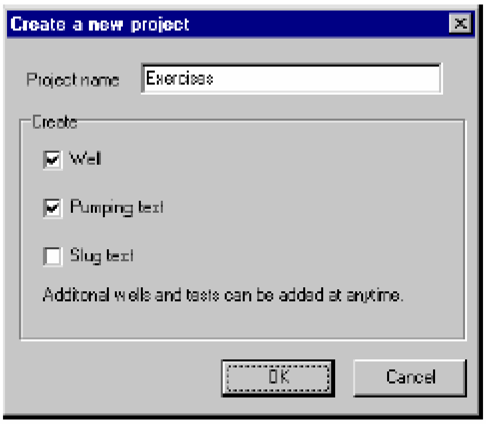
[5] Click File, Open Project... from the Main menu bar, followed by the folder icon located in the upper right corner of the window that appears. Navigate to the Exercises folder, and select the

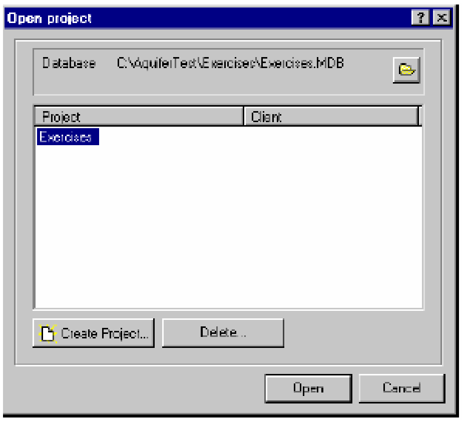
Exercises.MDB database you just created, followed by Open.



[6] In the Open project window that appears, click Create Project...

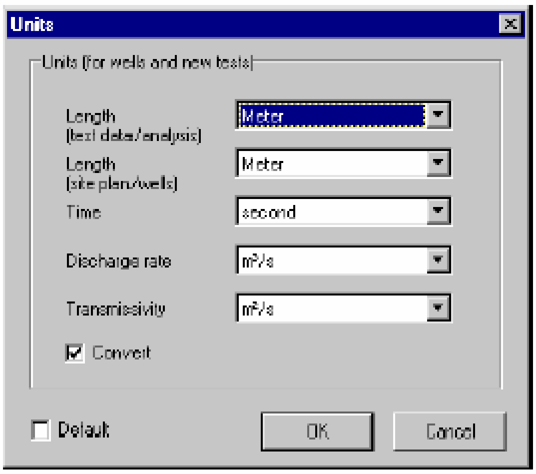
[7] In the Create a new project window that appears, type Exercises, and click [OK].





Then, click Open from the Open Project window (Exercises is highlighted).

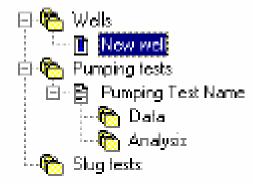
[8] From the Main menu bar, click Project then Units.



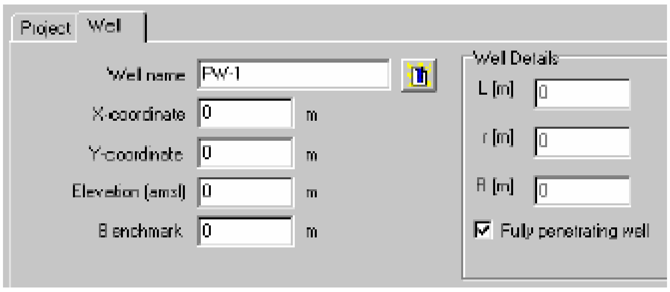
[9] For this example, we will use the units shown above. If your units are different, change them accordingly, and click [OK].

Wells

[10] On the left (navigator) panel, right-click your mouse and select Expand all from the dialogue that appears. Then, click New Well.

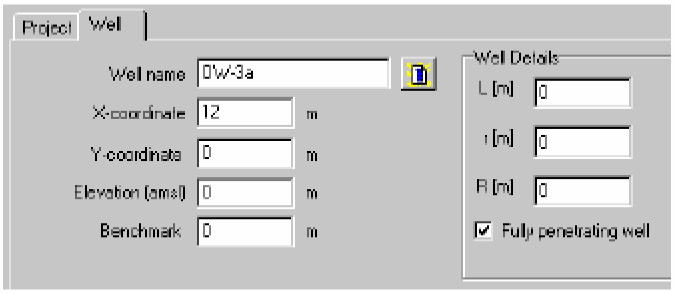


[11] On the Well page of the notebook, fill in the name PW-1. This will be a pumping well.



[12] On the navigator panel, select Wells and then click the right mouse button. Click New well.

[13] In the Create well dialogue that appears, type OW-3a and click [OK].

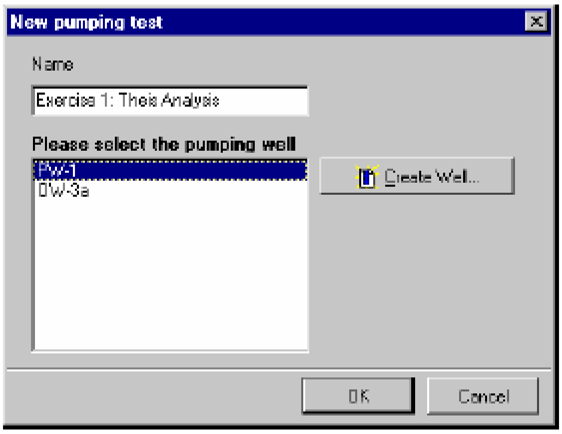


[14] On the Well page of the notebook, fill in the X coordinate 12. This will be an observation well. You do not need to enter the geometry of the well because we will be doing a Theis analysis, which assumes fully penetrating wells.

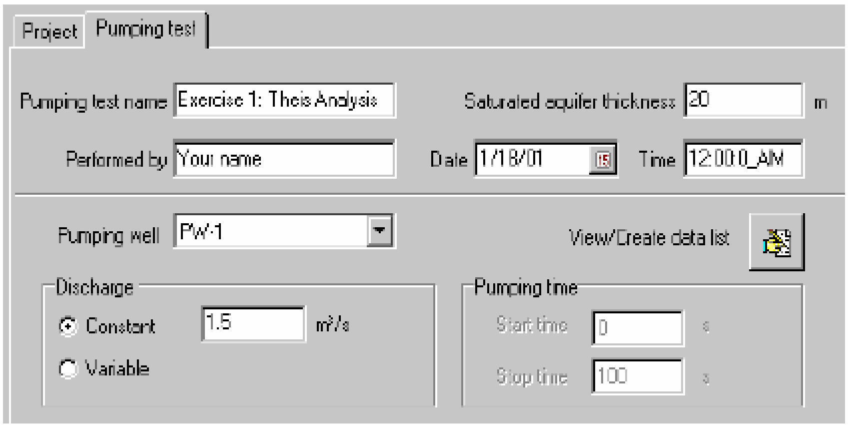
Pumping Test

[15] From the Main menu, select Test followed by Create pumping test...

[16] In the dialogue that appears, name the test, `Exercise 1: Theis Analysis', and select PW-1 as the pumping well. Click [OK].



[17] Fill out the Pumping Test page of the notebook, as shown on the following page. Enter a Constant Discharge rate of 1.5 m 3/s, and a Saturated aquifer thickness of 20 m.



Observed Data

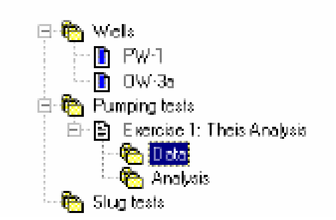
[18] In the navigator panel, right-click your mouse. From the window that appears, select Expand all.

[19] Before we proceed, let's delete the default pumping test entitled, Pumping Test Name.

[20] Highlight the default pumping test, and then right-click your mouse. From the window that appears, select Delete...

