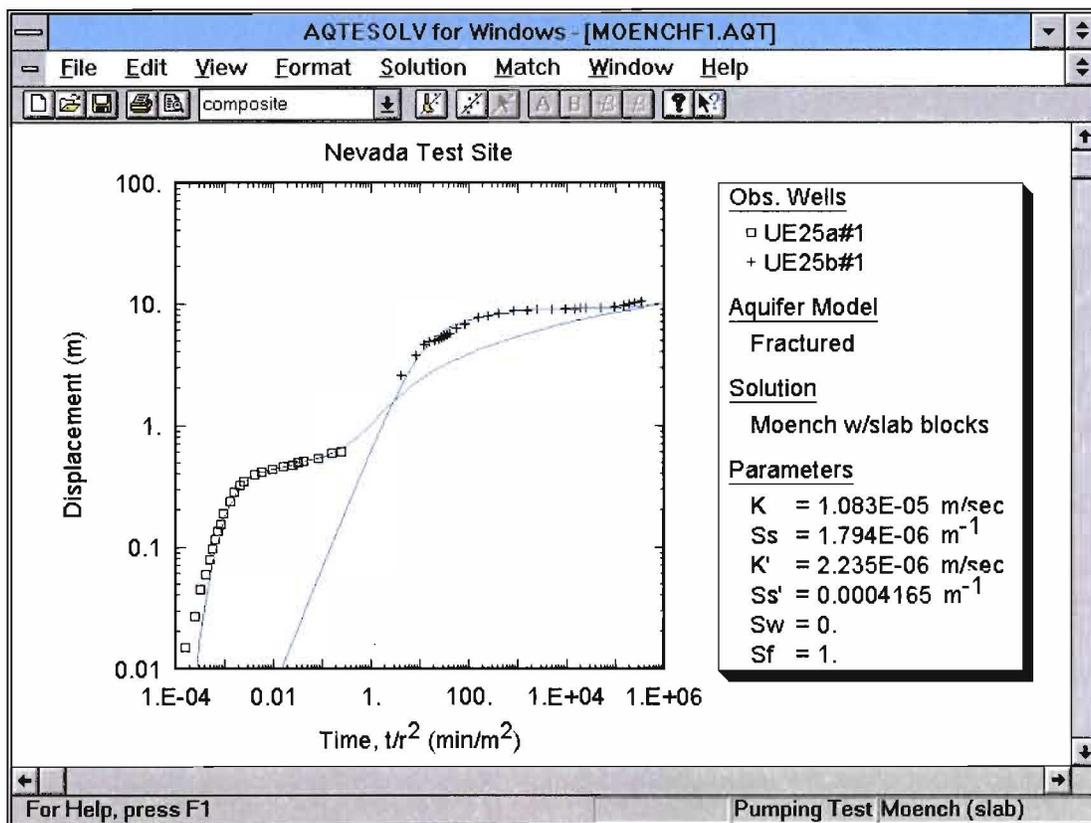


AQTESOLV for Windows

User's Guide

By HydroSOLVE, Inc.



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Getting Started

AQTESOLV for Windows Features

AQTESOLV for Windows is the leading software package for the analysis of aquifer tests featuring a sophisticated suite of analytical solutions, curve matching tools and report graphics. A typical analysis session will follow the steps below.

- Enter data into the program using convenient **Data Set Wizards** for pumping tests or slug tests. An **Import Wizard** streamlines the process of importing test readings from data loggers.
- Use **diagnostic plots** and **derivative analysis** to evaluate conditions during a pumping test such as wellbore storage, delayed gravity response and linear flow in a fractured aquifer.
- Choose an appropriate **solution method** for confined, leaky, unconfined and fractured aquifers.
- Estimate aquifer properties using **visual** or **automatic curve matching**.
- Output results in a variety of **graphical** or **report formats**.

Data Management

AQTESOLV for Windows helps you manage aquifer test data with data management tools for entering, editing and importing data. **Data Set Wizards** guide you through the creation of data sets for pumping tests and slug tests. Error checking ensures consistent and complete data entry. Flexible specification of measurement units lets you enter data in English and metric systems. Retrieval of data from a pressure transducer is easy using the **Import Wizard** in AQTESOLV for Windows.

Visual Matching

The **visual curve matching** feature in AQTESOLV for Windows lets you analyze aquifer tests using the traditional method of matching type curves to **time-displacement** and **derivative data** measured during an aquifer test.

AQTESOLV for Windows provides a comprehensive set of tools for visual type curve analysis. With a plot of the data displayed on the computer screen, you can match a type curve to your data in an interactive manner. By simply moving your

mouse, you can move a type curve on the screen and watch AQTESOLV for Windows update the values of aquifer properties. Use the new **Active Type Curve** feature to overcome limitations of traditional static type curves and extend visual curve matching to any solution including derivatives. Adjust hydraulic properties with the **Tweak Parameters** option to perform sensitivity analysis and fine-tune the match of a solution.

Automatic Matching

The powerful **automatic curve matching** feature provided by AQTESOLV for Windows uses nonlinear weighted least-squares parameter estimation to match type curves or straight lines to time-displacement data measured during an aquifer test.

The automatic curve matching feature minimizes the errors between the position of the type curve and your data and provides statistical measures of the type curve “fit” such as the precision of the estimated aquifer properties and error distributions.

Statistical Analysis

Automatic curve matching provides statistical criteria measuring the “fit” of a type curve to your data. The statistics give you an objective basis for comparing the match of several different solutions to the same set of data.

Automatic curve matching computes standard errors of the estimated parameters that allow you to evaluate the precision of the parameter estimates and to construct approximate confidence intervals. Statistics for the model errors provide a basis for choosing between different aquifer test solutions that produce similar visual matches.

Plots and Reports

AQTESOLV for Windows helps you visualize the results of your aquifer test analyses by providing 12 **plot options**.

- displacement vs. time plot
- composite plot (for multi-well analysis)
- residual drawdown plot (for recovery analysis)
- residuals vs. time plot
- residuals vs. simulated displacement plot
- normality test for residuals
- derivative vs. time plot
- discharge vs. time plot
- radial flow plot (diagnostic)
- linear flow plot (diagnostic)
- bilinear flow plot (diagnostic)
- spherical flow plot (diagnostic)

In addition, AQTESOLV for Windows includes **report options** that document the contents of data sets and summarize the results of matching analytical solutions to data.

- complete aquifer test analysis report
- diagnostic statistics summary
- error log

Help

The **Help** menu provides you with options for exploring the AQTESOLV for Windows User's Guide.

Contents, Index and Search

Choose **Contents and Index** from the **Help** menu to view the contents and index in the AQTESOLV for Windows User's Guide.

Select **Search...** from the **Help** menu and click the **Find** tab to search the documentation for help topics.

Choose **What's This?** From the **Help** menu or click  on the toolbar to obtain Help about a specific menu option or button. Move the Context Help cursor over a menu option or button, and click the mouse to obtain context-sensitive help.

Using Help

Choose **Using Help** from the **Help** menu to view instructions for navigating the Windows help system.

Quick Tips

Select **Quick Tips** from the **Help** menu to display helpful hints and tips for using AQTESOLV for Windows.

Tip of the Day

Choose **Tip of the Day...** from the **Help** menu to display helpful tips.

AQTESOLV on the Web

Choose **AQTESOLV on the Web** from the **Help** menu to select options for product information and technical support available at the AQTESOLV for Windows web site (<http://www.aqtesolv.com>).

Select the **Support** option to access the AQTESOLV for Windows **Knowledge Base**, a free web-based service providing answers to frequently asked questions (FAQs), tips and examples.

About AQTESOLV

Choose **About AQTESOLV...** from the **Help** menu or click  on the toolbar to display program copyright and version information for AQTESOLV for Windows.

Interface Features

Options for various interface features are available in the **View** and **Window** menus.

Opening a New Window

Choose **New Window** from the **Window** menu to open a new window for the active data set.

Cascading Windows

Choose **Cascade** from the **Window** menu to cascade windows from the upper left corner of the AQTESOLV for Windows client area.

Tiling Windows

Choose **Tile Horizontal** or **Tile Vertical** from the **Window** menu to tile windows horizontally or vertically, respectively.

Arrange Icons

Choose **Arrange Icons** from the **Window** menu to arrange window icons at the bottom of the screen.

Refresh

Choose **Refresh** from the **View** menu to refresh (redraw) the plot or report in the active window.

Click  on the toolbar to refresh the display

Toolbar

Choose **Toolbar** from the **View** menu to enable/disable the AQTESOLV for Windows toolbar.

Status Bar

Choose **Status Bar** from the **View** menu to enable/disable the status bar shown at the bottom of the AQTESOLV for Windows display. The status bar contains four panes that indicate messages and status information.

Message Pane

The first pane in the status bar supplies descriptive messages for menu options.

Check Errors Indicator

The second pane in the status bar displays the message **Check Errors** if AQTESOLV for Windows detects errors in active data set. To view the errors, choose **Error Log** from the **View** menu.

Test Type Indicator

The third pane in the status bar displays either **Pumping Test** or **Slug Test** to indicate the type of test contained in the active data set.

Solution Indicator

The fourth pane in the status bar displays the current solution for the active data set. AQTESOLV for Windows will prompt you to choose a solution if the data set contains sufficient data to perform a forward solution.

Tools

The **Tools** menu provides options for running other Windows applications (e.g., ModelCad for Windows, TWODAN and WinSitu). Use these applications in conjunction with AQTESOLV for Windows to increase your productivity. Choose **Customize...** from the **Tools** menu to configure the applications and select other preferences.

Guided Tours

Overview

The **Guided Tours** provide you with step-by-step instructions illustrating the use of AQTESOLV for Windows in the analysis of pumping tests and slug tests. The tours show you how to perform visual and automatic curve matching, change between plot and report views, open multiple windows for the same data set, obtain printed output and much more. Regardless of your experience in analyzing aquifer test data, it is recommended that you take the time to go through the guided tours to become familiar with AQTESOLV for Windows.

You can find additional examples and tutorials at the AQTESOLV web site. Please visit <http://www.aqtesolv.com/examples/>.

Analyzing a Pumping Test

The first step in the guided tour shows you how to use AQTESOLV to analyze a constant-rate pumping test in a confined aquifer. This step-by-step example illustrates the use of visual and automatic curve matching to estimate the hydraulic properties of the aquifer.

Open a New Data Set

Open a new data set by choosing **New** from the **File** menu. In the **New Data Set** dialog box, choose **Guided Tour** from the list box to initialize the new data set with default values. AQTESOLV for Windows opens an **Error Log** window that reports any errors or missing elements identified in the data set.

TIPS

The **Check Errors** indicator shown on the status bar notifies you when the data set contains errors. Choose **Error Log** from the **View** menu to see a list of the errors.

Enter Data for Pumping Test

Units

Choose **Units...** from the **Edit** menu to select units of measurement for the data set.

1. Select **ft** (feet) for **Length**, **min** (minutes) for **Time**, **consistent** for **Pumping Rate** and **consistent** for **Hyd. Conductivity**.
2. Click **OK**.

Consistent units

For this data set, consistent units for pumping rate are cubic feet-per-minute; consistent units for hydraulic conductivity are feet-per-minute.

Title

Choose **Annotations...** from the **Edit** menu to edit the data set title.

1. In the **Title** tab, enter **Theis Verification** for the **Title**.
2. Click **OK**.

Aquifer data

Choose **Aquifer Data...** from the **Edit** menu to edit aquifer data.

1. In the **General** tab, enter **100.0** for the value of **Saturated Thickness**.
2. Enter **1.0** for the value of **Hydraulic Conductivity Anisotropy Ratio** (i.e., isotropic conditions).
3. Click **OK**.

Pumping well data

Choose **Pumping Well>Edit...** from the **Edit** menu to edit pumping well data.

1. In the **General** tab, enter **0.0** for the values of the **X** and **Y** coordinates.
2. In the **Construction** tab, enter **0.1** for both **Wellbore Radius** and **Casing Radius**.
3. In the **Rates** tab, enter values of **0.0** and **3.14159** for time and rate, respectively, where time is in minutes since the start of the test and rate is in cubic feet-per-minute.

TIPS

Enter the pumping rate history as a sequence of pumping periods. Define each pumping period by entering (1) its starting time as elapsed time since the beginning of the test (not the duration of the period) and (2) the pumping rate for the period. The first pumping period should have a time = 0.0 indicating the start of the test.

Only enter a new pumping period when the rate changes. To simulate recovery, enter an additional period with the elapsed time since the start of the test when the pump was shut off and a pumping rate = 0.0. For example, if the test lasted 1440 minutes (one day), enter values of **1440.0** and **0.0** for time and rate, respectively, to mark the start of recovery.

4. Click **OK**.

Observation well data

Choose **Obs. Well>Edit...** from the **Edit** menu to edit observation well data.

1. In the **General** tab, enter a value of **100.0** for the **X-Coordinate** location of the well. This places the observation well at a radial distance of 100 ft from the pumping well.
2. In the **Observations** tab, you can enter observation data from the keyboard or import data from a file. All of the time values should be greater than the start of the first pumping period entered for the pumping well (i.e., > 0.0). All of the displacement values should be greater than zero.

Enter the following 10 measurements (set all weights equal to 1.0):

<i>Time</i>	<i>Displacement</i>
0.5	0.0489
1	0.2194
5	1.223
10	1.823
50	3.355
100	4.038
500	5.639
1000	6.332
5000	7.94
10000	8.633

2. **TIPS**

To save time, you can copy the values of time and displacement from the table shown above and paste them into AQTESOLV using the **Paste** button. The same copy-and-paste procedure works for spreadsheets.

3. When you have finished entering the observations, click **OK**.

After you have completed the previous data entry steps, the **Error Log** displayed in the active window should show that the data set contains no errors. Now you are ready to display the data, choose a solution and estimate aquifer properties.

Save Data Set

Choose **Save As...** from the **File** menu to save the data you have entered into the current data set.

1. Enter **TOUR1.AQT** for the file name.
2. Click **OK** to save the data set.

Display Plot in Window

Choose **Displacement-Time** from the **View** menu to display a plot of displacement vs. time in the active window. The window displays a plot of the observation well data on semi-logarithmic axes.

Choose Theis Solution

Choose **Solution...** from the **Match** menu to choose a solution for analyzing the pumping test.

1. Choose the **Confined Theis (1935)** solution.
2. Click **OK**.

After you have selected the Theis solution for a pumping test in a confined aquifer, AQTESOLV updates the window by plotting the data, superimposing the Theis type curve on the plot, and adding the current values of transmissivity (T), storage coefficient (S), hydraulic conductivity anisotropy ratio (K_z/K_r , K_z/K_r) and saturated thickness (b) to the legend.

For details concerning the Theis solution, see "Theis (1935) Solution for a Pumping Test in a Confined Aquifer" on page 54.

Perform Visual Matching with Theis

The Theis type curve solution computes drawdown for fully penetrating wells in a confined aquifer using the following equations:

$$s = \frac{Q}{4\pi T} \int_u^{\infty} \frac{e^{-y}}{y} dy$$

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

where s is drawdown, Q is pumping rate, T is transmissivity, r is radial distance between pumping and observation wells, S is storage coefficient, and t is time.

Hydrogeologists commonly refer to the exponential integral in the drawdown equation as the *Theis well function*, abbreviated as $w(u)$. Therefore, we can write the Theis drawdown equation in compact notation as follows:

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

To analyze a pumping test using the Theis type curve method, one plots drawdown as a function of time on double logarithmic axes. By matching a type curve drawn by plotting $w(u)$ as a function of $1/u$, one can estimate the values of transmissivity and storage coefficient by visual analysis.

First, choose **Log Axes** from the **View** menu to plot the data and type curve on double logarithmic axes.

Next, choose **Visual** from the **Match** menu to perform visual curve matching with the Theis type curve.