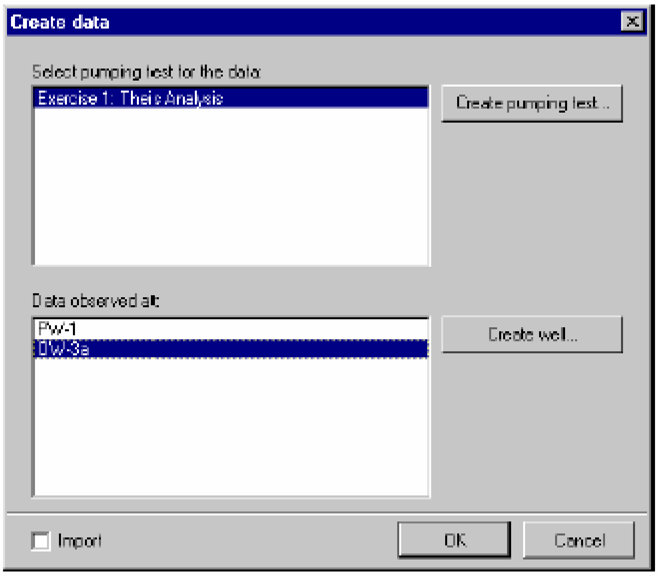
[21] Click Yes to confirm the deletion of the default pumping test.

[22] Now expand the navigator panel again and then click Data under the Exercise 1: Theis Analysis pumping test.



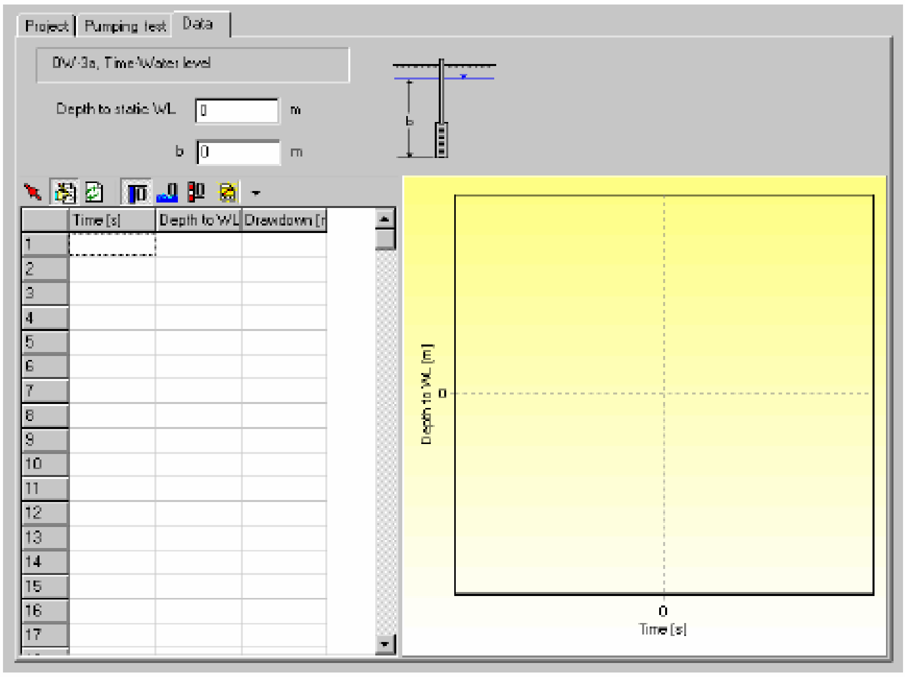
[23] Click the right mouse button, followed by Create Datalist...

[24] The Create Data window appears. Select which test the data applies to, and then under `Data observed at:', select OW-3a.



[25] Click [OK].

[26] The Data notebook page appears, as seen below:

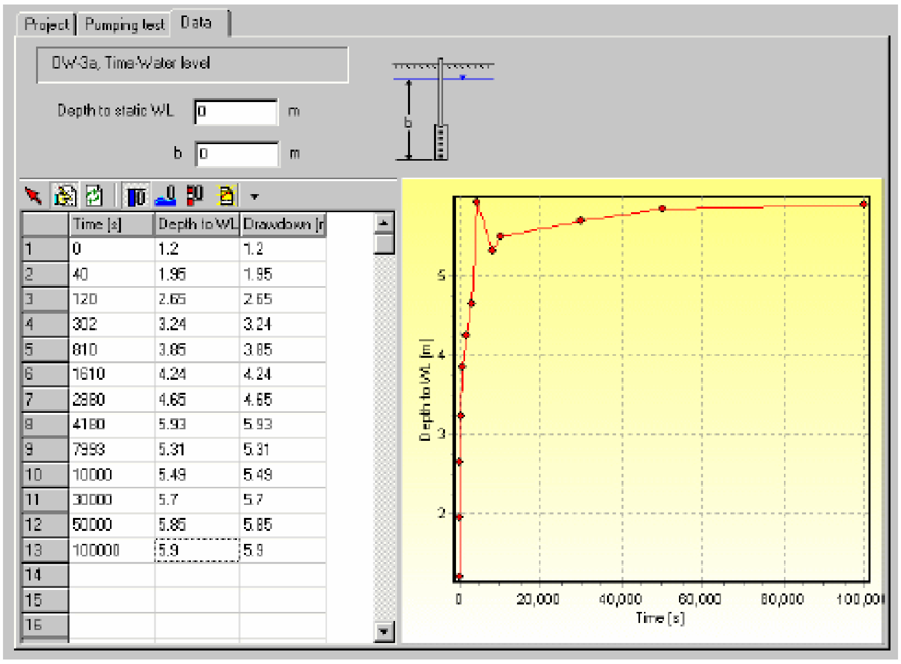


[27] In the Time (s) and Depth to WL (m) columns, enter the following data. Press Enter after each value to move to the next field.

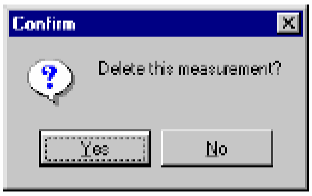
Do not type anything in the Drawdown column.

[28] Click the right mouse button anywhere on the right side of the window. Click Refresh graph in the window that appears (or click F5). A graph of the data is displayed.

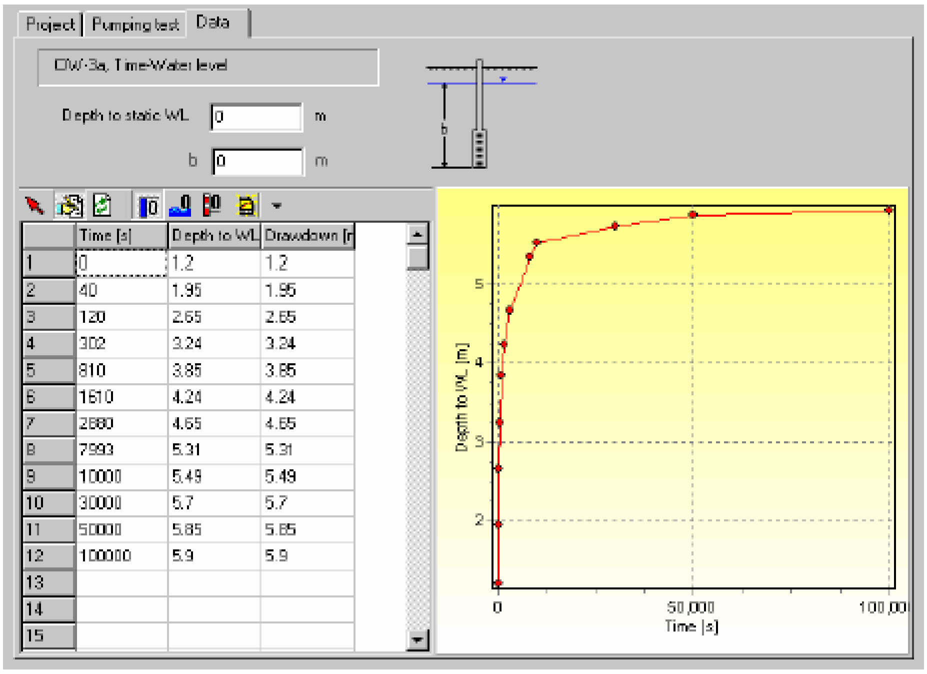
Time [s]	Water Level [m]
0	1.20
40	1.95
120	2.65
302	3.24
810	3.85
1610	4.24
2880	4.65
4180	5.93
7993	5.31
10000	5.49
30000	5.70
50000	5.85
100000	5.90



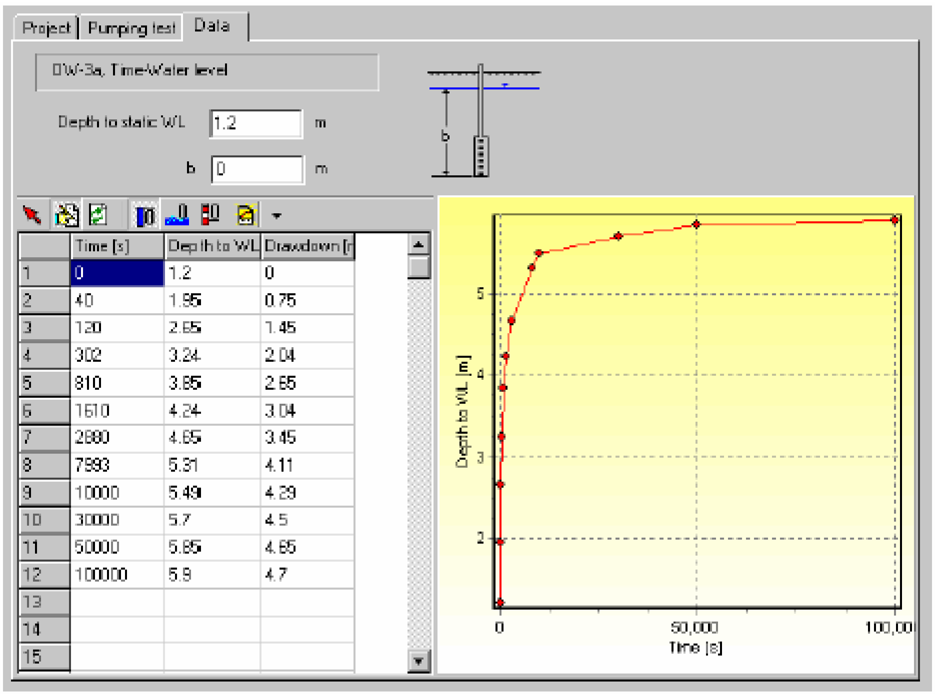
[29] One data point appears to be wrong, so let's remove it. In the table or graph, select the item at time 4180 s and click the right mouse button. In the window that appears, click Delete.



[30] Then, click Yes to confirm the deletion of the erroneous data point. The graph should update automatically.

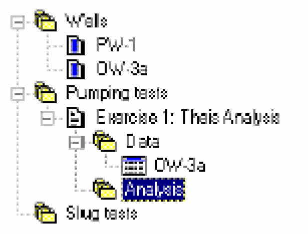


[31] Add a Depth to static water level of 1.2 m, and refresh the graph.

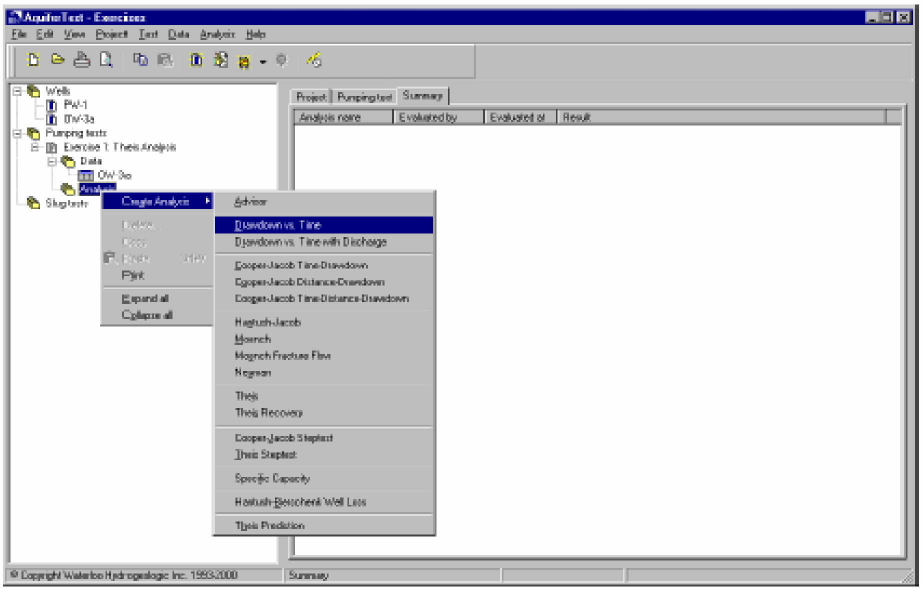


Theis Analysis

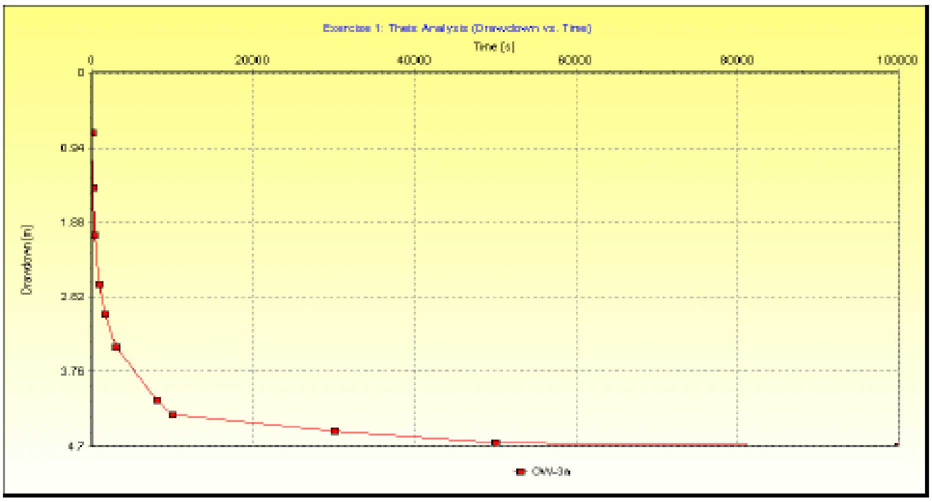
[32] In the navigator panel, select Analysis under the Exercise 1: Theis Analysis pumping test.



[33] Click the right mouse button, followed by Create Analysis.

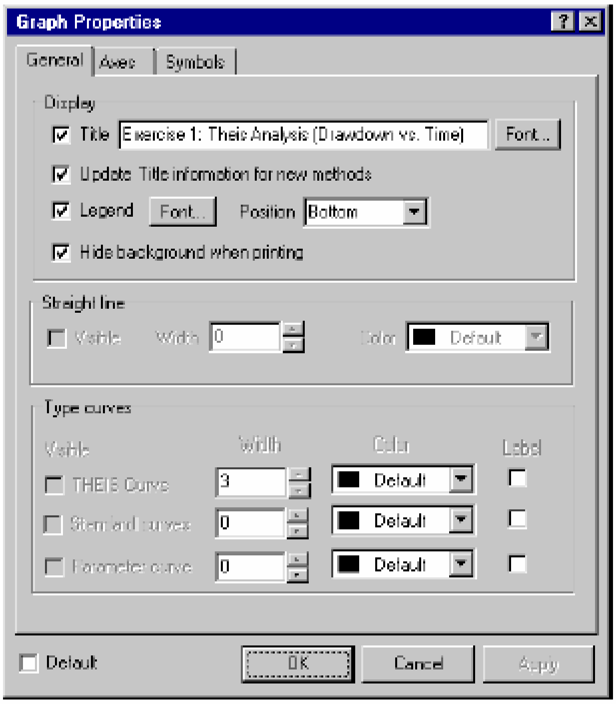


From the pop-up window that appears, select a Drawdown vs. Time plot.



[34] Notice the graph on the previous page displays the legend (OW-3a) at the bottom of the graph, while your legend is displayed to the right of the graph. The legend position can be set by right-clicking on the graph, and selecting Properties...