1. To begin interactively moving the type curve, move the mouse cursor over the plot, click the left mouse button, and hold it down (note: it is not necessary to click on or grab the type curve to perform this operation).
2. As you move the mouse, the type curve also moves. AQTESOLV updates the values of the aquifer properties, T and S , in the legend as the type curve position changes.
3. When you have finished matching the type curve to the data, release the left mouse button to end visual curve matching.

Perform Automatic Matching with Theis

Choose **Automatic...** from the **Match** menu to perform automatic curve matching with the Theis type curve solution.

AQTESOLV for Windows uses nonlinear least-squares parameter estimation to match a solution to observation well data. The estimation procedure performs a sequence of iterations to minimize the residual sum of squares (RSS) criterion. The residuals are the errors between the computed and observed values of displacement.

1. Click the **Estimate** button to begin the automatic estimation procedure.
2. As the automatic estimation procedure completes iterations, a progress window displays the changes in the residual sum of squares (RSS) criterion and the values of the aquifer properties. After the automatic estimation procedure finishes, AQTESOLV displays a message box containing residual summary statistics. Click **OK** to close the message box.

3. Click the **Close** button to close the progress window and click **OK** to finish.

Print Results

Choose **Print...** from the **File** menu to print a copy of the type curve solution. To select a printer other than the default, click the **Setup...** button and choose a new printer. Click the **OK** button to print the type curve plot.

Open a New Window for a Diagnostic Plot

Choose **New Window** from the **Window** menu to open a second window for the active data set. The initial view in the second window is the same as the previously active window.

1. Select **Normal Probability** from the **View** menu to plot values of residuals (errors) plotted on normal probability axes in the new window. This view option is only available after you have performed automatic curve matching.
2. After you have inspected the normal probability plot, close the window.

Diagnostic test for normal distribution of residuals

If the residuals are normally distributed, they will fall on a straight line when plotted on normal probability axes. Deviations from a normal distribution may indicate that the chosen analytical solution is inadequate for the analysis.

Grid/Contour Results

Choose **Contour...** from the **View** menu to prepare a grid file for contouring and optionally create and display a contour plot with Surfer (version 6 or higher). Enter the following data in the **Grid Wizard**.

1. In Step 1 of the Grid Wizard, enter **TOUR1.GRD** for the **Grid file**. Choose **X-Y (Plan)** for the **Grid Orientation**. Click **Next >** to continue.
2. In Step 2 of the Grid Wizard, enter values of **-100, 100** and **26** for the **Min, Max** and **No. of Lines**, respectively, for each coordinate direction. Enter values of **0** and **100** for the **Min** and **Max Depths**. Enter a value of **10** for the **Time** since the start of pumping.
3. In Step 3 of the Grid Wizard, check **Display grid file with Surfer** if you wish to display a contour plot with Surfer for Windows (version 6 or higher).
4. Click the **Finish** button to prepare the grid file and optionally create and display the contour plot.

Save Data Set

Choose **Save** from the **File** menu to save your work in the **TOUR1.AQT** data set.

Analyzing a Slug Test

The second sample in the guided tour illustrates the analysis of a slug test in a confined aquifer using a type-curve solution by Cooper, Bredehoeft and Papadopoulos and a straight-line solution by Bouwer and Rice. The step-by-step instructions in this example lead you through the use of visual and automatic curve matching to estimate aquifer properties from slug test data.

Open a New Data Set

Open a new data set by choosing **New** from the **File** menu. In the **New Data Set** dialog box, choose **Guided Tour** from the list box to initialize the new data set with default values. AQTESOLV for Windows opens a new window with an **Error Log** view that reports any errors or missing elements identified in the data set.

TIPS

The **Check Errors** indicator shown on the status bar notifies you when the data set contains errors. Choose **Error Log** from the **View** menu to see a list of the errors.

Enter Data for Slug Test

Units

Choose **Units...** from the **Edit** menu to select units of measurement for the data set.

1. Select **m** (meters) for **Length**, **min** (minutes) for **Time**, and **cm/sec** (centimeters-per-second) for **Hyd. Conductivity**.
2. Click **OK**.

Title

Choose **Annotations...** from the **Edit** menu to edit the data set title.

1. In the **Title** tab, enter **Confined Slug Test** for the **Title**.
2. Click **OK**.

Slug test data

Choose **Slug Test Well...** from the **Edit** menu to edit slug test data.

1. In the **General** tab, enter **0.56** for **Initial Displacement** and **100.0** for **Static Water Column Height**.
2. In the **Aquifer** tab, enter **100.0** for **Saturated Thickness** and **1.0** for **Hydraulic Conductivity Anisotropy Ratio** (i.e., isotropic conditions).
3. In the **Screen** tab, enter **100.0** for **Screen Length** and **100.0** for **Total Depth of Penetration**.
4. In the **Radius** tab, enter **0.076** for **Casing Radius**, **Effective Well Radius** and **Outer Radius of Well Skin**.

TIPS

The **Outer Radius of Well Skin** only applies to the KGS Model with well skin. The well skin is a disturbed zone of finite thickness enveloping the wellbore with hydraulic properties differing from the aquifer. If you are not using this solution, it is sufficient to enter **the Outer Radius of Well Skin** equal to the **Effective Well Radius**.

5. In the **Observations** tab, you can enter observation data from the keyboard or import data from a file. Enter the following 21 measurements (set all weights equal to 1.0):

<i>Time</i>	<i>Displacement</i>
3	0.457
6	0.392
9	0.345
12	0.308
15	0.28
18	0.252
21	0.224
24	0.205
27	0.187
30	0.168
33	0.149
36	0.14
39	0.131
42	0.112
45	0.108
48	0.093
51	0.089
54	0.082
57	0.075
60	0.071
63	0.065

TIPS

To save time, you can copy the values of time and displacement from the table shown above and paste them into AQTESOLV using the **Paste** button. The same copy-and-paste procedure works for spreadsheets.

6. When you have finished entering the observations, click **OK**.

After you have completed the previous data entry steps, the **Error Log** displayed in the active window should show that the data set contains no errors. Now you are ready to display the data, choose a solution and estimate aquifer properties.

Save Data Set

Choose **Save As...** from the **File** menu to save the data you have entered into the current data set.

1. Enter **TOUR2.AQT** for the file name.
2. Click **OK**.

Display Report in Window

Choose **Report** from the **View** menu to display a complete report of the data set in the active window.

Complete report

The complete report displays in report format all of the data contained in the active data set. The report also shows parameters estimated by visual or automatic curve matching. The report includes diagnostic statistics if you have performed automatic estimation.

Display Plot in Window

Choose **Displacement-Time** from the **View** menu to display a plot of displacement vs. time in the active window. The window displays the data plotted on log-linear semi-logarithmic axes.

To plot the displacement data as normalized head or relative displacement, i.e., $H/H(0)$, choose **Options** from the **View** menu and select the **Normalized Head** option in the **Plots** tab. This option normalizes all displacement data, H , by the initial displacement, $H(0)$.

Choose Cooper Et Al. Solution

Choose **Solution...** from the **Match** menu to choose a solution for analyzing the slug test.

1. Choose the **Confined Cooper-Bredehoeft-Papadopoulos (1967)** solution.
2. Click **OK**.

For details concerning the Cooper-Bredehoeft-Papadopoulos slug test solution, see "Please visit <http://www.aqtesolv.com/examples/> for additional tutorials and sample data sets.

Cooper-Bredehoeft-Papadopoulos (1967) Solution for a Slug Test in a Confined Aquifer" on page 77.

Perform Automatic Matching with Cooper Et Al.

Choose **Automatic...** from the **Match** menu to perform automatic curve matching with the Cooper-Bredehoeft-Papadopoulos type curve solution.

1. Click the **Estimate** button to begin the automatic estimation procedure.
2. As the automatic estimation procedure completes iterations, a progress window displays the changes in the residual sum of squares (RSS) criterion and the values of the aquifer properties. After the automatic estimation procedure finishes, AQTESOLV displays a message box containing residual summary statistics. Click **OK** to close the message box.
3. Click the **Close** button to close the progress window and click **OK** to finish.

Display Diagnostic Report in Window

Choose **Diagnostics** from the **View** menu to display a report containing diagnostic statistics for the estimated aquifer properties in the active window.

Diagnostic report

In the diagnostic report, the standard errors indicate the precision of the estimated parameters. Ideally, the standard errors should be small compared to the estimates. The correlation matrix shows correlations between the estimated parameters and may indicate estimation difficulties when strong correlations exist. The diagnostic report also displays summary statistics for the model residuals.

Display Plot in Window

Choose **Displacement-Time** from the **View** menu to display a plot of displacement vs. time in the active window.

Choose Bouwer-Rice Solution

Change the solution by choosing **Solution...** from the **Match** menu.

1. Choose the **Confined Bouwer-Rice (1976)** solution.
2. Click **OK**.

After you have selected the Bouwer-Rice straight-line solution for a slug test in a confined aquifer, AQTESOLV updates the window by plotting the data on linear-log semi-logarithmic axes and superimposing a straight line predicted by the Bouwer-Rice solution on the plot.

For details on the Bouwer-Rice slug test solution, see "Bouwer-Rice (1976) Solution for a Slug Test in an Unconfined Aquifer" on page 107.

Perform Visual Matching with Bouwer-Rice

First, choose **Options** from the **View** menu and select the **Recommended Head Range** option in the **Plots** tab. This option superimposes on the plot the head range recommended by Butler (1998) to obtain the most reliable matching results for solutions such as Bouwer-Rice (1976) and Hvorslev (1951) that assume a quasi-steady-state representation of flow for the slug test.

Next, choose **Visual** from the **Match** menu to perform visual curve matching of the Bouwer-Rice solution to the slug test data.

1. To begin interactively matching the Bouwer-Rice solution to the data, click the left mouse button and hold it down to anchor a point along the new straight line you wish to match to the data (note: do not attempt to click on or grab the existing line shown on the plot to perform this operation).
2. As you move the mouse, AQTESOLV draws a straight line between the anchor point and the mouse cursor.
3. When you have finished matching the Bouwer-Rice solution to the observation well data, release the left mouse button. AQTESOLV computes new estimates of hydraulic conductivity (K) and y-axis intercept (y_0) and updates the straight line displayed on the plot.

Estimation tip

For most slug tests, one should use visual matching to obtain the most meaningful estimate of K with the Bouwer-Rice solution because visual matching gives you greater control over the range of data that you want to match with the straight line. If you choose to attempt automatic matching with the Bouwer-Rice solution, you should assign weights of zero to the measurements not within the range of data that you want to match.

Perform Sensitivity Analysis

Choose **Toolbox...** from the **Match** menu and click the **Tweak** tab to perform sensitivity analysis for the Bouwer-Rice solution.

1. From the **Parameter** list, choose **K** (i.e., hydraulic conductivity) as the parameter that you want to tweak.
2. Click the arrow buttons or the scroll bar to tweak the value of the parameter. For the Bouwer-Rice solution, tweaking the value of K changes the slope of the line. Check **Apply changes automatically** to update the plot while you tweak the parameters.
3. Click **Cancel** to ignore your changes.

Save Data Set

Choose **Save** from the **File** menu to save your work in the **TOUR2.AQT** data set.

Additional Tutorials

In addition to the tutorials found in this manual, please visit the AQTESOLV web site at <http://www.aqtesolv.com/examples/> for more examples and tutorials.

Pumping Test Tutorials

Theis (1935) solution for a confined aquifer

Cooper-Jacob (1946) solution for a confined aquifer

Papadopulos-Cooper (1967) large-diameter well solution for a confined aquifer

Theis (1935) solution for a recovery test in a confined aquifer

Theis (1935) solution for a step drawdown test in a confined aquifer

Hantush (1962) solution for a wedge-shaped aquifer

Murdoch (1994) solution for a interceptor trench

Theis (1935) solution for an unconfined aquifer

Cooper-Jacob (1946) solution for an unconfined aquifer

Neuman (1974) and Quick Neuman solutions for an unconfined aquifer

Streltsova (1974) solution for an unconfined aquifer

Moench (1997) large-diameter well solution for an unconfined aquifer

Hantush-Jacob (1955) solution for a leaky aquifer

Hantush (1960) solution for a leaky aquifer

Moench (1985) large-diameter well solution for a leaky aquifer

Neuman-Witherspoon (1969) solution for leaky two-aquifer system

Moench (1984) solution for a double-porosity fractured aquifer (slab-shaped blocks)

Moench (1984) solution for a double-porosity fractured aquifer (spherical blocks)

Gringarten-Witherspoon (1972) solution for a fractured aquifer with a plane vertical fracture

Gringarten-Ramey (1974) solution for a fractured aquifer with a plane horizontal fracture

Slug Test Tutorials

Cooper-Bredehoeft-Papadopulos (1967) solution for a confined aquifer

Bouwer-Rice (1979) solution for an unconfined aquifer

Hvorslev (1951) solution for a confined aquifer

Hyder et al. (1995) solution for an unconfined aquifer

Tutorials Illustrating Selected Topics

Importing data logger files (Tutorial, Tutorial, Tutorial, Tutorial, Tutorial)

Variable pumping rates with recovery (Tutorial, Tutorial)

Multiple observation wells (Tutorial, Tutorial)

Active type curves (Tutorial, Tutorial)

Type curve families (Tutorial)

Tweaking parameters (Tutorial)

Sensitivity analysis (Guided Tour, Tutorial)

Linear flow plot (Tutorial)

Contouring results (Guided Tour)

In addition to the tutorials found in this manual, please visit the AQTESOLV web site at <http://www.aqtesolv.com/examples/> for more examples and tutorials.

Working With Data Sets

What is an AQTESOLV for Windows Data Set?

An **AQTESOLV for Windows data set** is a file that you create using AQTESOLV for Windows to save work from an aquifer test analysis session. It contains data from an aquifer test (e.g., aquifer geometry data, test well data, pumping data and time-displacement data) and information concerning the solution method used to analyze the test data (e.g., solution method and aquifer properties). A data set also contains data that you enter to format plots and reports. In other words, an AQTESOLV for Windows data set contains a complete record of your aquifer test analysis at the time you save it.

Managing Data Set Files

Click  on the toolbar to open a new data set

Creating a New Data Set

Select **New** from the **File** menu to create a new AQTESOLV for Windows data set.

From the **New Data Set** dialog box, choose a template or wizard from the list box to create a new data set.

When you create a new data set, AQTESOLV for Windows automatically opens an **Error Log** window that indicates data items that you need to enter for a complete data set. The **Error Log** view displays deficiencies and inconsistencies in the data set. After completing data entry, view the data by choosing an option from the **View** menu.

Default (File>New)

1. Choose **New...** from the **File** menu.
2. Select the **Default** template from the list to create a new data set with default values. You can choose options from the **Edit** menu to modify the default values in the data set.

Forward Solution Wizard (File>New)

1. Choose **New...** from the **File** menu.

2. Select the **Forward Solution Wizard** from the list to help you create a new data set for the purposes of designing and simulating a pumping test.
3. In the **Prediction Data** step of the wizard, enter the starting and ending times for the forward (predictive) simulation and estimates of aquifer properties.

Guided Tour (File>New)

1. Choose **New...** from the **File** menu.
2. Select the **Guided Tour** template from the list to create a new data set containing default values for a "Guided Tour" example (see "Guided Tours" on page 7).

Import AQTESOLV for DOS Wizard (File>New)

1. Choose **New...** from the **File** menu.
2. Select the **Import AQTESOLV for DOS Wizard** from the list to help you import a data set created with a DOS version of AQTESOLV.

Pumping Test Wizard (File>New)

1. Choose **New...** from the **File** menu.
2. Select the **Pumping Test Wizard** from the list to help you create a new data set for a typical pumping test. This wizard also allows you to import time-displacement data from a pressure transducer file.

Slug Test Wizard (File>New)

1. Choose **New...** from the **File** menu.
2. Select the **Slug Test Wizard** from the list to help you create a new data set for a typical slug test. This wizard also allows you to import time-displacement data from a pressure transducer file.

Template Wizard (File>New)

1. Choose **New...** from the **File** menu.
2. Select the **Template Wizard** from the list to help you create a new data set using an existing AQTESOLV for Windows data set as a custom template. For example, use the **Template Wizard** to copy data from a master data set when you have performed duplicate tests (e.g., slug tests) in the same test well.