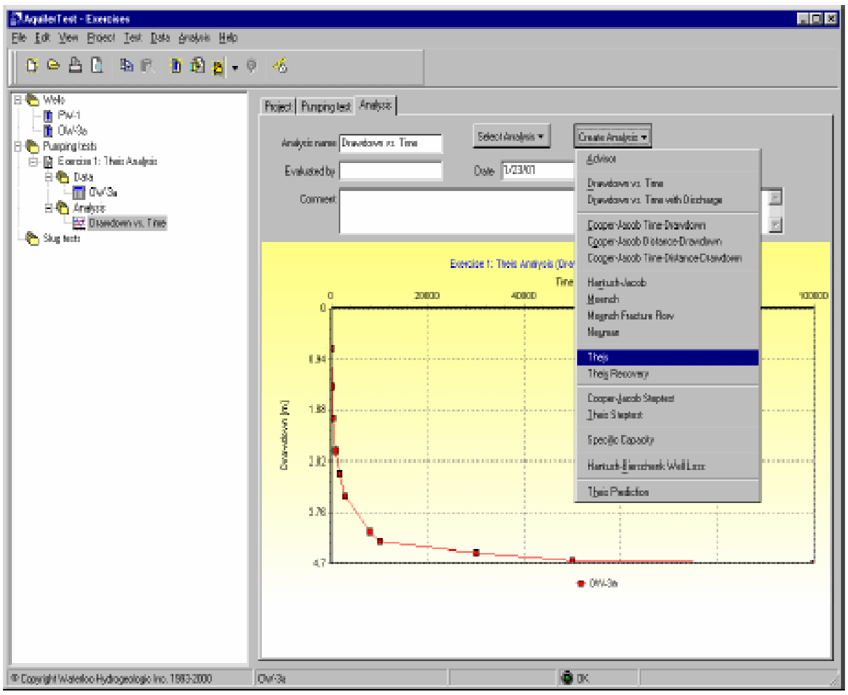
[35] In the dialogue that appears under the Legend option, set the Position to Bottom. Your display should appear as seen below:



[36] Click [OK]. Your legend should now appear at the bottom of your graph.

[37] Now, let's create a new analysis. There are several ways to do so; however, the most obvious is to select the Create Analysis button located above the graph.

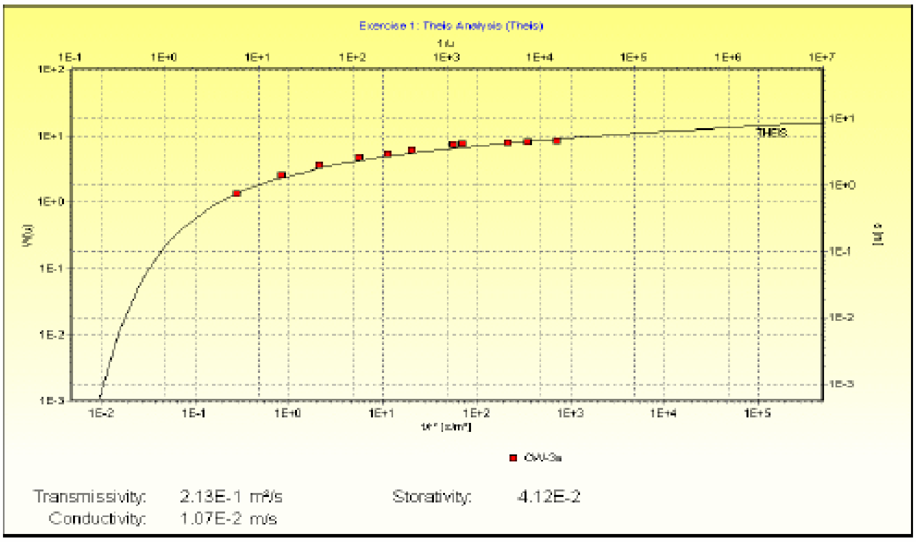
[38] From the pop-up window that appears, select Theis.



[39] A Theis analysis is displayed. Alternatively, you can create a new analysis by selecting Analysis from the top menu bar, followed by Create. As well, there is a shortcut icon located in

the menu bar that can create a new analysis.

NOTE: As opposed to creating a new analysis, you can simply change the current analysis by clicking the Select Analysis button located above the graph. Or, you can right-click your mouse and select Method, followed by the analysis you wish to display.



The Theis curve, based on a least squares fit, has been overlaid on the data. The estimated parameters with this fit are:

Transmissivity = 2.13E-1 m^2/s
Conductivity = 1.07E-2 m/s
Storativity = 4.12E-2

Zooming In and Out

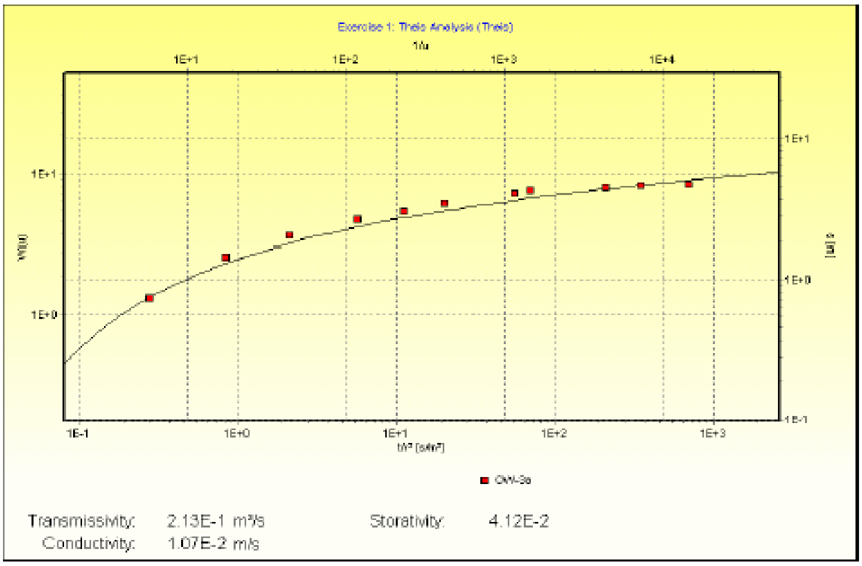
On all graphs, using your mouse you can zoom in and zoom out to change the display.

To zoom in, click in the upper left corner of the area that you want to see. Hold the mouse button down, and drag the mouse to the lower right corner of the area. When you release the mouse button, the area that you marked expands to fill the entire graph display.

To zoom out, click any point in the graph. Hold the mouse button down, and drag the mouse up to the right. When you release the mouse button, the entire graph is shown.

NOTE: It makes no difference where you click the mouse, or how large an area you delineate.

[40] Using the description above, zoom in on your data points. Your display should appear similar to the figure below:



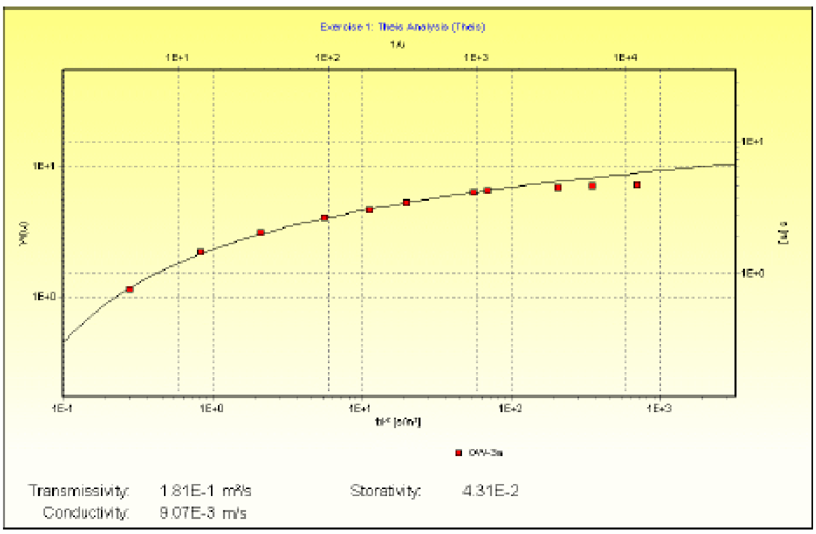
[41] Once you have examined your graph, zoom out by using the description above. Then, proceed to the next section.