Tutorial (File>New)

1. Choose **New...** from the **File** menu.
2. The **Tutorial** template creates a new data set containing default values for a tutorial contained in this manual.

Saving a Data Set

You have two options for saving an AQTESOLV for Windows data set.

Click  on the toolbar to save the active data set

To save data set using the current file name

Choose **Save** from the **File** menu to save an AQTESOLV for Windows data set on disk using the current file name.

To save data set with a new file name

1. Select **Save As...** from the **File** menu to specify a file name before you save the data set.
2. Enter a file name for the data set you want to save.
3. Click **OK** to save the data set using the file name.

Opening a Data Set

Click  on the toolbar to open an existing data set

Choose **Open...** from the **File** menu to open an existing data set created with AQTESOLV for Windows.

1. Enter the file name of the data set you want to open.
2. Click the **OK** button to retrieve the data set.

Closing a Data Set

Choose **Close** from the **File** menu to close the active data set. If you have changed any data, AQTESOLV for Windows prompts you to save the modified data set.

Mailing a Data Set

Choose **Send Mail...** from the **File** menu to send the active data set as an e-mail attachment.

Opening a Recently Used Data Set

Select a file name from the list at the bottom of the **File** menu to open a recently used data set.

Exiting AQTESOLV for Windows

To exit AQTESOLV for Windows, choose **Exit** from the **File** menu.

Import Wizards

AQTESOLV for Windows provides easy-to-use wizards for importing data into the software. These wizards allow you to import AQTESOLV for DOS data sets and files (e.g., from data loggers) containing field measurements.

AQTESOLV for DOS Import Wizard

Import data sets created with DOS versions of AQTESOLV.

Use the **Import AQTESOLV for DOS Wizard** to import data sets created with any DOS version of AQTESOLV.

1. Choose **New** from the **File** menu and select **Import AQTESOLV for DOS Wizard** from the **New Data Set** dialog box to import the AQTESOLV for DOS data set.
2. Follow the steps in the **Import AQTESOLV for DOS Wizard** to import a file containing an AQTESOLV for DOS data set.
3. Check **Convert all data sets with .DAT extension in this folder** if you want to convert all of your old AQTESOLV for DOS data sets (with a .DAT extension) in the folder you have selected into AQTESOLV for Windows data sets (with a .AQT extension).

TIPS

1. You also can select **Import...** from the **File** menu and choose **AQTESOLV for DOS Data Set** from the **Import** dialog box to import an AQTESOLV for DOS data set into the active data set.
2. Before using this procedure for importing an AQTESOLV for DOS data set, be sure you have created a new data set or opened an existing data set file.

Observation Data Import Wizard

Create a delimited text file to import measurements recorded by a pressure transducer.

Import time, displacement and measurement weight data for an observation or slug test well with the **Observation Data Import Wizard**, a flexible tool for importing measurements from text files. The **Import Wizard** supports delimited text files created by many different types of loggers.

The import file may contain one or more columns of data separated by comma, blank or tab delimiters. The wizard automatically searches for the row containing the first observation, or you can specify the starting row in the file. Transformation and filter operations also allow you to modify and reduce the data during the import process.

Time values for all measurements (including recovery) are entered as elapsed time since the start of the test. Displacement is the change in water level from the static condition prior to the test (do not enter depth to water or the water column height above a transducer). Measurement weight data, used in automatic curve matching (see "Automatic Curve Matching" on page 161) are optional and need not be imported from the file. If necessary, use the transformation options in the third step of the wizard to convert measurements in your file to these definitions of time and displacement.

Importing Observation Data for a Pumping Test

Choose **Obs. Well>Edit...** from the **Edit** menu. In the **Observations** tab, click **Import**.

Importing Observation Data for a Slug Test

Choose **Slug Test Well...** from the **Edit** menu. In the **Observations** tab, click **Import**.

TIPS

1. You also can select **Import...** from the **File** menu and choose **Observation Well Measurements** from the **Import** dialog box to import observation data for either a pumping test or slug test.
2. Before using one of these procedures for importing observation data, be sure you have created a new data set or opened an existing data set file.

Step 1. Open Import File (Import Observations)

1. Enter a path and filename for a text file containing observation data. Click **Browse...** to search for a file.
2. To view a specified file, click **View Import File...**
3. To append data from the import file to observation data already in the data set, check the **Append observations from import file to data set** box.
4. Click **Next >** to proceed to Step 2.

Step 2. Identify File Structure (Import Observations)

1. Enter the **No. of Columns** contained in the file. The total number of columns contained in the file may be greater than the number of columns that you wish to import.
2. Enter a number for the **Starting Row** containing the first observation that you wish to import from the file.

TIPS

Click **Select Starting Row...** to view the import file. You can select the first row in the file that you want to import by double-clicking it.

3. Specify the **Data to Import** from the file. Check the data items (elapsed time, date/clock time, displacement and measurement weight) that you are importing and their column locations in the file. Each file must contain time and displacement data, but measurement weights are optional.

TIPS

When importing date/clock time values, AQTESOLV for Windows computes elapsed time assuming the **Starting Row** contains the date and time at the start of the test.

4. Click **Next >** to proceed to Step 3.

Step 3. Specify Transformation and Filter Operations (Import Observations)

1. Select **Pre-Filter Operations** for transforming time and displacement data contained in the file. Enter constants for subtraction and multiplication operations.

TIPS

Subtract the static water level from each value of displacement contained in the file to transform depth to water values to displacement values. To transform negative displacements to positive displacements, multiply each displacement value by -1.

2. Click **Filters...** to select options for filtering the data imported from the file.

TIPS

Use filters to reduce the number of observations contained in the import file. Retain time values with a uniform logarithmic spacing or displacement values that exceed a minimum threshold.

3. Click **Finish** to import the file.

Create a delimited text file to import measurements recorded by a data logger.

Pumping Rate Data Import Wizard

Import pumping rate data for a pumping well with the **Pumping Period Data Import Wizard**, a flexible tool for importing measurements from text files. The **Import Wizard** supports delimited text files created by many different types of data loggers.

The import file may contain one or more columns of data separated by comma, blank or tab delimiters. The wizard automatically searches for the row containing the first pumping period, or you can choose the starting row in the file. Transformation and filter operations also allow you to modify and reduce the data during the import process.

Import the pumping rate history as a sequence of pumping periods. Define each pumping period by entering (1) its starting time as elapsed time since the beginning of the test (not the duration of the period) and (2) the pumping rate for the period. The time and rate for the first pumping period (i.e., the start of the test) is given by time = 0.0 and the initial pumping rate. New periods are only required when the rate changes. Define a recovery period by the elapsed time since the start of test when the pump was shut off and rate = 0.0.

Importing Pumping Rate Data for a Pumping Test

Choose **Pumping Well>Edit...** from the **Edit** menu. In the **Rates** tab, click **Import**.

TIPS

1. You also can select **Import...** from the **File** menu and choose **Pumping Rate Measurements** from the **Import** dialog box to import pumping rate data for a pumping test.
2. Before using one of these procedures for importing observation data, be sure you have created a new data set or opened an existing data set file.

Step 1. Open Import File (Import Rates)

1. Enter a path and filename for a text file containing pumping period data. Click **Browse...** to search for a file.
2. To view a specified file, click **View Import File...**
3. To append data from the import file to pumping period data already in the data set, check the **Append pumping periods from import file to data set** box.
4. Click **Next >** to proceed to Step 2.

Step 2. Identify File Structure (Import Rates)

1. Enter the **No. of Columns** contained in the file. The total number of columns contained in the file may be greater than the number of columns that you wish to import.
2. Enter a number for the **Starting Row** containing the first pumping period that you wish to import from the file.

TIPS

Click **Select Starting Row...** to view the import file. You can select the first row in the file that you want to import by double-clicking it.

3. Specify the **Data to Import** from the file. Check the data items (starting time of the pumping period expressed as an elapsed time or date/clock value and pumping rate) that you are importing and their column locations in the file.

TIPS

When importing date/clock time values, AQTESOLV for Windows computes elapsed time assuming the **Starting Row** contains the date and time at the start of the test.

4. Click **Next >** to proceed to Step 3.

Step 3. Specify Transformation and Filter Operations (Import Rates)

1. Select **Pre-Filter Operations** for transforming time and pumping rate data contained in the file. Enter constants for subtraction and multiplication operations.
2. Click **Filters...** to select options for filtering the data imported from the file.

TIPS

Use filters to reduce the number of pumping periods. Retain rate values exceeding a minimum threshold (AQTESOLV for Windows time-averages intermediate values not retained).

3. Click **Finish** to import the file.

Editing Data Sets

The **Edit** menu provides options for entering or modifying data in the active data set. Selecting any of the options will open property sheets that prompt you for information stored in AQTESOLV data sets.

Units

Choose **Units...** from the **Edit** menu to select units of measurement for time, length, pumping rate and hydraulic conductivity.

Dimensionally consistent units

Unless otherwise specified, AQTESOLV for Windows assumes that pumping rates and hydraulic conductivity/transmissivity units are dimensionally consistent with the units specified for length and time. For example, if the units of length and time were feet and minutes, respectively, the dimensionally consistent units would be ft³/min cubic feet per minute for pumping rate and ft²/day square feet per day for transmissivity.

Optional units for pumping rate and hydraulic conductivity

For those not wishing to use dimensionally “consistent” units, AQTESOLV for Windows provides options for pumping rate units including gallons and liters (e.g., gpm and L/sec). For units of hydraulic conductivity/transmissivity, you also can select units containing gallons (e.g., gpm/ft² gal/min/sq. ft).

Annotations

Select **Annotations...** from the **Edit** menu to enter information used to annotate plots and reports prepared by AQTESOLV for Windows.

Title Tab (Edit>Annotations)

Choose **Annotations...** from the **Edit** menu and click the **Title** tab to enter a title for the data set.

Project Info Tab (Edit>Annotations)

Choose **Annotations...** from the **Edit** menu and click the **Project Info** tab to enter information for any of the following items into the active data set (each item may contain up to 30 characters):

- client name
- project number
- location of test
- test well name
- observation well name
- date of test

End Notes Tab (Edit>Annotations)

Choose **Annotations...** from the **Edit** menu and click the **End Notes** tab to enter end notes for a report.

Aquifer Data

Select **Aquifer Data...** from the **Edit** menu to enter aquifer geometry and special hydraulic property data into the active data set.

General Tab (Edit>Aquifer Data)

Choose **Aquifer Data...** from the **Edit** menu and click the **General** tab to enter general aquifer information.

Saturated Thickness

1. Enter the **saturated thickness** [L] of the aquifer measured from the top of the aquifer (or the water table) to the bottom of the aquifer.
2. In an unconfined aquifer, the maximum displacement should not exceed the saturated thickness.

Hydraulic Conductivity Anisotropy Ratio

1. Enter the **vertical to horizontal hydraulic conductivity anisotropy ratio** (K_z/K_r , K_z/K_r) [dimensionless] for pumping test solutions applying the Hantush (1961a,b) corrections for partially penetrating wells.
2. The Neuman (1974) solution for pumping tests in unconfined aquifers, which estimates the value of K_z/K_r , K_z/K_r in the value of

the β beta parameter, does not use the hydraulic conductivity ratio value entered in the aquifer data unless you have more than one observation well.

Double-Porosity Tab (Edit>Aquifer Data)

Choose **Aquifer Data...** from the **Edit** menu and click the **Double Porosity** tab to enter data for a double-porosity fractured aquifer. These data are only required for pumping test solutions in double-porosity fractured aquifers and may be ignored otherwise.

Thickness of Slab-Shaped Matrix Blocks

Enter the **thickness** [L] of slab-shaped matrix blocks for the Moench (1984) solution for a double-porosity fractured aquifer with slab-shaped blocks.

Diameter of Spherical Blocks

Enter the **diameter** [L] of spherical blocks for the Moench (1984) solution for a double-porosity fractured aquifer with spherical blocks.

Single Fracture Tab (Edit>Aquifer Data)

Choose **Aquifer Data...** from the **Edit** menu and click the **Single Fracture** tab to enter data for a single vertical or horizontal fracture. These data are only required for single-fracture pumping test solutions in fractured aquifers and may be ignored otherwise.

Vertical Fracture

Enter the **total length** [L] (equals two times half-length) of a vertical plane fracture for the Gringarten-Witherspoon (1972) solution for a confined aquifer with a single vertical fracture.

Horizontal Fracture

1. Enter the **radius** [L] of a horizontal plane fracture for the Gringarten-Ramey (1974) solution for a confined aquifer with a single horizontal fracture.
2. Enter the **depth** [L] from the top of the aquifer to the horizontal fracture.

Wedge Tab (Edit>Aquifer Data)

Choose **Aquifer Data...** from the **Edit** menu and click the **Wedge** tab to enter data for a wedge-shaped aquifer. These data are only required for pumping test solutions in wedge-shaped aquifers and may be ignored otherwise.

Slope Orientation Angle

1. Enter the orientation of the slope on the base of a wedge-shaped aquifer as the **angle measured in a counterclockwise direction** from the positive x-coordinate axis to the vector oriented in the updip direction of the slope.
2. Enter the slope orientation angle in **degrees**.

Trench Tab (Edit>Aquifer Data)

Choose **Aquifer Data...** from the **Edit** menu and click the **Trench** tab to enter data for a trench. These data are only required for pumping test solutions with a trench and may be ignored otherwise.

Trench Length

Enter the **total length** [L] (equals two times half-length) of a trench for the Murdoch (1994) solution for a confined aquifer with a fully penetrating trench.

Pumping Well

Choose the **Pumping Well** option from the **Edit** menu. Select **Edit...**, **Add...** or **Delete...** from the popup submenu to edit, add or delete a pumping well. Choosing the option to edit or add a pumping well also allows you to enter or modify well data.

General Tab (Edit>Pumping Well)

Choose **Pumping Well>Edit...** from the **Edit** menu and click the **General** tab to edit general information for a pumping well.

Well Name

Enter a name to identify the well.

Well Coordinates

1. AQTESOLV for Windows uses an **x-y coordinate system** [L] to compute distances between pumping wells and observation wells.
2. For a simple pumping test involving only one pumping well and one observation well, locate the pumping well at $x=0.0$ and $y=0.0$. Locate the observation well at $x=r$ and $y=0.0$ where r is the radial distance between the pumping and observation wells.

Construction Tab (Edit>Pumping Well)

Choose **Pumping Well>Edit...** from the **Edit** menu and click the **Construction** tab to edit well construction data for a pumping well.

Large-diameter well data

1. To analyze pumping tests using large-diameter well solutions, enter values for the **casing radius** [L] and **effective well radius** [L] of the pumping well.
2. Enter a value for each radius greater than 0.0.

Well Penetration Data

1. A well is **fully penetrating** if its screen or perforated interval extends over the full saturated thickness of the aquifer.
2. The screen of a **partially penetrating** well only extends over a portion of an aquifer's saturated thickness. For a partially penetrating well, enter **depths** [L] measured from the top of the aquifer (or water table) to the top and bottom of the well screen. **Do not enter depths from land surface.**

3. The depth to the bottom of well screen must be greater than the depth to the top of well screen. The minimum depth for the top of the well screen is 0.0; the maximum depth for the bottom of the well screen is the saturated thickness of the aquifer.

Rates Tab (Edit>Pumping Well)

Choose **Pumping Well>Edit...** from the **Edit** menu and click the **Rates** tab to enter pumping rate data for the well. Options allow you to enter rates from the keyboard, import rates from a file or copy/paste data from another application.

To enter pumping period data from the keyboard

1. Enter pumping history data in the spreadsheet as a sequence of pumping periods.
2. Click **Insert Row** to insert a row in the spreadsheet.
3. Click **Add Rows...** to add rows to the spreadsheet.

TIPS

Enter the pumping rate history as a sequence of pumping periods. Define each pumping period by entering (1) its starting time as elapsed time since the beginning of the test (not the duration of the period) and (2) the pumping rate for the period. The first pumping period should have a time = 0.0 indicating the start of the test.

Only enter a new pumping period when the rate changes. To simulate recovery, enter an additional period with the elapsed time since the start of the test when the pump was shut off and a pumping rate = 0.0. For example, if the test lasted 1440 minutes (one day), enter values of **1440.0** and **0.0** for time and rate, respectively, to mark the start of recovery.

To delete pumping period data

1. Select one or more rows in the spreadsheet.
2. Click **Delete** to delete the selected row(s). Before deleting the data, AQTESOLV for Windows prompts to confirm your action.

To copy pumping period data to the clipboard

1. Select one or more rows in the spreadsheet.
2. Click **Copy** to copy the selected row(s) to the clipboard.

To paste pumping period data from the clipboard

1. Copy time and pumping rate data to the clipboard using another Windows application (e.g., a spreadsheet).
2. Click **Paste** to paste the time and pumping rate data from the clipboard into the spreadsheet.

To import pumping period data from a file

1. Click **Import** to start the **Pumping Period Data Import Wizard** for importing pumping history data from a file.
2. Follow the steps in the wizard (see "Pumping Rate Data Import Wizard" on page 24) to import delimited text files created by many different types of data loggers. Transformation and filter

operations also allow you to modify and reduce the data during the import process.

To search for a specific time or pumping rate

1. Click **Search** to open a dialog box for the search.
2. Enter the data vector (time or pumping rate) that you wish to search and the specific value.
3. Click **OK** to search for the value.

To transform pumping period data

1. Select the row(s) for the pumping period(s) that you want to transform.
2. Click **Math** to choose a transformation.
3. Enter the data vector (time or pumping rate) that you wish to transform.
4. Select a transformation operation (add, subtract, multiply, divide or replace).
5. Check the box to perform the transformation and click **OK**. Before transforming the data, AQTESOLV for Windows prompts to confirm your action.

To filter pumping period data

1. Click **Filters** to choose filtering operations.
2. Select filter operations for discarding or retaining pumping periods.

TIPS

Use filters to reduce the number of pumping periods. Retain rate values exceeding a minimum threshold (AQTESOLV for Windows uses a time-averaging scheme for intermediate values not retained).

3. Click **OK** to filter the data. Before filtering the data, AQTESOLV for Windows prompts to confirm your action.

Symbols Tab (Edit>Pumping Well)

Choose **Pumping Well>Edit...** from the **Edit** menu and click the **Symbols** tab to change the properties of symbols used for pumping rate data displayed on plots.

Pumping Rate Symbol Properties

1. Select a symbol type (circle, square, etc.) from the **Symbol** box.
2. Select a symbol size from the **Size** box.
3. Enter a **Thickness** for the symbol.
4. Click **Color** to choose a color for the symbol.

Curves Tab (Edit>Pumping Well)

Choose **Pumping Well>Edit...** from the **Edit** menu and click the **Curves** tab to change the properties of pumping rate curves displayed on plots.

Discharge Curve Properties

1. Select a line style from the **Style** box.

2. Enter a **Thickness** for the curve.
3. Click **Color** to choose a color for the curve.

Observation Well

Choose the **Obs. Well** option from the **Edit** menu. Select **Edit...**, **Add...** or **Delete...** from the popup menu to edit, add or delete an observation well. If you are editing or adding an observation well, the **Observation Well Data** dialog box allows you to enter data for the observation well.

General Tab (Edit>Observation Well)

Choose **Obs. Well>Edit...** from the **Edit** menu and click the **General** tab to edit general information for an observation well.

Well Name

Enter a name to identify the well.

Well Coordinates

1. AQTESOLV for Windows uses an **x-y coordinate system** [L] to compute distances between pumping wells and observation wells.
2. For a simple pumping test involving only one pumping well and one observation well, locate the pumping well at $x=0.0$ and $y=0.0$. Locate the observation well at $x=r$ and $y=0.0$ where r is the radial distance between the pumping and observation wells.

Construction Tab (Edit>Observation Well)

Choose **Obs. Well>Edit...** from the **Edit** menu and click the **Construction** tab to edit well construction data for an observation well.

Well Penetration Data

1. A well is **fully penetrating** if its screen or perforated interval extends over the full saturated thickness of the aquifer.
2. The screen of a **partially penetrating** well only extends over a portion of an aquifer's saturated thickness. For a partially penetrating well, enter **depths** [L] measured from the top of the aquifer (or water table) to the top and bottom of the well screen. **Do not enter depths from land surface.**
3. The bottom of well screen depth must be greater than the top of well screen depth. The minimum depth for the top of the well screen is 0.0; the maximum depth for the bottom of the well screen is the saturated thickness of the aquifer.
4. A **piezometer** (in contrast to an observation well) is an open-ended pipe installed in an aquifer to measure hydraulic head at a specific depth. The **piezometer depth** [L] is distance from the top of the aquifer (or water table) to the piezometer opening.

Observations Tab (Edit>Observation Well)

Choose **Obs. Well>Edit...** from the **Edit** menu and click the **Observations** tab to enter time-displacement data for the well. Options allow you to enter observation

data from the keyboard, import observations from a file or copy/paste data from another application.

To enter observation data from the keyboard

1. Enter values of time, displacement and weight in the spreadsheet.
2. Click **Insert Row** to insert a row in the spreadsheet.
3. Click **Add Rows...** to add rows to the spreadsheet.

TIPS

Enter time values for all measurements (including recovery) as elapsed time since the start of the test. Enter displacement as the change in water level from the static condition prior to the test (do not enter depth to water or the water column height above a transducer).

Assign weights to indicate the relative weight of each measurement during automatic curve matching. Assign a weight of zero for measurements that you wish automatic curve matching to ignore.

To delete observation data

1. Select one or more rows in the spreadsheet.
2. Click **Delete** to delete the selected row(s). Before deleting the data, AQTESOLV for Windows prompts to confirm your action.

To copy observation data to the clipboard

1. Select one or more rows in the spreadsheet.
2. Click **Copy** to copy the selected row(s) to the clipboard.

To paste observation data from the clipboard

1. Copy observation data to the clipboard using another Windows application (e.g., a spreadsheet). Each observation should include time and displacement values (weights are optional).
2. Click **Paste** to paste the observation data from the clipboard into the spreadsheet.

To import observation data from a file

1. Click **Import** to start the **Observation Data Import Wizard** for importing observation data from a file.
2. Follow the steps in the wizard (see "Observation Data Import Wizard" on page 22) to import delimited text files created by many different types of data loggers. Transformation and filter operations also allow you to modify and reduce the data during the import process.

To search for a specific time, displacement or weight

1. Click **Search** to open a dialog box for the search.
2. Enter the data vector (time, displacement or weight) that you wish to search and the specific value.
3. Click **OK** to search for the value.

To transform observation data

1. Select the row(s) for the observation(s) that you want to transform.
2. Click **Math** to open a dialog box for the transformation operation.
3. Enter the data vector (time, displacement or weight) that you wish to transform.
4. Select a transformation operation (add, subtract, multiply, divide or replace).
5. Check the box to perform the transformation and click **OK**. Before transforming the data, AQTESOLV for Windows prompts to confirm your action.

To filter observation data

1. Click **Filters** to open a dialog box for the filtering operations.
2. Select filter operations for discarding or retaining observations.

TIPS

Use filters to reduce the number of observations. Retain time values having a uniform logarithmic spacing or displacement values exceeding a minimum threshold.

3. Click **OK** to filter the observations. Before filtering the data, AQTESOLV for Windows prompts to confirm your action.

Symbols Tab (Edit>Observation Well)

Choose **Obs. Well>Edit...** from the **Edit** menu and click the **Symbols** tab to change the properties of symbols used for observation and derivative data displayed on plots.

Observed Data Symbol Properties

1. Select a symbol type (circle, square, etc.) from the **Symbol** box.
2. Select a symbol size from the **Size** box.
3. Enter a **Thickness** for the symbol.
4. Click **Color** to choose a color for the symbol.

Derivative Symbol Properties

1. Check **Use properties of observed data symbols** to apply the same properties to the observation and derivative symbols.
2. Otherwise, edit **Symbol**, **Size**, **Thickness** and **Color** properties for the derivative symbols.

Curves Tab (Edit>Observation Well)

Choose **Obs. Well>Edit...** from the **Edit** menu and click the **Curves** tab to change the properties of type curves and derivative curves displayed on plots.

Type Curve Properties

1. Select a line style from the **Style** box.
2. Enter a **Thickness** for the curve.
3. Click **Color** to choose a color for the curve.

Derivative Curve Properties

1. Check **Use type curve properties** to apply the same properties to the observation and derivative curves.
2. Otherwise, edit **Style, Thickness** and **Color** properties for the derivative curves.

Slug Test Well

Choose **Slug Test Well...** from the **Edit** menu to enter data for a slug test.

General Tab (Edit>Slug Test Well)

Choose **Slug Test Well...** from the **Edit** menu and click the **General** tab to enter general information for a slug test.

Well Name

Enter a **name** to identify the well.

Initial Displacement

Enter the **initial displacement** [L] measured in the well due the instantaneous withdrawal or injection of water.

Static Water Column Height

Enter the **static water column height** [L] measured from the bottom of the well to the potentiometric surface in the well.

Well Coordinates

1. AQTESOLV for Windows uses an **x-y coordinate system** [L] to compute distances between the test well and observation wells.
2. For a simple slug test involving the test well and one observation well, locate the test well at $x=0.0$ and $y=0.0$. Locate the observation well at $x=r$ and $y=0.0$ where r is the radial distance between the test and observation wells.

Aquifer Tab (Edit>Slug Test Well)

Choose **Slug Test Well...** from the **Edit** menu and click the **Aquifer** tab to enter aquifer data for a slug test.

Aquifer Saturated Thickness

1. Enter the **saturated thickness** [L] of the aquifer measured from the top of the aquifer (confining unit or the water table) to the bottom of the aquifer.
2. In an unconfined aquifer, the maximum displacement should not exceed the saturated thickness.

Hydraulic Conductivity Anisotropy Ratio

Enter the **vertical to horizontal hydraulic conductivity anisotropy ratio** (K_v/K_h) [dimensionless].

Screen Tab (Edit>Slug Test Well)

Choose **Slug Test Well...** from the **Edit** menu and click the **Screen** tab to enter well construction information for a slug test.

Screen Length

Enter the **length of the well screen** [L].

Total Depth of Well Screen Penetration

1. Enter the **total depth** [L] of penetration in the aquifer by the well screen.
2. For **unconfined aquifers**, enter the depth from the water table (not from land surface) to the bottom of the well screen (static water column height).
3. For **confined aquifers**, enter the depth from the top of the aquifer (not from land surface) to the bottom of the well screen.

Radius Tab (Edit>Slug Test Well)

Choose **Slug Test Well...** from the **Edit** menu and click the **Radius** tab to enter well construction information for a slug test.

Casing Radius

Enter the **inner radius of the well casing** [L]. Butler (2002) recommends correcting the nominal casing radius for transducer cable or other downhole equipment.

Well Radius

Enter the **effective radius of the well screen** [L]. The effective well radius is often taken to include the filter or gravel pack envelope when the filter pack material is much more permeable than the aquifer.

Well Skin Radius

Enter the **outer radius of the well skin** [L] (see "Hyder et al. (1994) Solution for a Slug Test in a Confined Aquifer (KGS Model)" on page 81 and "Hyder et al. (1994) Solution for a Slug Test in an Unconfined Aquifer (KGS Model)" on page 109). The well skin is conceptualized as a finite-thickness shell or envelope immediately adjacent to the well with different hydraulic characteristics than the surrounding aquifer.

Filter Pack Porosity

Enter the **effective porosity of the filter or gravel pack envelope** [dimensionless].

Apply Correction for Partially Submerged Screen

Check this option to correct the casing radius for the porosity of the gravel pack (see "Bouwer-Rice (1976) Solution for a Slug Test in an Unconfined Aquifer" on page 107 and "Hvorslev (1951) Solution for a Slug Test in a Confined Aquifer" on page 79).

Well Loss Tab (Edit>Slug Test Well)

Choose **Slug Test Well...** from the **Edit** menu and click the **Well Loss** tab to enter well loss data for a slug test. The correction for frictional loss applies to methods of the analysis of slug tests in high-K aquifers.

Apply Correction For Frictional (Viscous) Well Loss

Check this option to correct for frictional losses in slug tests conducted in high-K aquifers (see "Butler (1998) Solution for a Slug Test in a High-K Confined Aquifer" on page 84 and "Springer-Gelhar (1991) Solution for a Slug Test in a High-K Unconfined Aquifer" on page 114).

Kinematic Viscosity

Enter the **kinematic viscosity** of water in SI units [m^2/sec]. The kinematic viscosity of water is temperature dependent (e.g., $1.2 \times 10^{-6} \text{ m}^2/\text{sec}$ at 13.2°C [55.8°F]).

Gravitational Acceleration

Enter the **gravitational acceleration** in SI units [m/sec^2]. The average value is $9.8 \text{ m}/\text{sec}^2$.

Observations Tab (Edit>Slug Test Well)

Choose **Slug Test Well...** from the **Edit** menu and click the **Observations** tab to enter time-displacement data for the well. Options allow you to enter observation data from the keyboard, import observations from a file or copy/paste data from another application.

To enter observation data from the keyboard

1. Enter values of time, displacement and weight in the spreadsheet.
2. Click **Insert Row** to insert a row in the spreadsheet.
3. Click **Add Rows...** to add rows to the spreadsheet.

TIPS

Assign weights to indicate the relative weight of each measurement during automatic curve matching. Assign a weight of zero for measurements you wish automatic curve matching to ignore.

To delete observation data

1. Select one or more rows in the spreadsheet.
2. Click **Delete** to delete the selected row(s). Before deleting the data, AQTESOLV for Windows prompts to confirm your action.

To copy observation data to the clipboard

1. Select one or more rows in the spreadsheet.
2. Click **Copy** to copy the selected row(s) to the clipboard.

To paste observation data from the clipboard

1. Copy observation data to the clipboard using another Windows application (e.g., a spreadsheet). Each observation should include time and displacement values (weights are optional).

2. Click **Paste** to paste the observation data from the clipboard into the spreadsheet.

To import observation data from a file

1. Click **Import** to start the **Observation Data Import Wizard** for importing observation data from a file.
2. Follow the steps in the wizard (see "Observation Data Import Wizard" on page 22) to import delimited text files created by many different types of data loggers. Transformation and filter operations also allow you to modify and reduce the data during the import process.

To search for a specific time, displacement or weight

1. Click **Search** to open a dialog box for the search.
2. Enter the data vector (time, displacement or weight) that you wish to search and the specific value.
3. Click **OK** to search for the value.

To transform observation data

1. Select the row(s) for the observation(s) that you want to transform.
2. Click **Math** to open a dialog box for the transformation operation.
3. Enter the data vector (time, displacement or weight) that you wish to transform.
4. Select a transformation operation (add, subtract, multiply, divide or replace).
5. Check the box to perform the transformation and click **OK**. Before transforming the data, AQTESOLV for Windows prompts to confirm your action.

To filter observation data

1. Click **Filters** to open a dialog box for the filtering operations.
2. Select filter operations for discarding or retaining observations.

TIPS

Use filters to reduce the number of observations. Retain time values having a uniform logarithmic spacing or displacement values exceeding a minimum threshold.

3. Click **OK** to filter the observations. Before filtering the data, AQTESOLV for Windows prompts to confirm your action.

Symbols Tab (Edit>Slug Test Well)

Choose **Slug Test Well...** from the **Edit** menu and click the **Symbols** tab to change the properties of symbols used for observation and derivative data displayed on plots.

Observed Data Symbol Properties

1. Select a symbol type (circle, square, etc.) from the **Symbol** box.
2. Select a symbol size from the **Size** box.

3. Enter a **Thickness** for the symbol.
4. Click **Color** to choose a color for the symbol.

Derivative Symbol Properties

1. Check **Use properties of observed data symbols** to apply the same properties to the observation and derivative symbols.
2. Otherwise, edit **Symbol, Size, Thickness** and **Color** properties for the derivative symbols.