Moving the Curve

You can use your professional judgement to adjust the curve as you see fit. For example, you may wish to place more emphasis on the early time data if you suspect that the aquifer is leaky or that some other boundary feature is affecting your results.

You can move the curve in any direction, using the up, down, right, and left arrow keys on the keyboard. When you press an arrow key, the Theis curve moves, and the transmissivity and storativity values are updated.

The figure below is an example of a manual fit, which has been subsequently zoomed-in to encompass the data points.



The least squares fit curve is not always the most appropriate curve; professional judgement is essential for the proper assessment of AquiferTest data.

NOTE: You can display an enlarged graph by clicking Ctrl+E. Once enlarged, the Navigator tree is hidden and data analysis becomes easier. To cancel the enlarged view, click Ctrl+E again. In this manner, you can toggle back-and-forth between the two display modes.

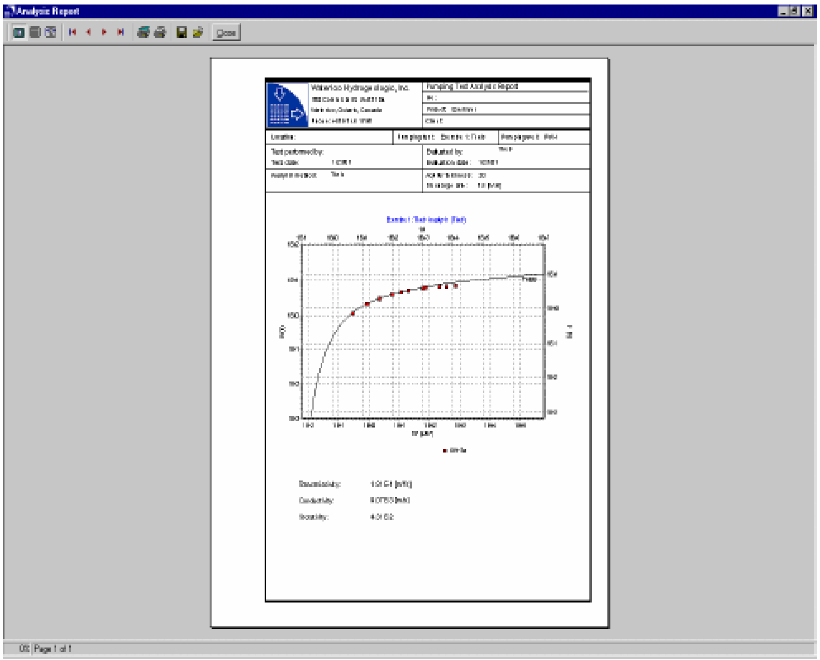
Printing

[42] To see what a printout of this analysis would look like, click File on the menu bar, then Print Preview.

[43] In the dialogue that appears, select the Zoom to fit icon located in the upper-left of the window

NOTE: Move your mouse over each icon to display a pop-up bubble description for each button.

[44] To print the analysis, click the Printer icon in Print Preview OR click File followed by Print.



[45] Click the Close button to exit the Print Preview.

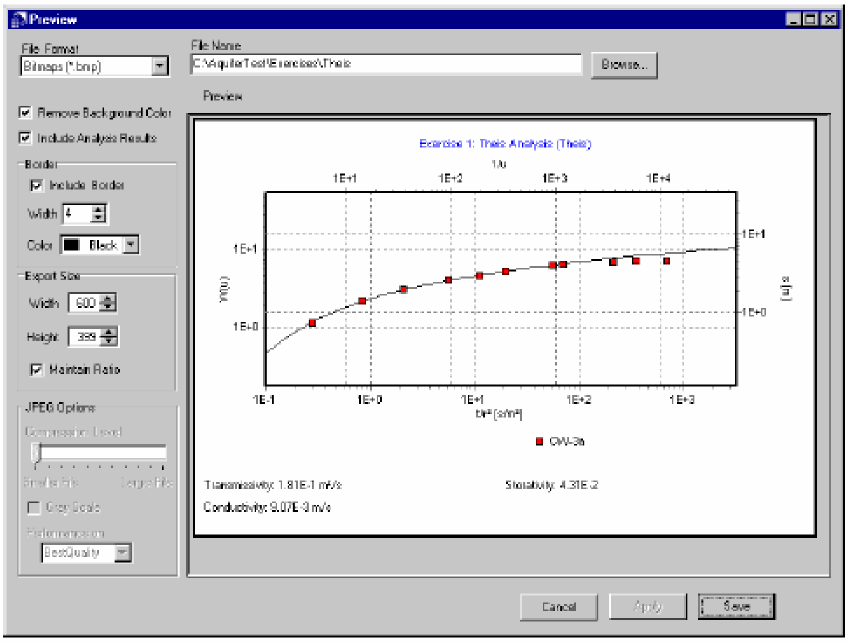
AquiferTest also allows you to export the analysis graph to a graphics file (.bmp, .jpg, .wmf, .emf) which can subsequently be included in your report.

[46] Click File from the Main menu bar, followed by Export then Analysis to Graphic. Alternatively you can simply right-click your mouse over the desired graph and select Export to Graphic from the dialogue that appears.

[47] In the Preview dialogue that appears, select the following options:

Remove Background Color check-box
Include Analysis Results check-box
Include Border check-box
Set the Border Width = 4
Maintain Ratio check-box
Set the Export Size Width = 600

[48] Once completed, click Apply and your display should appear similar to the figure below:



[49] Click Save to export the analysis to a graphics file (.bmp).

You have reached the end of Exercise 1. You can quit AquiferTest (click File on the menu bar, then Exit) or remain in AquiferTest and continue to "Exercise 2: Cooper-Jacob Analysis Confined Aquifer Pumping Test".

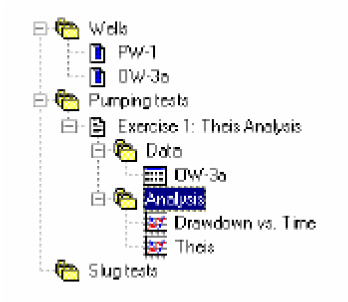
5.2 Exercise 2: Cooper-Jacob Analysis Confined Aquifer Pumping Test

Exercise 2: Cooper-Jacob Analysis Confined Aquifer Pumping Test
This example uses the same data as Exercise 1. You must perform the steps in Exercise 1 before you can proceed to Exercise 2.

[1] If the project named "Exercises" is not already open, click File on the menu bar and then Open Project. Select the Exercises project and click Open.

Cooper-Jacob Analysis

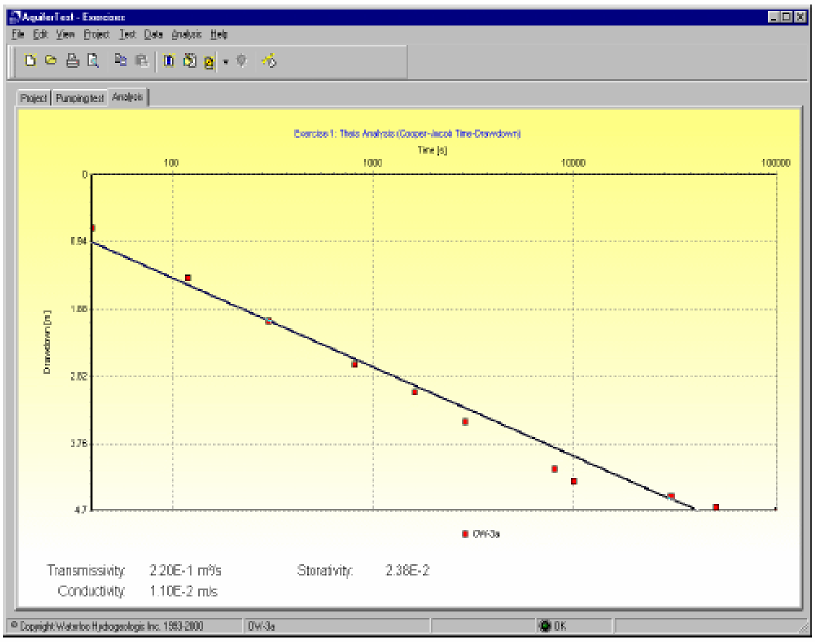
[2] In the navigator panel, select Analysis under the Exercise 1: Theis Analysis pumping test.