Curves Tab (Edit>Slug Test Well)

Choose **Slug Test Well...** from the **Edit** menu and click the **Curves** tab to change the properties of type curves and derivative curves displayed on plots.

Type Curve Properties

1. Select a line style from the **Style** box.
2. Enter a **Thickness** for the curve.
3. Click **Color** to choose a color for the curve.

Derivative Curve Properties

1. Check **Use type curve properties** to apply the same properties to the observation and derivative curves.
2. Otherwise, edit **Style, Thickness** and **Color** properties for the derivative curves.

Test Type

Choose **Test Type...** from the **Edit** menu to select the type of test (pumping test or slug test) contained in an AQTESOLV for Windows data set.

Setting the test type in a new data set

1. When you open a new AQTESOLV for Windows data set, the test type is defined automatically when you enter pumping test or slug test data.
2. If you enter data for a pumping well, AQTESOLV for Windows defines the test type as **Pumping Test**.
3. If you enter data for a slug test well, AQTESOLV for Windows defines the test type as **Slug Test**.

Changing the test type in a data set

1. The **Edit** menu only enables options for the type of test contained in a data set.
2. Choose **Test Type...** from the **Edit** menu to change the test type.

Plots

Overview

*Select **plot views** from the View menu or the toolbar list box*

*Use **diagnostic plots** to identify appropriate aquifer test solutions*

*Perform automatic estimation to view **residual plots***

The **View** menu provides options for viewing data, solutions and estimation results. Two general types of views, plots and reports, are available for viewing data and solutions, and evaluating estimation results. Other options in the **View** menu allow you to customize the appearance of your plot.

Graphical formats for viewing aquifer test (displacement) data and matching analytical solutions include **displacement vs. time**, **composite** and **derivative vs. time** plots. AQTESOLV for Windows also provides **discharge vs. time** plots to view discharge rates from variable rate pumping tests.

Radial flow, **linear flow**, **bilinear flow** and **spherical flow** plots help you to choose appropriate models for your data set. Use these diagnostic plots to identify behavior produced by wellbore storage, fracture flow and double-porosity phenomena.

Graphical formats for examining residuals (errors) from the matching of analytical solutions to aquifer test data include **residual vs. time**, **residual vs. simulated displacement** and **normal probability** plots.

Choosing a Plot

Choose a plot view (**Displacement-Time**, **Composite**, etc.) from options contained in the **View** menu or from the list box on the toolbar.

Displacement vs. Time Plot

Choose the **Displacement-Time** option from the **View** menu to plot values of displacement as a function of time in the active window.

- The **Displacement-Time** plot allows you to analyze displacement data from one or more observation wells.

- **Displacement-Time** plots show one type curve for each observation well.

TIPS

Choose **Visual** from the **Match** menu to match a solution to the data.

Choose **Options** from the **Visual** menu and select **Derivative Curves** to display displacement and derivative data on the plot.

Composite Plot

Select **Composite** from the **View** menu to plot values of displacement as a function of time divided by the square of radial distance (t/r^2).

- The **Composite** plot allows you to analyze displacement data from one or more observation wells.
- For pumping test solutions containing only two parameters, **Composite** plots display a single type curve regardless of the number of observation wells shown on the plot. For solutions involving three or more parameters, **Composite** plots show one type curve for each observation well.
- **Composite** plots are only active for pumping tests.

TIPS

Choose **Visual** from the **Match** menu to match a solution to the data.

Choose **Options** from the **Visual** menu and select **Derivative Curves** to display displacement and derivative data on the plot.

Residual Drawdown Plot

Choose the **Residual Drawdown** option from the **View** menu to plot values of residual drawdown measured during the recovery phase of a pumping test as a function of adjusted time, t/t' , where t is the time since pumping began and t' is the time since pumping stopped.

- The **Residual Drawdown** plot allows you to analyze recovery data from one or more observation wells.
- **Residual Drawdown** plots show one type curve for each observation well.
- You may view **Residual Drawdown** plots with any pumping test solution as long as the test data include recovery measurements (i.e., readings recorded after pumping stopped).
- As recovery (the time since pumping stopped) progresses, the adjusted time ratio, t/t' , approaches unity. Therefore, as the time of recovery increases and residual drawdown approaches zero (the pre-pumping or static condition), the recovery data plot closer to the origin of the **Residual Drawdown** plot where t/t' equals unity.

TIPS

Choose **Visual** from the **Match** menu to match a solution to the data.

Perform automatic matching to view a residual vs. time plot

Residual vs. Time Plot

Plot residual values as a function of time by choosing **Residual-Time** from the **View** menu.

- Ideally, the residual values should not exhibit correlation with time.
- When **Residual-Time** data are plotted linear axes, AQTESOLV for Windows fits a straight line to the data to indicate the degree to which the residuals are biased with respect to time.

Perform automatic matching to view a residual vs. simulated plot

Residual vs. Simulated Plot

Plot residual values as a function of simulated displacement by choosing **Residual-Simulated** from the **View** menu.

- Ideally, the residual values should not exhibit correlation with the values of simulated displacement.
- When **Residual-Simulated** data are plotted on linear axes, AQTESOLV for Windows fits a straight line to the data to indicate the degree to which the residuals are biased with respect to simulated displacement.

Perform automatic matching to view a normal probability plot

Normal Probability Plot

Choose **Normal Probability** from the **View** menu to plot residual values on normal probability axes.

- A **Normal Probability** plot displays the standard normal deviates of the ranked residuals (residuals sorted from smallest to largest) as a function of the residual values.
- If the residuals are normally distributed, they will fall on a straight line when plotted on normal probability axes. AQTESOLV for Windows fits a straight line to residuals shown on the **Normal Probability** plot to measure the degree to which the residuals fit the normality assumption.
- Deviations from a normal distribution may indicate inadequacy in the fit of the aquifer model to the data.
- After sorting the residual values for all observation wells, AQTESOLV for Windows plots the standard normal deviates using the plot symbol for the first observation well.

Discharge vs. Time Plot

To view pumping well discharge rates from a variable-rate pumping test, choose **Discharge-Time** from the **View** menu.

- The **Discharge-Time** view option allows you to view constant or variable pumping rates for one or more pumping wells.
- **Discharge-Time** plots are only active for pumping tests.

Derivative vs. Time Plot

Choose **Derivative-Time** from the **View** menu to display the derivative of displacement data as a function of logarithmic time. If you have chosen a solution, AQTESOLV for Windows also plots the derivative of the solution.

- The **Derivative-Time** view option allows you to view the derivative of displacement measurements from one or more observation wells.
- **Derivative-Time** plots provide a useful diagnostic tool for detecting deviations in the rate of displacement change. For example, interpretation of a **Derivative-Time** plot can help in the identification of wellbore storage, aquifer boundaries, leakage and delayed gravity response.
- AQTESOLV for Windows computes derivatives for displacement using either **nearest neighbor** or **smoothing** techniques. Choose **Options...** from the **View** menu to select the method used to calculate derivatives from displacement data.
- AQTESOLV for Windows computes the derivative of displacement with respect to logarithmic time.

Radial Flow Plot

Choose **Radial Flow** from the **View** menu to plot displacement as a function of time.

- **Radial Flow** plots are useful diagnostic tools for identifying radial (infinite-acting aquifer) flow behavior or wellbore storage.
- On **semi-logarithmic (log-linear) axes**, late-time data exhibiting a **straight line** on a **Radial Flow** plot are indicative of **radial flow conditions in an infinite-acting aquifer**. This late-time behavior on a semi-log plot is the basis for the Cooper-Jacob straight-line method of analysis (see "Cooper-Jacob (1946) Solution for a Pumping Test in a Confined Aquifer" on page 59).
- On **double logarithmic axes**, early-time data exhibiting a **unit slope** on a **Radial Flow** plot are indicative of **wellbore storage**.

TIPS

Choose **Visual** from the **Match** menu to match a line with unit slope to data plotted on a Radial Flow plot with log-log axes (see "Visual Matching With Radial Flow Plots" on page 166).

- View one or more observation wells on **Radial Flow** plots.

Linear Flow Plot

Choose **Linear Flow** from the **View** menu to plot displacement as a function of the square root of time.

- **Linear Flow** plots are useful diagnostic tools for identifying fracture flow behavior.
- On **double logarithmic axes**, early-time data exhibiting a **unit slope** on a **Linear Flow** plot are indicative of **linear flow**

conditions to a single fracture with infinite conductivity or uniform flux along the fracture.

TIPS

Choose **Visual** from the **Match** menu to match a line with unit slope to data plotted on a Linear Flow plot with log-log axes (see "Visual Matching With Linear Flow Plots" on page 166).

- View one or more observation wells on **Linear Flow** plots.

Bilinear Flow Plot

Choose **Bilinear Flow** from the **View** menu to plot displacement as a function of the fourth root of time.

- **Bilinear Flow** plots are useful diagnostic tools for identifying fracture flow behavior.
- On **double logarithmic axes**, early-time data exhibiting a **unit slope** on a **Bilinear Flow** plot are indicative of **bilinear flow conditions to a single fracture with finite conductivity**.

TIPS

Choose **Visual** from the **Match** menu to match a line with unit slope to data plotted on a Bilinear Flow plot with log-log axes (see "Visual Matching With Bilinear Flow Plots" on page 166).

- View one or more observation wells on **Bilinear Flow** plots.

Spherical Flow Plot

Choose **Spherical Flow** from the **View** menu to plot displacement as a function of the inverse square root of time.

- **Spherical Flow** plots are useful diagnostic tools for identifying spherical flow behavior.
- On **double logarithmic axes**, early-time data exhibiting a **unit slope** on a **Spherical Flow** plot are indicative of **spherical flow conditions**.

TIPS

Choose **Visual** from the **Match** menu to match a line with unit slope to data plotted on a Spherical Flow plot with log-log axes (see "Visual Matching With Spherical Flow Plots" on page 167).

- View one or more observation wells on **Spherical Flow** plots.

Plot Axes

Choose convenient options from the **View** menu to change the scale of plot axes. Options include **linear axes**, **log-linear axes**, **linear-log axes** and **logarithmic axes**.

Linear Axes

Choose **Linear Axes** from the **View** menu to display a plot with linear x and y axes.

Log-Linear Axes

Choose **Log-Linear Axes** from the **View** menu to display a plot with logarithmic x and linear y axes.

Linear-Log Axes

Choose **Linear-Log Axes** from the **View** menu to display a plot with linear x and logarithmic y axes.

Log Axes

Choose **Log Axes** from the **View** menu to display a plot with logarithmic x and y axes.

Plot Options

Choose **Options...** from the **View** menu to select optional plot items and enter parameters controlling the display of type curve families, derivatives and valid times.

Plots Tab (View>Options)

Choose **Options...** from the **View** menu and click the **Plots** tab to select optional items to display on plots.

What To Display

1. Check options to display on plots (**Data, Legend, Type Curve, Curve Family, This Curve, Derivative Curve, Valid Time, Normalized Head** and **Recommended Head Range**).
2. The option to display a **Type Curve** applies to displacement vs. time and composite plots.
3. The **Curve Family** option only applies to certain solutions having three or more parameters and displacement vs. time, composite or residual drawdown plots. Click the **Family** tab to set more options for type curve families.
4. The **This Curves** option applies to selected solutions and displacement vs. time, composite and residual drawdown plots.

For example, this option displays two bounding Theis curves for the Neuman (1974) solution for unconfined aquifers. The first curve uses the values of T and S and the second curve uses T and S_y .

5. Choose the **Derivative Curves** option to superimpose derivative curves on a displacement vs. time or composite plot. When this option is active, you can simultaneously match a solution to displacement and derivative data using visual curve matching (most

effective using **Active Type Curves**). Click the **Derivative** tab to set more options for derivative data and curves.

6. The **Valid Time** option applies to the Cooper-Jacob (1946) solution for confined or unconfined aquifers. Selecting this option shows the time after which the straight-line approximation solution becomes valid on displacement vs. time and composite plots. See "Valid Time Tab (View>Options)" on page 46 to set the critical value of u used to compute the valid time.
7. The option to display **Normalized Head** (H/H_0) applies to slug test solutions.
8. The **Recommended Head Range** option displays the range of displacement recommended by Butler (1998) for matching certain slug test solutions such as "Bouwer-Rice (1976) Solution for a Slug Test in an Unconfined Aquifer" on page 107 and "Hvorslev (1951) Solution for a Slug Test in an Unconfined Aquifer" on page 109 that assume a steady-state representation of flow.
9. **Solution Critically Damped When $C(D) = 2$** calculates and displays the dimensionless damping factor, $C(D)$, assuming the solution is critically damped when $C(D) = 2$. The default value is 1 when this option is not checked. This feature applies to slug test solutions for high-K aquifers such as "Butler (1998) Solution for a Slug Test in a High-K Confined Aquifer" on page 84 and "Springer-Gelhar (1991) Solution for a Slug Test in a High-K Unconfined Aquifer" on page 114.

Family Tab (View>Options)

Choose **Options...** from the **View** menu and click the **Family** tab to select options for displaying type curve families.

Type Curve Family Attributes

1. For a type curve family consisting of two curves, select the option to **Show Two Curves Using Multipliers**. The **Upper** curve, displayed above the active type curve, has a multiplier less than 1; the **Lower** curve, displayed below the active type curve, has a multiplier greater than 1.
2. For a complete set of type curves, choose the option to **Show Preset Family of Curves**.
3. Select **Show Custom Family of Curves** to display type curves from the values shown in the list box. Use the **New** and **Delete** buttons to add or remove curve values. Click the **Clear** button to remove all curves from the list. The **Reset** button restores curve values.
4. Choose the **Show Family** option in the **Plots** tab to enable the display of type curve families.

Derivative Tab (View>Options)

Choose **Options...** from the **View** menu and click the **Derivative** tab to select options for derivative plots.

Calculation Method

1. Choose a method for calculating derivatives from time-displacement data (**nearest neighbor** or **smoothing**).
2. The **nearest neighbor** option provides the least amount of smoothing and works well for displacement data that show ideal response.
3. The **smoothing** option allows you to choose a "smoothing factor" for the calculation of derivatives from "noisy" data. Enter the smallest smoothing **factor** to discern the derivative pattern from the data.
4. The standard method of computing the derivative is $d(H)/d(\log(t))$ for pumping tests and slug tests where H is the head or displacement and t is time. For slug tests, you may choose the **Compute slug test derivative as $d(\log(H))/dt$** option to show the deviation of the derivative from the steady-state model of slug-induced flow.

Valid Time Tab (View>Options)

Choose **Options...** from the **View** menu and click the **Valid Time** tab to select options for displaying the valid time for the Cooper-Jacob (1946) and Theis (1935) residual drawdown solutions.

Validity Criterion for Straight-Line Methods

1. Set the **Critical Value of u** used to compute the valid time displayed for the Cooper-Jacob (1946) solution when you enable the **Show Valid Time** option in the **Plots** tab. A conservative critical value of u is **0.01**.
2. Enter the **Estimated Value of S** (storativity) to compute the valid time displayed with the Theis (1935) residual drawdown method for recovery tests.

Step Test Tab (View>Options)

Choose **Options...** from the **View** menu and click the **Step Test** tab to select options for the Theis (1935) step drawdown solution.

Step Test Prediction Time

1. Set the **Step test prediction time** used in the well loss prediction equation.
2. For more information on the well loss prediction equation, see "Theis (1935) Solution for a Step Drawdown Test in a Confined Aquifer" on page 70.

Settings Tab (View>Options)

Choose **Options...** from the **View** menu and click the **Settings** tab to select options for the resolution of type curves drawn on **Displacement-Time**, **Composite**, **Residual Drawdown** and **Derivative-Time** plots. The **Curve**

Resolution Levels only affect the appearance (smoothness) of the plotted type curve not the accuracy of the underlying solution method (well function).

Curve Resolution Levels

1. Choose a level for the **Plotting Interval** to set the overall resolution of the type curve displayed on the plot. Higher levels plot the type curve at finer intervals, but refresh more slowly.
2. Change the resolution of the type curve for variable-rate pumping tests by selecting a resolution level for **Pumping Periods**. Higher levels increase the resolution of the type curve within pumping periods at the expense of the refresh rate. This option has no effect on the appearance of type curves drawn for constant-rate tests and slug tests.

Formats for Plots

Choose **Options...** from the **View** menu to select options for formatting a plot's graph and axes, legend and colors.

For report formatting options, see "Formats for Reports" on page 51.

Graph Tab (View>Format)

Choose **Format...** from the **View** menu and click the **Graph** tab to edit parameters controlling the appearance of plots.

Properties

1. Enter values controlling the **Border thickness** and **Tickmark thickness** of the plot.
2. Click **Font** to change the font used to display axis labels.
3. Click **Color** to change the color used for drawing the axis labels.

Options

1. Check the **Upper Left Origin** box to place the origin of the plot axes in the upper left corner of the plot.
2. Check the **Show Graph Paper** box to display horizontal and vertical lines at the major tickmarks of the graph.
3. Enter a value between 0.5 and 1.5 for the **Magnification Factor** to adjust the length of the plot axes.

X and Y Axis Tabs (View>Format)

Choose **Format...** from the **View** menu and click the **X Axis** or **Y Axis** tab to edit parameters for plot axes.

Range

1. Check **Auto** to use minimum and maximum axis values selected automatically by the program for your data.
2. Remove the **Auto** check to edit minimum and maximum axis values.

Tickmarks

1. Edit values controlling **major** and **minor tickmark intervals**.
2. Edit the **label spacing** for labels placed on the major tickmarks.

Labels

1. Edit **Text** for the axis label. Choose one of the predefined axis labels or enter a new label.
2. Choose a format for appending **Units** to the axis label.

Legend Tab (View>Format)

Choose **Format...** from the **View** menu and click the **Legend** tab to select options for plot legends.

Text Properties

1. Select the text to edit (**Standard, Title, Proj. Info**).
2. Click **Font** to change the font used to display the selected text.
3. Click **Color** to change the color used for the selected text.

Printer Options

1. Choose a **Style** from the list to format the appearance of printed output.
2. Click **Browse** to select a Windows bitmap (.bmp) file containing a company logo (or other graphic) that you would like to display on printed output (not all **Styles** include a logo).
3. Check the items that you would like display in the printed legend (e.g., title, project info, aquifer data, well data, etc.).

Family Tab (View>Format)

Choose **Format...** from the **View** menu and click the **Family** tab to edit the properties of the optional curves plotted for a type curve family.

Style

Choose a **Style** for the optional type curve family.

Thickness

Enter the **Thickness** of the optional type curve family.

Color

Click **Color** to change the color of the optional type curve family.

Font

Click **Font** to change the font used for labeling members of the optional type curve family.

Theis Curve Tab (View>Format)

Choose **Format...** from the **View** menu and click the **Theis Curve** tab to edit the properties of optional Theis curve(s) superimposed on pumping test solutions.

Style

Choose a **Style** for the optional Theis curve.

Thickness

Enter the **Thickness** of the optional Theis curve.

Color

Click **Color** to change the color of the optional Theis curve.

Fitted Tab (View>Format)

Choose **Format...** from the **View** menu and click the **Fitted** tab to edit the properties of the optional fitted line plotted on residual plots.

Style

Choose a **Style** for the optional fitted line.

Thickness

Enter the **Thickness** of the optional fitted line.

Color

Click **Color** to change the color of the optional fitted line.

Zoom

Choose **Zoom...** from the **View** menu to change the size of the plot within the active window.

1. Enter a **Zoom Factor** ranging from **0.5 to 5**.
2. Use this option to scale the size of a plot within the active window. To scale the length of axes for all plots attached to the active data set, see "Plots Tab (View>Options)" on page 44.

Contouring

Click  on the toolbar to grid and contour data

Choose **Contour...** from the **View** menu to prepare a grid file for contouring and optionally create a contour plot with Surfer for Windows (version 6 or higher).

TIPS

1. Enter values greater than zero for casing radius and wellbore radius for each pumping well (see "Construction Tab (Edit>Pumping Well)" on page 28).

Step 1. Grid Output File (Grid Wizard)

1. Enter a path and filename for a **Grid File** that will contain the gridded data for a contour plot. Click **Browse...** to search for a file.
2. Choose the **Grid Orientation** for a contour plot in plan or cross-sectional view.
3. Click **Next >** to proceed to Step 2.

Step 2. Specify Grid Dimensions (Grid Wizard)

1. Enter **Grid Dimensions** using X-Y coordinates for a plan view or X-Z/Y-Z coordinates for cross-sectional views. Enter **Minimum** and **Maximum** values to define the extent of the grid. Enter the **No. of Lines** to specify the number of grid lines in each coordinate direction.
2. Enter **Constants** to define the depth interval for a contour plot in plan view or the constant coordinate in cross-sectional view. Enter the **Time** (i.e., the elapsed time since the start of pumping) for the calculations.
3. Click **Next >** to proceed to Step 3.

Step 3. Display Contour Plot (Grid Wizard)

1. Check **Display grid file with Surfer** to create and display a contour plot with Surfer for Windows (version 6 or higher). If you do not have the Surfer application or if you only wish to create a grid file, simply click **Finish**.
2. Choose a plot option (**Contour**, **Surface** or **Surface w/ fill contours**).
3. If you have created a file containing contour levels for use with Surfer, you can select a **Contour Levels** file. Click **Browse** to search for a Levels file.
4. If you have created a file containing posting data for use with Surfer, you can select a **Posting Data** file. Click **Browse** to search for a posting file. To append pumping well and observation well coordinate data to the file, check **Add well data to posting file**.
5. Click **Finish** to create the grid file and optionally display a contour plot.

Reports

Overview

Select Report Views from the View menu or the toolbar list box

The View menu provides you with a **Diagnostic** report and a **Complete** report that display text summaries of your data set and the results of your aquifer test analysis. An **Error Log** report identifies any errors that your active data set may contain.

Choosing a Report

Perform automatic estimation to view diagnostic report

Diagnostic Report

Choose **Diagnostics** from the **View** menu to display a report containing estimation statistics for parameters (hydraulic properties) and residuals. The diagnostics report contains standard errors for estimated parameters, correlations between estimated parameters and residual summary statistics.

Complete Report

Choose **Report** from the **View** menu to display a complete report summarizing the contents of the AQTESOLV for Windows data set and estimation results in text format.

Error Log

Choose **Error Log** from the **View** menu to display a report identifying any errors contained in the active data set. Select this report option if you are entering data into a new data set or if the message **Check Errors** appears on the status bar.

Formats for Reports

Choose **Format...** from the **View** menu to open a dialog box for formatting reports. For plot formatting options, see "Formats for Plots" on page 47.

Text Tab (View>Format)

Choose **Format...** from the **View** menu and click the **Text** tab to select options for report text.

Text Properties

1. Click the **Font...** button to change the font used to display the report text.
2. Click the **Color...** button to change the color used for the report text.

Sections

1. Check items to display in the report

Header/Footer Tab (View>Format)

Choose **Format...** from the **View** menu and click the **Header/Footer** tab to enter text for the header and footer of the report.

Choosing a Solution

Overview

AQTESOLV for Windows provides analytical solutions for confined, unconfined, leaky and fractured aquifers. The solutions allow you to determine the hydraulic properties of aquifers through automatic or visual curve matching.

Choose **Solution...** from the **Match** menu to select a solution for analyzing pumping tests or slug tests.

Confined Aquifer Solutions

Choose **Solution...** from the **Match** menu to choose a solution for analyzing a pumping test or slug test in a confined aquifer.

Solutions for Pumping Tests in Confined Aquifers

1. Theis (1935) type curve solution
2. Cooper-Jacob (1946) straight line solution
3. Papadopulos-Cooper (1967) type curve solution for a large-diameter pumping well
4. Theis (1935) straight line solution for residual drawdown during recovery
5. Theis (1935) type curve solution for drawdown in a pumping well during a step drawdown test including linear and nonlinear well losses
6. Hantush (1962) type curve solution for a wedge-shaped aquifer
7. Murdoch (1994) type curve solution for flow to a trench

Solutions for Slug Tests in Confined Aquifers

1. Cooper-Bredehoeft-Papadopulos (1967) type curve solution
2. Bouwer-Rice (1976) straight line solution
3. Hvorslev (1951) straight line solution
4. Hyder et al. (1995) type curve solution (KGS Model)

5. Butler (1998) type curve solution

Theis (1935) Solution for a Pumping Test in a Confined Aquifer

Theis (1935) derived an equation which predicts water-level displacement in a confined aquifer in response to pumping:

$$s = \frac{Q}{4\pi T} \int_u^{\infty} \frac{e^{-y}}{y} dy$$

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

Hydrogeologists commonly refer to the exponential integral in the drawdown equation as the *Theis well function*, abbreviated as **w(u)**. Therefore, we can write the Theis drawdown equation in compact notation as follows:

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

Refer to the "List of Symbols" on page 157 for a description of the parameters and variables contained in the equations for this solution.

Hantush (1961a,b) derived equations for the effects of partial penetration in a confined aquifer. For a piezometer, the partial penetration correction is as follows:

$$s = \frac{Q}{4\pi T} \left(w(u) + \frac{2b}{\pi(1-d)} \sum_{n=1}^{\infty} \frac{1}{n} \left[\sin\left(\frac{n\pi l}{b}\right) - \sin\left(\frac{n\pi d}{b}\right) \right] \cdot \cos\left(\frac{n\pi z}{b}\right) \cdot w\left(u, \sqrt{K_z / K_r} \frac{n\pi r}{b}\right) \right)$$

For an observation, the following partial penetration correction applies:

$$s = \frac{Q}{4\pi T} \left(w(u) + \frac{2b^2}{\pi^2(1-d)(1-d')} \sum_{n=1}^{\infty} \frac{1}{n^2} \left[\sin\left(\frac{n\pi l}{b}\right) - \sin\left(\frac{n\pi d}{b}\right) \right] \cdot \left[\sin\left(\frac{n\pi l'}{b}\right) - \sin\left(\frac{n\pi d'}{b}\right) \right] \cdot w\left(u, \sqrt{K_z / K_r} \frac{n\pi r}{b}\right) \right)$$

where $w(u)$ is the Theis well function confined aquifers, $w(u, \beta)$ is the Hantush well function for leaky aquifers (see "Hantush-Jacob (1955) Solution for a Pumping Test in a Leaky Aquifer" on page 119) and

$$\beta = \sqrt{K_z / K_r} \frac{n\pi r}{b}$$

With these equations, it is possible to estimate values of T and S from time-displacement data measured during a constant-rate pumping test. For partially penetrating wells, AQTESOLV for Windows also estimates the values of K_z/K_r , K_z/K_r and b.

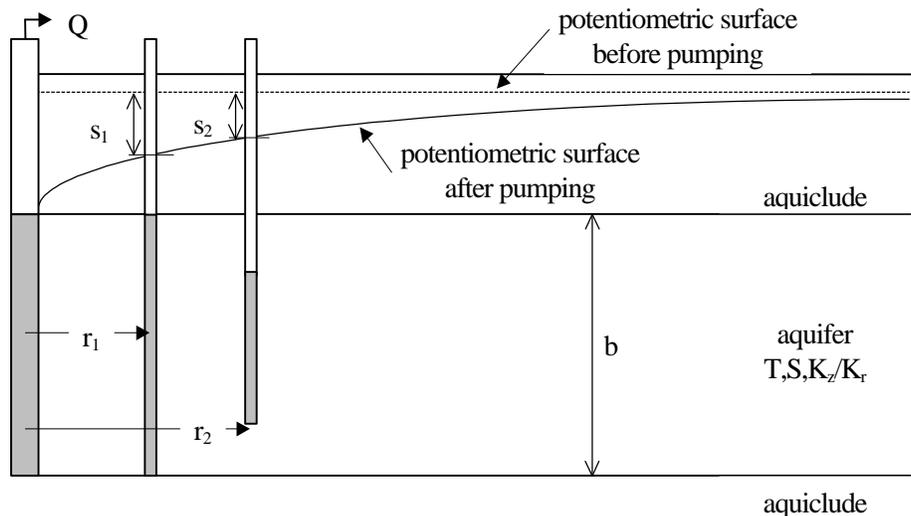
AQTESOLV for Windows uses a general procedure involving the principle of superposition in the form of the Duhamel integral to analyze variable-rate pumping tests (Streltsova 1988). A particularly useful application of this method of

integration is piecewise approximation of the discharge rate by a sequence of step functions. In this form, the discharge rate is considered constant for a sequence of discrete time intervals. The equations for the Theis solution with variable pumping rate are as follows:

$$s = \frac{1}{4\pi T} \sum_{i=1}^n (Q_i - Q_{i-1}) w(u) , Q_0 = 0$$

$$u = \frac{r^2 S}{4T(t - t_{i-1})} , t > t_{n-1} \text{ and } t_0 = 0$$

where n is the number of pumping intervals.



Solution Assumptions

- aquifer has infinite areal extent
- aquifer is homogeneous, isotropic and of uniform thickness
- pumping well is fully or partially penetrating
- flow to pumping well is horizontal when pumping well is fully penetrating
- aquifer is confined
- flow is unsteady
- water is released instantaneously from storage with decline of hydraulic head
- diameter of pumping well is very small so that storage in the well can be neglected

Data Requirements

- pumping and observation well locations
- pumping rate(s)

- observation well measurements (time and displacement)
- partial penetration depths (optional)
- saturated thickness (for partially penetrating wells)
- hydraulic conductivity anisotropy ratio (for partially penetrating wells)

Solution Options

- variable pumping rates
- multiple pumping wells
- multiple observation wells
- partially penetrating wells

Visual Curve Matching Tips

- Choose **Visual** from the **Match** menu to perform visual curve matching using the procedure described in "Visual Matching With Type Curve Solutions" on page 165.
- Use **Active Type Curves** for more effective visual matching with variable-rate pumping tests (see "Active Type Curves" on page 167).
- Select values of Kz/Kr from the **Family** and **Curve** lists on the toolbar (only affects partially penetrating wells).
- Use **Parameter Tweaking** to perform visual curve matching and sensitivity analysis (see "Tweak Tab (Match>Toolbox)" on page 169).

Reference

Hantush, M.S., 1961a. Drawdown around a partially penetrating well, Jour. of the Hyd. Div., Proc. of the Am. Soc. of Civil Eng., vol. 87, no. HY4, pp. 83-98.

Hantush, M.S., 1961b. Aquifer tests on partially penetrating wells, Jour. of the Hyd. Div., Proc. of the Am. Soc. of Civil Eng., vol. 87, no. HY5, pp. 171-194.

Streltsova, T.D., 1988. Well Testing in Heterogeneous Formations, John Wiley & Sons, New York, 413p.

Theis, C.V., 1935. The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage, Am. Geophys. Union Trans., vol. 16, pp. 519-524.

Tutorial

In this tutorial, you will use the Theis type curve solution to create and analyze a variable-rate pumping test. This tutorial shows you how to use visual curve matching with active type curves and automatic curve matching to match the Theis type curve to drawdown and recovery data.

Please visit <http://www.aqtesolv.com/examples/> for additional tutorials and sample data sets.

Open a New Data Set

Open a new data set by choosing **New** from the **File** menu. In the **New Data Set** dialog box, choose **Tutorial** in the list box and click **OK** to initialize the new data set with default values. AQTESOLV for Windows opens an **Error Log** window that reports any errors identified in the data set.

TIPS

The **Check Errors** indicator shown on the status bar notifies you when the data set contains errors. Choose **Error Log** from the **View** menu to see a list of the errors.

Enter Data for Pumping Test

Choose **Units...** from the **Edit** menu to select units of measurement for the data set.