[3] Click the right mouse button, and select Create Analysis, followed by Cooper-Jacob Time-Drawdown.

[4] Press Ctrl + E (or select View on the menu bar, then Enlarge Graph). The graph now takes up the entire window.

[5] Click on a data point to activate the data set, and subsequently perform an automatic fit using the light bulb icon from the top menu bar.



A Cooper-Jacob line, based on a least squares fit, is overlaid on the data. The estimated parameters with this fit are:

Transmissivity = 2.20E-1 m^2/s
Conductivity = 1.10E-2 m/s
Storativity = 2.38E-2

Removing Unwanted Data Points

The Cooper-Jacob analysis is valid for data points with u < 0.01, as described in Chapter 3: Theoretical Background - Cooper-Jacob Method.
In this example, the first four data points have a u value that is too high. They should be removed from the analysis, as described below.

[6] Move the mouse pointer into the graph, and click the right mouse button and select Data.
[7] Under Select data for analysis, click to highlight the OW-3a, Time-Water level data.
[8] Click [Details...]. In the window that appears, unselect the four earliest data values (t = 0, 40, 120, and 302).
[9] Click [Close] in both windows.
[10] Use the light bulb icon to autofit the type curve to your data. Your display should appear similar to the figure below:
The first 4 data points have been removed from the analysis results; however, they are still displayed in the graph. To remove unwanted data points from the graph, you must use the Time limit(s) option located in the Data dialogue window.
[11] Once completed, press Ctrl+E to return your display to normal size (if you have not already done so) and then select a data point using your mouse (activates the data set).
To make this exercise more interesting, we have chosen a data set that shows a boundary effect. The Cooper-Jacob method is an appropriate analysis method to show the effect of nearby recharge boundaries or impermeable boundaries. The last few data points in this data set deviate from the straight line. This indicates a nearby recharge boundary or a leaky aquifer. This could be analyzed using the Walton (Hantush-Jacob) method (leaky, no aquitard storage) which is also available in AquiferTest.
[12] Using the arrow keys, rotate and shift the line to achieve a good fit (ignoring the last three data points). The left and right cursor keys rotate the line, and the up and down keys shift the line.
Using the manual fit option allows you to use expertise and knowledge of site conditions to more precisely fit the curve to your data. However, if you were to click the Autofit icon the program would still take into account all but the first 4 data points. To eliminate the unwanted data points from the graph completely (and not just the analysis results), let's use the Time limit option.
[13] Right-click your mouse over the graph, then select Data... from the window that appears.
[14] Under Time limit [s], select Between and type 800 and 20000. Your display should appear as follows:
[15] Click Close and then use the Autofit icon to fit the curve to your data. Your graph should appear similar to the figure below Correction for Unconfined Conditions
The evaluation of pumping test data from an unconfined aquifer is usually done using the Neuman method. However, simple correction terms have been introduced.
[16] From the Main menu bar, click Analysis then Settings... In the window that appears, select unconfined.

[17] Click [OK], and then use the Autofit icon to fit the curve to your data.
As you can see, the correction for unconfined conditions has changed the results to:
Transmissivity_ 2.21E-1 m^2/s
Conductivity_ 1.10E-2 m/s
You have reached the end of Exercise 2. You can quit AquiferTest (click File on the menu bar, then Exit) or remain in AquiferTest and continue to "Exercise 3: Theis Recovery

Analysis with Data Logger Data".
The instructions in this exercise assume that you have performed the previous exercises.

5.3 Exercise 3: Theis Recovery Analysis with Data Logger Data

The instructions in this exercise assume that you have performed the previous exercises.

Observation Well

[1] In the navigator panel, select the Wells folder (becomes highlighted) and then right-click your mouse. From the dialogue window that appears, select New well.

[2] A Create well dialogue window appears. Type OW-1, and click OK.

[3] In the Well page of the notebook, fill in the X coordinate 10. This will be an observation well. You do not need to enter the well geometry because we will be doing a Theis recovery analysis, which assumes fully penetrating wells.

Observed Data

[4] In the navigator panel, select the Pumping tests folder and then right-click your mouse. From the dialogue window that appears, select New pumping test.
[5] In the dialogue that appears, type the test name "Exercise 3: Theis Recovery Analysis", and select PW-1 as the pumping well. Click OK.
[6] In the Pumping test Notebook page, specify a Constant Discharge rate of 0.0015 m^3/s. As well, add a Saturated aquifer thickness of 20 m.
[7] Click the View/Create data list button, located above the pumping time fields.
[8] The Create data window appears. Under Select pumping test for the data, highlight Exercise 3: Theis Recovery Analysis.
[9] Under Data observed at, select OW-1. Your screen should appear as seen in following figure:
[10] Click [OK]. The Data Notebook page appears. In the next section, you will import a data set from a data logger file.

Data Logger File

[11] From the top menu bar, click Data followed by Data logger file...
[12] Navigate to the Exercises folder, and select Logger.asc.
[13] Select Open OR double-click Logger.asc.
The logger file is an ASCII file with the following format:
day/month/year hour:minute:second water-level
In the first step, you can specify the row number where you want to start importing.
[14] Click [Next]. In the second step, you specify the column separators (delimiters). Select Space and unselect Tab. The records are now divided into columns. If you are unsure which delimiter is used by your data logger, select by trial-and-error the various options under Separators until your data is separated into columns.
[15] Click [Next]. In the third step, you specify which column represents the Date. Select the box above the first column, and the word Date appears in the box. Select the DD/MM/YY date format from the pull-down menu located in the bottom left of the window.

[16] Click [Next]. In the fourth step, you specify which column represents the Time. Select the box above the second column.
[17] Click [Next]. In the fifth step, you specify which column represents the Depth to water level (WL). Select the box above the third column. The fourth column (containing "m" for "meters") will be ignored. Verify that the Unit field contains "m".
[18] Click [Next]. Fill in the window for step 6 as shown below.
NOTE: Most data loggers collect data at equal time intervals (e.g. every 10 seconds), which can produce very large files (in this case, 6,000 data points). There is little value in importing many data points with the same water level. By filtering your data by the change in water level, you can drastically reduce the number of data points imported into AquiferTest.
[19] Click [Import], and the program reads the data file. After a few seconds, it should return with the message 233 data points imported. Click [OK] to close the window.
[20] Specify a Depth to static water level (WL) of 2.5 m.
[21] Click the right mouse button anywhere on the right side of the window. Click Refresh graph from the pop-up menu.

Recovery Analysis

[22] Click the Create a new analysis button, located above the data table. Select Theis Recovery from the pull-down menu that appears.
[23] Click the status panel, or Error message, located below the graph. In the Analysis state window that appears, click Details to expand the box.
[24] We must specify a pumping duration, as the graphical display will show all data "squished" against the y-axis. The model requires that we tell it the time at which the pumping was stopped. The X axis on the graph shows t/t' which is defined as:
[25] Click OK to close the Analysis state window.
[26] From the top menu bar, click Analysis followed by Settings. In the window that appears, specify a pumping time of 30000 s and ensure the Subtract pump duration from data option is selected.
[27] Click [OK].
[28] Click on a data point or the legend (to activate the data series).
Then, click the light bulb icon to re-do the analysis. This fits a straight line to the measured data, and displays the transmissivity.
NOTE: The analysis graph legend has been turned off from the Analysis/
Properties dialogue.
As you can see, the Theis Recovery produced the following results:
Transmissivity_ 5.03E-4 m^2/s
Conductivity_ 2.51E-5 m/s
You have reached the end of Exercise 3. You can quit AquiferTest (click File on the menu bar, then Exit) or remain in AquiferTest and continue to "Exercise 4: Hvorslev and Bouwer-Rice Slug Test Analyses".