1. Select **m** (meters) for **Length**, **day** (days) for **Time**, **consistent** for **Pumping Rate** and **m/day** (meters/day) for **Hyd. Conductivity**.
2. Consistent units for pumping rate are cubic meters-per-day.
3. Click **OK**.

Choose **Annotations...** from the **Edit** menu to edit the data set title.

1. In the **Title** tab, enter **Variable Rate Pumping Test with Recovery** for the **Title**.
2. Click **OK**.

Choose **Aquifer Data...** from the **Edit** menu to edit aquifer data.

1. In the **General** tab, enter **20.0** for the value of **Saturated Thickness**.
2. Click **OK**.

Choose **Pumping Well>Edit...** from the **Edit** menu to edit pumping well data.

1. In the **Rates** tab, enter the following four pumping periods in the spreadsheet:

<i>Time</i>	<i>Rate</i>
0	500
0.020833	700
0.055556	600
0.10417	0

2. Click **OK**.

Choose **Obs. Well>Edit...** from the **Edit** menu to edit observation well data.

1. In the **General** tab, enter a value of **5.0** for the **X-Coordinate** location of the well.
2. In the **Observations** tab, enter the following 19 measurements in the spreadsheet (set all weights equal to 1.0):

<i>Time</i>	<i>Displacement</i>
0.0034722	1.38
0.0069444	1.65
0.010417	1.81
0.013889	1.93
0.017361	2.02

0.020833	2.09
0.024306	2.68
0.027778	2.85
0.03125	2.96
0.034722	3.05
0.038194	3.12
0.041667	3.18
0.048611	3.29
0.055556	3.38
0.0625	3.13
0.069444	3.15
0.076389	3.17
0.090278	3.23
0.10417	3.29
0.10486	2.38
0.10764	1.65
0.11111	1.34
0.12153	0.95

3. Click **OK**.

After you have completed the previous data entry steps, the **Error Log** window should show that the data set contains no errors. Now you are ready to display the data, choose a solution and estimate aquifer properties.

Save Data Set

Choose **Save As...** from the **File** menu to save the data you have entered into the current data set.

1. Enter **THEIS1.AQT** for the file name.
2. Click **OK** to save the data set.

Change View in Window

Choose **Displacement-Time** from the **View** menu to display a plot of displacement vs. time in the active window. The window displays a plot of the observation well data on semi-logarithmic axes.

Choose Theis Solution

Choose **Solution...** from the **Match** menu to choose a solution for analyzing a pumping test in a confined aquifer.

1. Choose the **Confined Theis (1935)** solution.
2. Click **OK**.

After you have selected the Theis solution for a pumping test in a confined aquifer, AQTESOLV for Windows updates the window by plotting the data, superimposing the Theis type curve on the plot, and adding the current values of transmissivity (T), storage coefficient (S), hydraulic conductivity anisotropy ratio (K_z/K_r) and saturated thickness (b) to the legend. For fully penetrating wells, the Theis solution only estimates T and S.

For solutions such as the Theis (1935) solution that support AQTESOLV for Windows' variable pumping rate feature, you can plot type curves for data sets that include both drawdown *and* recovery data. AQTESOLV for Windows uses the principle of superposition to compute displacements for the pumping and recovery phases of the test.

Perform Visual Matching with Theis

First, choose **Log Axes** from the **View** menu to plot the data and type curve on double logarithmic axes.

Next, choose **Visual** from the **Match** menu to perform visual curve matching with the Theis type curve.

1. To begin interactively moving the type curve, move the mouse cursor over the plot, click the left mouse button and hold it down.
2. As you move the mouse, the type curve also moves. AQTESOLV for Windows updates the values of the aquifer properties, T and S, in the legend as the type curve position changes.
3. When you have finished matching the type curve to the observation well data, release the left mouse button to end visual curve matching.

Use Active Type Curves with Theis

Choose **Toolbox...** from the **Match** menu to invoke **active type curves**.

1. In the **Options** tab, check the option for **Active type curves**.
2. Click **OK**.

Choose **Visual** from the **Match** menu and repeat the steps for visual curve matching using the **active type curve** feature. Compared with static type curves, **active type curves** allow you to match variable-rate pumping tests more effectively with visual curve matching.

Perform Automatic Matching with Theis

Choose **Automatic...** from the **Match** menu to perform automatic matching with the Theis type curve solution.

1. Click **Estimate** to begin automatic estimation.
2. As the automatic estimation procedure completes iterations, a progress window displays the changes in the residual sum of squares (RSS) criterion and the values of the aquifer properties. After the automatic estimation procedure finishes, AQTESOLV for Windows displays a message box containing residual summary statistics. Click **OK** to close the message box.
3. Click the **Close** button to close the progress window and click **OK** to finish.

The plot shown in the active window displays the values of transmissivity (T=100.1) and storage coefficient (S=0.0009994) determined by automatic estimation.

Save Data Set

Choose **Save** from the **File** menu to save your work in the **THEIS1.AQT** data set.

Cooper-Jacob (1946) Solution for a Pumping Test in a Confined Aquifer

For large values of time, Cooper and Jacob (1946) proposed the following equation for displacement in a confined aquifer in response to pumping:

$$s = \frac{2.30Q}{4\pi T} \log\left(\frac{2.25Tt}{r^2S}\right)$$

Refer to the "List of Symbols" on page 157 for a description of the parameters and variables contained in this equation.

The Cooper-Jacob solution derives from the truncation of an infinite series expression for the Theis well function (see "Theis (1935) Solution for a Pumping Test in a Confined Aquifer" on page 54). The following expression computes the value of the Theis well function, abbreviated as $w(u)$:

$$w(u) = -0.5772 - \ln(u) + u - \frac{u^2}{2 \cdot 2!} + \frac{u^3}{3 \cdot 3!} - \frac{u^4}{4 \cdot 4!} + \dots$$

For small values of the variable u (e.g., $u \leq 0.01$), the Cooper-Jacob solution approximates the Theis well function using only the first two terms of the expression for $w(u)$:

$$w(u) \cong -0.5772 - \ln(u)$$

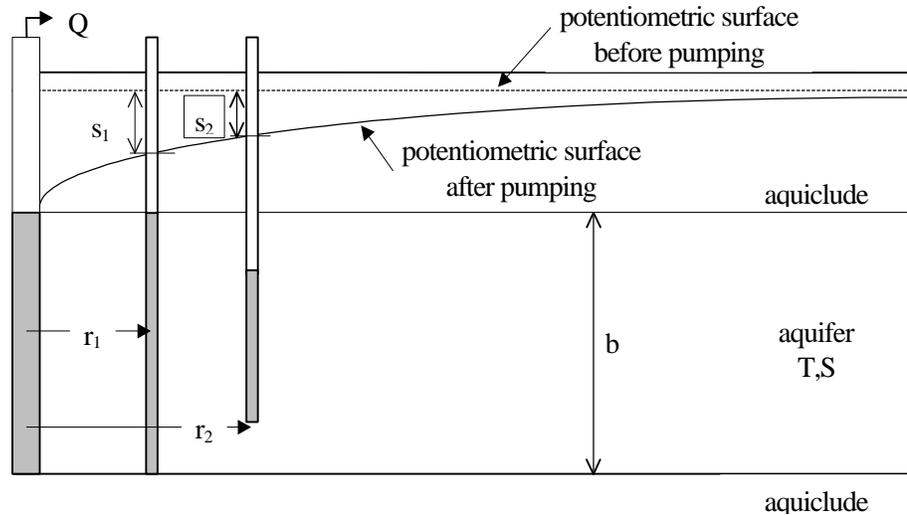
Therefore, the Cooper-Jacob equation for displacement becomes as follows:

$$s = \frac{Q}{4\pi T} \left(-0.5772 - \ln\left(\frac{r^2 S}{4Tt}\right) \right)$$

where r is distance between the pumping and observation wells, S is storage coefficient, T is transmissivity and t is time. After rearranging and rewriting as decimal logarithms, the drawdown equation reduces to the following relationship:

$$s = \frac{2.30Q}{4\pi T} \log\left(\frac{2.25Tt}{r^2 S}\right)$$

By plotting s as a function of $\log(t)$ on semi-logarithmic axes, one can determine values of T and S by drawing a straight line through the data. When using this method, it is important to match the line to data points with values of time large enough to make the variable u less than a critical value (e.g., $u \leq 0.01$).



Assumptions

- aquifer has infinite areal extent

- aquifer is homogeneous, isotropic and of uniform thickness
- aquifer potentiometric surface is initially horizontal
- pumping well is fully penetrating
- flow to pumping well is horizontal
- aquifer is confined
- flow is unsteady
- water is released instantaneously from storage with decline of hydraulic head
- diameter of pumping well is very small so that storage in the well can be neglected
- values of u are small (i.e., r is small and t is large)

Data Requirements

- pumping and observation well locations
- pumping rate(s)
- observation well measurements (time and displacement)

Solution Options

- variable pumping rates
- multiple observation wells

Visual Curve Matching Tips

- Choose **Visual** from the **Match** menu to perform visual curve matching using the procedure described in "Visual Matching With Straight-Line Solutions" on page 165.
- Display the **Valid Time** when the critical value of u criterion is satisfied (see "Plots Tab (View>Options)" on page 44).
- Use **Parameter Tweaking** to perform visual curve matching and sensitivity analysis (see "Tweak Tab (Match>Toolbox)" on page 169).

Reference

Cooper, H.H. and C.E. Jacob, 1946. A generalized graphical method for evaluating formation constants and summarizing well field history, Am. Geophys. Union Trans., vol. 27, pp. 526-534.

Tutorial

You will open the data set created and saved in the tutorial for the Theis (1935) solution for a confined aquifer (see "Tutorial" on page 56).

Please visit <http://www.aqtesolv.com/examples/> for additional tutorials and sample data sets.

Open Data Set

Choose **Open...** from the **File** menu to open a data set stored on disk.

1. Enter **THEIS1.AQT** for the name of the data set.
2. Click **OK** to open the data set.

Change View in Window

If necessary, choose **Displacement-Time** from the **View** menu to display a plot of displacement vs. time in the active window.

Choose Cooper-Jacob Solution

Choose **Solution...** from the **Match** menu to choose a solution for analyzing a pumping test in a confined aquifer.

1. Choose the **Confined Cooper-Jacob (1946)** solution.
2. Click **OK**.

After you have selected the Cooper-Jacob solution, AQTESOLV for Windows updates the window by plotting the data on semi-logarithmic axes, superimposing the Cooper-Jacob straight line on the plot, and adding the current values of transmissivity (T) and storage coefficient (S) to the legend.

The Cooper-Jacob (1946) solution supports variable pumping rates, but only during pumping phases of a test; therefore, AQTESOLV for Windows ignores the recovery data contained in this data set.

Check Validity of Cooper-Jacob

Choose **Options...** from the **View** menu.

1. In the **Plots** tab, check the **Valid Time** option to display the time after which the Cooper-Jacob straight-line approximation of the Theis (1935) solution is valid. Click the **Valid Time** tab to change the critical value of u.
2. Click **OK**.

Perform Visual Matching with Cooper-Jacob

Choose **Visual** from the **Match** menu to perform visual matching using the Cooper-Jacob straight-line solution.

1. To begin interactively matching the Cooper-Jacob solution to the data, click the left mouse button and hold it down to anchor a point along the new straight line you wish to match to the data.
2. As you move the mouse, AQTESOLV for Windows draws a straight line between the anchor point and the mouse cursor.
3. When you have finished matching the Cooper-Jacob solution to the observation well data, release the left mouse button. AQTESOLV for Windows computes new estimates of transmissivity (T) and storage coefficient (S) and updates the straight line displayed on the plot.

Perform Automatic Matching with Cooper-Jacob

Choose **Automatic...** from the **Match** menu to perform automatic matching using the Cooper-Jacob solution.

1. Click **Estimate** to begin automatic estimation.
2. As the automatic estimation procedure completes iterations, a progress window displays the changes in the residual sum of squares (RSS) criterion and the values of the aquifer properties. After the automatic estimation procedure finishes, AQTESOLV for Windows displays a

message box containing residual summary statistics. Click **OK** to close the message box.

3. Click the **Close** button to close the progress window and click **OK** to finish.

The plot shown in the active window displays the values of transmissivity (T=100.6) and storage coefficient (S=0.0009745) determined by automatic estimation.

Save Data Set

Choose **Save As...** from the **File** menu to save your work.

1. Enter **JACOBL.AQT** for the file name.
2. Click **OK** to save the data set.

Papadopoulos-Cooper (1967) Solution for a Pumping Test in a Confined Aquifer

Papadopoulos and Cooper (1967) derived a solution for a large-diameter pumping well in a confined aquifer as follows:

$$s = \frac{Q}{4\pi T} F(u, \alpha, \frac{r}{r_w})$$

$$F = \frac{8\alpha}{\pi} \int_0^{\infty} \frac{(1 - e^{-\beta^2 \rho^2 / 4u}) [J_0(\beta \rho) A(\beta) - Y_0(\beta \rho) B(\beta)]}{\{ [A(\beta)]^2 - [B(\beta)]^2 \} \beta^2} d\beta$$

$$A(\beta) = \beta Y_0(\beta) - 2\alpha Y_1(\beta)$$

$$B(\beta) = \beta J_0(\beta) - 2\alpha J_1(\beta)$$

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

$$\alpha = \frac{r_w^2 S}{r_c^2}$$

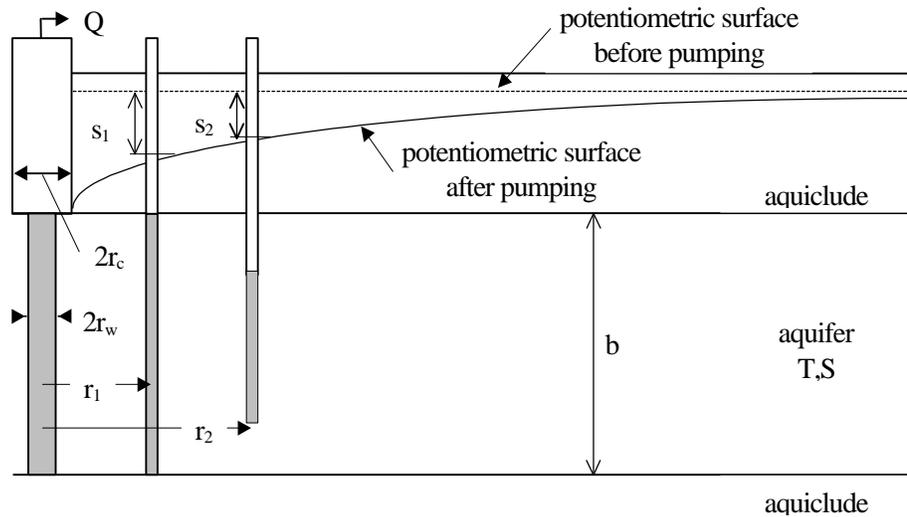
$$\rho = \frac{r}{r_w}$$

Refer to the "List of Symbols" on page 157 for a description of the parameters and variables contained in the equations for this solution.

AQTESOLV for Windows allows you to analyze both constant- and variable-rate pumping tests using the Papadopoulos-Cooper solution. For tests with a variable discharge rate, the program uses the principle of superposition to compute drawdown in the aquifer. For more information concerning the application of the principle of superposition in variable-rate pumping tests, refer to the "Theis (1935) Solution for a Pumping Test in a Confined Aquifer" on page 54.

By matching type curves of the Papadopoulos-Cooper well function to data plotted on double logarithmic axes, it is possible to determine values of T and S for a confined aquifer and the values of the pumping well radius (r_w) and casing radius (r_c). If a data

set contains more than one pumping well, AQTESOLV for Windows estimates the well radius and casing radius for the first pumping well contained in the data set.



Note that the well radius (r_w) may be larger or smaller than the casing radius (r_c).