5.4 Exercise 4: Hvorslev and Bouwer-Rice Slug Test Analyses

Exercise 4: Hvorslev and Bouwer-Rice Slug Test Analyses

During a slug test, a slug of known volume is lowered instantaneously into the well. This is equivalent to an instantaneous addition of water to the well, which results in a sudden rise in the water level in the well (also called a "falling head" test). The test can also be conducted in the opposite manner by removing water from a well (called a "bail" or "rising head" test). For both types of tests, the water level recovery is measured. The Hvorslev method is a popular method for evaluating slug test data.

Observation Well

[1] In the navigator panel, select the Wells folder and right-click your mouse. From the dialogue that appears, click New well.

[2] A Create well dialogue appears. Type OW-11.

[3] In the Well page of the notebook, fill in L = 3.0 m, r = 0.025 m, and R = 0.075 m, and finally unselect the Fully penetrating well box.

As only one well will be used, the X and Y coordinates are irrelevant.

Slug Test

[4] In the navigator panel, select the Slug tests folder and right-click your mouse. From the dialogue that appears, click New slug test.

[5] In the dialogue that appears, type the test name “Exercise 4: Hvorslev”. Select the test well, OW-11, and click OK.

[6] In the Slug test Notebook page, enter the following:

Saturated aquifer thickness: 7.2 m

Performed by: Your name

Depth to static water level (WL): 2.2 m

Water level at t=0: 2.62 m

b: 5.22 m.

NOTE: ‘b’ represents the depth from WL to bottom of the well screen.

[7] Enter the following data values, pressing Enter after each value to move to the next field:

Time[s]	Water Level [m]
2	2.57
5	2.54
10	2.47
21	2.38
46	2.29
70	2.25
100	2.22

Do not type anything in the Change in WL column.

[8] Refresh the graph, and your display should appear similar to the figure below.

[9] In the navigator panel under Exercise 4: Hvorslev Analysis slug test, click the ‘+’ sign to expand the tree. Subsequently, highlight the Analysis folder.

[10] Click the right mouse button, and select Create Analysis. From the list that appears, select

Hvorslev.
[11] Press Ctrl + E (or select View on the menu bar, then Enlarge Graph). The graph now takes up the entire window.
[12] Click a data point to activate the data series, then perform an automatic fit using the light bulb icon from the Main menu bar.
NOTE: The analysis legend has been turned off from the Analysis/ Properties dialogue window.
The graph on the screen should show a semi-log plot, with time on the X axis and h/h0 on the Y axis.
h/h0 is the recovery of the water table; the model extracts the time lag, TL, at which h/h0 = 0.37 and calculates the hydraulic conductivity, K, as follows:

$$K = \frac{r^2 \ln\left(L/R\right)}{2LT_L}$$

where L is the length of the screen, r is the radius of the stand pipe,
and R is the radius of the screen (this may include the sand pack).
You should produce a hydraulic conductivity of approximately: 1.1E-5 m/s.
[13] Press Ctrl + E (or select View on the menu bar, then Enlarge Graph). This cancels the enlarged view of the graph.

Bouwer-Rice Analysis

AquiferTest also contains the Bouwer-Rice method for the analysis of slug test data for unconfined aquifers.
In terms of the equations and parameters involved, the Bouwer-Rice method is more sophisticated than Hvorslev. It accounts for the geometry of the screen (fully or partially penetrating), the gravel pack, finite saturated thickness, height of the stagnant water column in the well, and an effective radial distance over which the initial drawdown is dissipated.
As a result, the Bouwer-Rice method may provide a more accurate calculation of the hydraulic conductivity.
In practice, the results from the Bouwer-Rice and Hvorslev tests are often quite close.
[14] Click the Create a new analysis button from the Main menu. From the list that appears, select Bouwer-Rice.
[15] Press Ctrl + E (or select View on the menu bar, then Enlarge Graph). The graph now takes up the entire window.
[16] Select a data point to activate the data series, and then perform an automatic fit using the light bulb icon from the top menu bar.

You should produce a hydraulic conductivity of approximately: 8.46E-6 m/s.
NOTE: The computed hydraulic conductivity value is less than that computed using the Hvorslev method, however the values are reasonably close (within a factor of 2).
[17] On the menu bar, click Analysis, followed by Settings... As the water level is above the screened interval, we do not need to make any changes.
NOTE: The value of the effective piezometer radius [r(eff)] depends upon
whether the water level is within the screened interval.
If the water level is above the screened interval, r is radius of the piezometer. If

the water level is within the screened interval, r can be calculated as follows:

$$r(eff)=(r_i^2(1-n)+nR^2)^{1/2},$$

where:

ri=piezometer radius,

R=radius of the gravel pack

(developed zone), and

n=porosity.

[18] Click [OK] or [Cancel].

You have reached the end of Exercise 4. You can quit AquiferTest (click File on the menu bar, then Exit) or remain in AquiferTest and continue to “Exercise 5: Moench Analysis - Unconfined Aquifer Pumping Test”.

5.5 Exercise 5: Moench Analysis - Unconfined Aquifer Pumping Test

Exercise 5: Moench Analysis - Unconfined Aquifer Pumping Test

This exercise is completely unconnected to the other exercises. To avoid confusion, you start by creating a new project.

New Project

[1] From the Main menu bar, click File.

[2] Click New Project, and fill out the dialogue window that appears as seen below. Be sure to unselect the Well and Pumping Test checkboxes. Click OK.

[3] From the Main menu bar, click Project, then Units... Select the units shown below, and click OK.

Wells

[4] In the navigator panel, select the Wells folder and right-click your mouse. In the dialogue that appears, click Import Wells.

[5] Select Ex5-Wells.txt from the dialogue that appears, then Open.

[6] In the Import Wizard - Step 1 dialogue that appears, select First record contains header information. As you can see, the Start import at row field automatically changes to 2.

[7] Click Next. In Step 2 that appears, you can match the import fields from the text file to the AquiferTest fields. By clicking and dragging the AquiferTest Data fields to the appropriate locations, you can line-up the corresponding fields.

[8] The data for this exercise has been already formatted for your convenience, so simply click Next to advance to the final step.

[9] In the final step, there are 2 tabs - Preview and Errors. The first tab, Preview, allows you to specify each well entry as either Add or Ignore. In this case, all of the wells will be added to the project.

[10] The second tab, Errors, contains any problems with the well data that must be resolved before you can complete the final step.

[11] Click Import to import the wells into the project. When completed, the well Summary tab will appear as seen below.

Pumping Test

[12] In the navigator panel, select the Pumping tests folder and then right-click your mouse. Click New pumping test.
[13] In the dialogue that appears, type the test name "Exercise 5: Moench". Then select the pumping well, PW-1, and click OK.
[14] In the Pumping Test page of the notebook, enter a Saturated aquifer thickness of 6.1 m, and a Constant Discharge rate of 86.4 m^3/d.
[15] Right-click your mouse over the navigator panel, and then click Expand all to see the entire tree structure.

Observed Data

[16] Click the View/Create Data List button from the Pumping test tab.
[17] The Create Data window appears. Select Exercise 5: Moench, P1 as the observation well, and activate the Import check-box. Your display should appear as seen on the following page.
[18] Click [OK]. An Open dialogue will appear prompting you to select an Excel (.xls) file. Click Ex5-Data.xls and then Open.
[19] An Import Data dialogue appears. This window allows you to highlight data you want to import for the new datalist.
[20] Click once with your mouse in the spreadsheet area of the dialogue to activate it, then on the cell A2. Hold down your mouse button and drag downwards to encompass the entire Time list. When completed click on the Depth to WL red arrow, and then highlight the P1 data column (ranges from B2 to B21).
[21] Click the Import button once your display appears similar to the figure above.
[22] The Pumping Test Data notebook appears. Specify a b (distance from bottom screen to water level) value = 4.272 m.
[23] Click the right mouse button anywhere on the right side of the window. From the window that appears, click Refresh graph. The Depth to WL vs. time curve is displayed.
[24] Repeat steps [16] to [23] for well P3 (and optionally wells P5, P7, P4, and P6). The following picture shows the data for well P3.
NOTE: Ensure to enter the depth from water level to the bottom of the well screen (b) for each well. These values can be found in the list below:

Well Name	b (m)
PW-1	6.021
P1	4.272
P3	4.048
P5	4.20
P7	4.546
P4	4.115
P6	4.335

[25] Once completed, click on each well individually from the Navigator panel and de-select the Fully penetrating well option box. This ensures that each well is defined as partially penetrating for this analysis, as seen in the following image for the pumping well, PW-1:

Moench Analysis

[26] Once you have imported the well data and specified each well as partially penetrating, you are ready to analyze the data. Right-click on the Analysis folder in the Navigator panel, and select Create Analysis. From the list that appears, select Moench.
[27] Press Ctrl + E (or select View on the menu bar, then Enlarge Graph). The graph now takes up the entire window.
[28] Right-click your mouse on the graph, and select Data. If you have created the optional additional wells, ensure that only P1 and P3 are selected. Click Close.
[29] Then, click the Status panel located below the graph. Once the Analysis state window appears, click Details to expand the box.
[30] To complete the analysis, we must set the distance from the bottom of the well screen to the water level in the pumping well. Rightclick your mouse on the graph, and select Settings from the window that appears.
[31] In the Moench Settings window, enter the following values:

Depth from WL to bottom of well screen	6.021 m
S/Sy	0.015
KV/KH	0.3

[32] Click OK.
[33] From the Main menu bar, click Test, then Units... This changes the units for the current test only (unlike Project - Units...). Alter the units according to the figure below:
[34] Click [OK].
[35] Select a data point from the graph to activate the data set, and subsequently perform an automatic fit using the light bulb icon from the Main menu bar.
[36] Now, use the arrow keys on the keyboard to manually fit the curves to the data points. The left and right arrow keys change only the specific yield.
NOTE: To move your data in larger steps, hold down the Shift button on your keyboard, then use the arrow keys.
The estimated parameters with this fit are (yours may be different depending on how you fitted the data to the type curves):

Transmissivity	6.04E+0	cm^2/s
Specific yield	3.03E-3	
Hydraulic conductivity	9.90E-3	cm/s
Hydraulic cond. vertical	2.97E-3	cm/s.

You have reached the end of Exercise 5. To quit AquiferTest, click File on the menu bar, then Exit. Otherwise, proceed to “Exercise 6: Theis Prediction - Planning a Pumping Test”.

5.6 Exercise 6: Theis Prediction - Planning a Pumping Test

In Chapter 2, you were introduced to the pumping test planning solution in AquiferTest. This "forward solution" allows you obtain estimated values of test parameters such as an optimum discharge rate, or distance between pumping and observation wells. The following exercise illustrates the steps necessary to obtain an estimate of the discharge rate required for a pumping test.

An aquifer test is a carefully planned and conducted scientific field experiment where a stress (discharge from a pumping well) is applied to an aquifer, and the resulting response (change in water level measured in observation wells) is carefully recorded for later analysis. A pumping test is conducted to gain estimates of the hydrogeologic parameters that control groundwater flow.

When planning a pumping test, it is instructive to begin with the requirements of final data analysis in mind. For example, when fitting time versus water level drawdown data to the Theis curve, the early time data (i.e. the first two minutes of the test) are crucial for achieving a good fit of the data to the curve. Where early time data are lacking, the fit is uncertain, and the resulting calculation of the storativity potentially inaccurate.

In this exercise, you will use AquiferTest to estimate the discharge rate required to produce a measurable drawdown of at least 0.01 feet, inside an observation well located 30 feet from the pumping well, within the first two minutes after pumping starts.

[1] After starting AquiferTest, create a new project by selecting File, New Project...

[2] In the dialogue that appears, enter the project name Exercise 6: Theis Prediction. Under Create, select Well and Pumping test to have these default components created with your new project. Click [OK] to create the new project.

[3] Expand the Navigator panel (using Expand all option), then highlight the default pumping test. In the Pumping test tab, replace the default name with Pumping Test Planning.

[4] Then, click Test from the Main menu bar followed by Units... Ensure your units match the figure on the following page:

[5] Click OK to confirm the units, and then select the Analysis folder.

[6] Right-click your mouse and select Create Analysis. From the window that appears, select Theis Prediction. Your display should appear similar to the figure shown below.

By default, AquiferTest displays a Drawdown vs. Time plot with a distance of 10 feet from the pumping well.

Note: You did not need to input any time versus drawdown data to view this plot. The forward solution in AquiferTest generates a synthetic set of data that corresponds to the characteristic Theis drawdown.

[7] The settings for the Theis Prediction solution can be edited to allow analysis of a variety of

cause-and-effect relationships typically encountered during pumping test planning. To view the Settings dialogue box, right-click anywhere on the analysis plot and select Settings. The dialogue below will appear:

Notice under Test conditions there are fields for storativity, transmissivity, and discharge. Based on an analysis of borehole and other data from your site, you should be able to estimate values for storativity and transmissivity. Then, you can iteratively vary the discharge rate until you find a rate that produces the desired water level drawdown in the aquifer at a specific distance from the discharge well.

Under Calculation, you can specify the number of data points to be plotted on the Time versus drawdown plot. As well, you can choose to view either a Time versus drawdown or Distance versus drawdown plot. Each of these options allows you to vary both the distance and time parameters to customize the prediction output to incorporate your site-specific pumping test planning details.

For example, in many situations existing wells are used as observation wells to save money. An existing well may be 50 feet - not 10 feet - from the pumping well. You can replace the 10 feet with 50 feet in the Distance field under Calculation which would display a plot of predicted water level drawdown over time at a distance of 50 feet from the pumping well. This provides you with an estimate of the drawdown that may be experienced 50 feet from the pumping well during the test.

[8] Using the Settings dialogue box, ensure that the Time vs. Drawdown option is enabled.

[9] Under Test Conditions, enter the following information:

Storativity = 0.0001
Transmissivity = 24,550 ft 2/day (= K of 700 ft/d and b of 35 ft)
Discharge = 15 (US Gal/min)

[10] Under Calculation, enter the following information:

Distance = 30 (feet) (to the observation well)
Time = 5 (minutes)

[11] Click OK to activate these settings and re-draw the plot, which should appear similar to the figure below (to enlarge the graph, press Ctrl + E).

According to this plot, a discharge rate of 15 US gal/min will produce a drawdown of 0.06 feet inside the observation well located 30 feet from the pumping well within the first 2 minutes of the test, thus satisfying the planning criterion set for this exercise.

Next, let's answer the question how far might the cone of depression extend away from the discharge well after 2,880 minutes (two days) of pumping at a discharge rate of 15 US GPM This question has practical consideration when there are concerns about other water supply wells in or near the test area being dewatered as a result of test discharge (well interference).

[12] In the analysis view, right-click anywhere on the graph and select Settings. In the dialogue that appears, enter the following information:

[13] Under Calculation, select Distance vs. Drawdown.

[14] Under Distance vs. Drawdown, set the Maximum distance to 150 feet and Time to 2880 min. The dialogue box should appear similar to the figure shown below.

[15] Click [OK] to apply the changes to the graph. Your analysis display should look similar to the figure shown below.

The previous figure allows you to visualize the extent of drawdown as a result of discharge from the pumping well. As you can see, discharging at a rate of 15 US GPM has very little effect on water level beyond 30 feet from the pumping well, thus non-test wells in the area do not appear to be at risk to dewatering.

This concludes the Demonstration Exercises.

5.7 Additional AquiferTest Samples

Once you have completed the Demonstration exercises, you may wish to explore the features of AquiferTest on your own. For this reason, we have included a sample project that includes the following:

- a detailed base plan (.BMP)
- 2 pumping wells
- 6 observation wells
- 4 separate pumping tests
- 2 slug tests
- 16 sample analysis methods

Click File from the top menu bar, followed by Open Project... Using the folder icon, navigate to the Samples folder. Then, select the Samples.MDB and click Open.

Once you have opened the Sample database, an Open project window will appear. Select the Brown Hill Airport Project, and click Open.

Once you have successfully opened the project, expand the data tree located in the Navigator panel. You will see the wells, tests, and analyses included with the project.

Experiment with this data; create new analyses, modify existing ones. By experimenting with this sample database, you can become more familiar with the interface and features of AquiferTest, and subsequently apply this knowledge to your own projects.

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