Assumptions

- aquifer has infinite areal extent
- aquifer is homogeneous, isotropic and of uniform thickness
- aquifer potentiometric surface is initially horizontal
- pumping well is fully penetrating
- flow to pumping well is horizontal
- aquifer is confined
- flow is unsteady
- water is released instantaneously from storage with decline of hydraulic head

Data Requirements

- pumping and observation well locations
- pumping rate(s)
- observation well measurements (time and displacement)
- casing radius and wellbore radius for pumping well(s)

Solution Options

- large-diameter pumping wells
- variable pumping rates
- multiple pumping wells
- multiple observation wells

Visual Curve Matching Tips

- Choose **Visual** from the **Match** menu to perform visual curve matching using the procedure described in "Visual Matching With Type Curve Solutions" on page 165.
- Use **Active Type Curves** for more effective visual matching with variable-rate pumping tests (see "Active Type Curves" on page 167).
- Choose **Radial Flow** from the **View** menu to help identify the presence of wellbore storage (see "Radial Flow Plot" on page 42).
- Select values of S, r(w) and r(c) from the **Family** and **Curve** lists on the toolbar.
- Use **Parameter Tweaking** to perform visual curve matching and sensitivity analysis (see "Tweak Tab (Match>Toolbox)" on page 169).

Reference

Papadopoulos, I.S. and H.H. Cooper, 1967. Drawdown in a well of large diameter, Water Resources Research, vol. 3, pp. 241-244.

Tutorial

In this tutorial, you will use the Papadopoulos-Cooper type curve solution to create and analyze a constant-rate pumping test with a large-diameter pumping well in a confined aquifer. This tutorial shows you how to use automatic curve matching to match the Papadopoulos-Cooper type curve to drawdown data measured during the test.

Please visit <http://www.aqtesolv.com/examples/> for additional tutorials and sample data sets.

Open a New Data Set

Open a new data set by choosing **New** from the **File** menu. In the **New Data Set** dialog box, choose **Tutorial** in the list box and click **OK** to initialize the new data set with default values. AQTESOLV for Windows opens a new window with an Error Log view that reports any errors identified in the data set.

Enter Data for Pumping Test

Choose **Units...** from the **Edit** menu to select units of measurement for the data set.

1. Select **ft** (feet) for **Length**, **min** (minutes) for **Time**, **cu. ft/min** (cubic feet-per-minute) for **Pumping Rate** and **consistent** units for **Hyd. Conductivity**.
2. Click **OK**.

Choose **Annotations...** from the **Edit** menu to edit the data set title.

1. In the **Title** tab, enter **Large-Diameter Well Pumping Test** for the **Title**.
2. Click **OK**.

Choose **Aquifer Data...** from the **Edit** menu to edit aquifer data.

1. In the General tab, enter **100.0** for the value of **Saturated Thickness**.
2. Click **OK**.

Choose **Pumping Well>Edit...** from the **Edit** menu edit pumping well data.

1. In the **Construction** tab, enter **1.0** for both **Wellbore Radius** and **Casing Radius**.
2. In the **Rates** tab, enter values of **0.0** and **0.000314159** for time and rate, respectively, where time is in minutes and rate is in cubic feet-per-minute.
3. Click **OK**.

Choose **Obs. Well>Edit...** from the **Edit** menu to edit data for the observation well.

1. In the **General** tab, enter a value of **1.0** for the **X-Coordinate** location of the well.
2. In the **Observations** tab, click the **Import** button to import observation well measurements from a delimited text file using the **Observation Data Import Wizard**. In Step 1 of the **Import Wizard**, enter **PC1.DAT** for the name of the import file. The file **PC1.DAT** contains time and displacement data arranged in two columns separated by a tab delimiter. Click **Next**.
3. In Step 2 of the **Import Wizard**, enter data describing the structure of the import file. The **Import Wizard** automatically determines that the import file contains 2 columns of data. Enter **1** for the **Elapsed Time** column and **2** for the **Displacement** column. Click **Next**.
4. In Step 3 of the **Import Wizard**, choose transformation and filter options for the data contained in the import file. Retain the default settings, and click **Finish**.
5. After AQTESOLV for Windows has finished importing the data, a message box displays the number of observations imported from the file. Click **OK**.
6. Click **OK**.

After you have completed the previous data entry steps, the **Error Log** displayed in the active window should show that the data set contains no errors. Now you are ready to display the data, choose a solution and estimate aquifer properties.

Save Data Set

Choose **Save As...** from the **File** menu to save the data you have entered into the current data set.

1. Enter **PAPADOPI.AQT** for the file name.
2. Click **OK** to save the data set.

Change View in Window

Choose **Displacement-Time** from the **View** menu to display a plot of displacement vs. time in the active window. The window displays a plot of the observation well data on semi-log axes.

Choose Papadopulos-Cooper Solution

Change the aquifer model and solution by choosing **Solution...** from the **Match** menu to choose a solution for analyzing a pumping test in a confined aquifer.

1. Choose the **Confined Papadopulos-Cooper (1967)** solution.
2. Click **OK**.

After you have selected the Papadopoulos-Cooper solution for a large-diameter well pumping test in a confined aquifer, AQTESOLV for Windows updates the window by plotting the data on double logarithmic axes, superimposing a Papadopoulos-Cooper type curve on the plot, and displaying values of transmissivity, storage coefficient, wellbore radius and casing radius in the legend.

Perform Automatic Matching with Papadopoulos-Cooper

Choose **Automatic...** from the **Match** menu to perform automatic matching using the Papadopoulos-Cooper type curve solution.

1. Click **Estimate** to begin automatic estimation.
2. As the automatic estimation procedure completes iterations, a progress window displays the changes in the residual sum of squares (RSS) criterion and the values of the aquifer properties. After the automatic estimation procedure finishes, AQTESOLV for Windows displays a message box containing residual summary statistics. Click **OK** to close the message box.
3. Click the **Close** button to close the progress window and click **OK** to finish.

The plot shown in the active window displays the values of transmissivity ($T=2.513E-05$), storage coefficient ($S=9.442E-05$) and wellbore radius ($R_w=0.9949$) determined by automatic estimation.

Display Theis Type Curve

Choose **Options...** from the **View** menu and click the **Plots** tab. Check the **Theis Curve(s)** option to superimpose a Theis type curve on the plot using the current values of T and S.

Save Data Set

Choose **Save** from the **File** menu to save your work in the **PAPADOPI.AQT** data set.

Theis (1935) Solution for a Recovery Test in a Confined Aquifer

Theis (1935) proposed a straight-line solution for determining transmissivity and storativity from residual displacement data collected during the recovery phase of a pumping test:

$$s' = \frac{Q}{4\pi T} [\ln(t/t') - \ln(S/S')]$$

where s' is residual displacement, Q is pumping rate, T is transmissivity, t is time since pumping began, t' is time since pumping stopped, S is storativity during pumping and S' is storativity during recovery.

By plotting s' as a function of $\log(t/t')$ on semi-logarithmic axes, one can determine values of T and S/S' by drawing a straight line through the data. Without the influence of boundary effects, the value of S/S' determined from the intercept of the straight line with the $\log(t/t')$ axis should be close to unity. A value of $S/S' > 1.0$ indicates the influence of a recharge boundary during the test. Conversely, a value of $S/S' < 1.0$ suggests the presence of a barrier or no-flow boundary.

When using this method, it is important to match the line to data points with values of time large enough to make the variable u less than a critical value (see "Cooper-Jacob (1946) Solution for a Pumping Test in a Confined Aquifer" on page 59).

Assumptions

- aquifer has infinite areal extent
- aquifer is homogeneous, isotropic and of uniform thickness
- aquifer potentiometric surface is initially horizontal
- pumping well is fully penetrating
- flow to pumping well is horizontal
- aquifer is confined
- flow is unsteady
- water is released instantaneously from storage with decline of hydraulic head
- diameter of pumping well is very small so that storage in the well can be neglected
- values of u are small (i.e., r is small and t is large)

Data Requirements

- pumping and observation well locations
- pumping rate(s)
- observation well measurements (time and displacement)

Solution Options

- variable pumping rates

Visual Curve Matching Tips

- Choose **Visual** from the **Match** menu to perform visual curve matching using the procedure described in "Visual Matching With Straight-Line Solutions" on page 165.
- Use **Parameter Tweaking** to perform visual curve matching and sensitivity analysis (see "Tweak Tab (Match>Toolbox)" on page 169).

Reference

Theis, C.V., 1935. The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage, Am. Geophys. Union Trans., vol. 16, pp. 519-524.

Tutorial

In this tutorial, you will use the Theis Recovery solution to analyze the variable rate pumping test data set created and saved in the tutorial for the Theis solution. This tutorial shows you how to use visual and automatic curve matching to fit a straight line to recovery data measured during a variable-rate pumping test.

Please visit <http://www.aqtesolv.com/examples/> for additional tutorials and sample data sets.

Open Data Set

Choose **Open...** from the **File** menu to open a data set stored on disk. You will open the data set created and saved in the tutorial for the Theis (1935) solution.

1. Enter **THEIS1.AQT** for the name of the data set.
2. Click **OK** to open the data set.

Change View in Window

If necessary, choose **Displacement-Time** from the **View** menu to display a plot of displacement vs. time in the active window.

Choose Theis Recovery Solution

Choose **Solution...** from the **Match** menu to choose a solution for analyzing a pumping test in a confined aquifer.

1. Choose the **Confined Theis Residual Drawdown (1935)** solution.
2. Click **OK**.

After you have selected the Theis Recovery solution for a pumping test in a confined aquifer, AQTESOLV for Windows changes the view to a **Residual Drawdown** plot, updates the window by plotting s' vs. t/t' on semi-logarithmic axes, superimposes the Theis Recovery straight line on the plot, and adds the current values of transmissivity (T) and ratio of storage coefficient during pumping to storage coefficient during recovery (S/S') to the legend.

You may analyze data from a variable-rate pumping test using the Theis Recovery (1935) method, but only during the first period of recovery. If pumping was intermittent during the test (i.e., more than one period of recovery), your analysis with this solution is restricted to the first recovery period.

Perform Visual Matching with Theis Recovery

Choose **Visual** from the **Match** menu to perform visual matching using the Theis Recovery straight line solution.

1. To begin interactively matching the Theis Recovery solution to the data, click the left mouse button and hold it down to anchor a point along the new straight line you wish to match to the data.
2. As you move the mouse, AQTESOLV for Windows drags a straight line between the anchor point and the mouse cursor.
3. When you have finished matching the Theis Recovery solution to the observation well data, release the left mouse button. AQTESOLV for Windows computes new estimates of transmissivity (T) and storage coefficient ratio (S/S') and updates the straight line displayed on the plot.

Perform Automatic Matching with Theis Recovery

Choose **Automatic...** from the **Match** menu to perform automatic matching using the Theis Recovery solution.

1. Click **Estimate** to begin automatic estimation.
2. As the automatic estimation procedure completes iterations, a progress window displays the changes in the residual sum of squares (RSS)

criterion and the values of the aquifer properties. After the automatic estimation procedure finishes, AQTESOLV for Windows displays a message box containing residual summary statistics. Click **OK** to close the message box.

3. Click the **Close** button to close the progress window and click **OK** to finish.

The plot shown in the active window displays the values of transmissivity ($T=103.3$) and storage coefficient ($S/S'=0.9275$) determined by automatic estimation.

Save Data Set

Choose **Save As...** from the **File** menu to save the data you have entered into the current data set.

1. Enter **THEISR1.AQT** for the file name.
2. Click **OK** button to save the data set.

Theis (1935) Solution for a Step Drawdown Test in a Confined Aquifer

A step drawdown test is a single-well pumping test designed to investigate the performance of a pumping well under variable discharge rate conditions. In a step test, the discharge rate in the pumping well is increased from an initially low constant rate through a sequence of pumping intervals of progressively greater constant rates. In each step of the test, the drawdown in the pumping well is allowed to stabilize. Each step is typically of equal duration, lasting from approximately 30 minutes to 2 hours (Kruseman and de Ridder 1990).

Various researchers have investigated the performance of pumping wells to determine well losses as a function of discharge rate. Jacob (1947) proposed the following drawdown equation that accounts for linear and nonlinear head losses in the pumping well:

$$s_w = B(r_e, t)Q + CQ^2$$

where $B(r_e, t)$ is the linear head-loss coefficient and C is the nonlinear well-loss coefficient. The linear head-loss coefficient $B(r_e, t)$ is a function of the effective or equivalent radius of the well r_e and time t . The equivalent well radius (r_e) is defined as the radial distance from the well at which the theoretical drawdown equals the drawdown immediately outside the well screen. The linear head-loss coefficient consists of two components:

$$B(r_e, t) = B_1(r_w, t) + B_2$$

where $B_1(r_w, t)$ is the linear aquifer-loss coefficient and B_2 is the linear well-loss coefficient. The linear aquifer-loss coefficient $B_1(r_w, t)$ is a function of the radius of the well (r_w) and time (t). Ramey (1982) defines the linear well-loss coefficient B_2 in terms of a wellbore skin factor (S_w) as follows:

$$S_w = B_2 \cdot 2\pi T$$

Rorabaugh (1953) modified Jacob's equation to account for variations in the nonlinear well-loss term:

$$s_w = B(r_e, t)Q + CQ^P$$

where P is the order of nonlinear well losses. According to Rorabaugh (1953), the value of P can assume values ranging from 1.5 to 3.5 depending on the value of Q, but many researchers accept the value of P=2 as proposed by Jacob (1947).

The efficiency of a pumping well, which expresses the relationship between theoretical and actual drawdown in the well, is computed as follows (Kruseman and de Ridder 1990):

$$E_w = \frac{\text{theoretical drawdown}}{\text{actual drawdown}} \cdot 100\%$$

$$E_w = \frac{B_1 Q}{(B_1 + B_2) Q + C Q^P} \cdot 100\%$$

The Theis (1935) solution ("Theis (1935) Solution for a Pumping Test in a Confined Aquifer" on page 54), modified to include linear and nonlinear well losses, for a pumping well in a confined aquifer is expressed as follows:

$$s_w = \frac{Q}{4\pi T} (w(u) + 2S_w) + C Q^P$$

$$u = \frac{r_w^2 S}{4Tt}$$

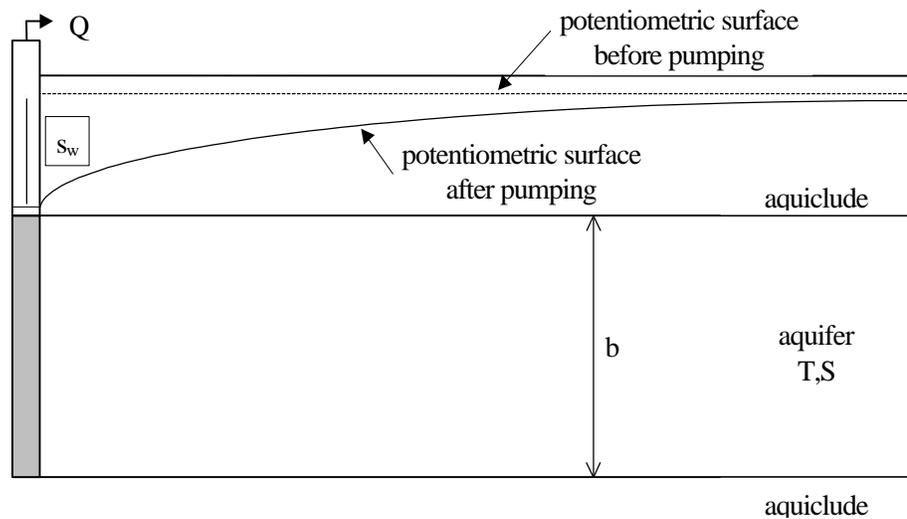
In this equation, the Theis well function $w(u)$, the wellbore skin factor and the term $C Q^P$ account for linear aquifer losses, linear well losses and nonlinear well losses, respectively. Refer to the "List of Symbols" on page 157 for a description of the parameters and variables contained in the equations for this solution.

AQTESOLV for Windows allows you to analyze both constant- and variable-rate pumping tests using the Theis solution. For tests with a variable discharge rate, the program uses the principle of superposition to compute drawdown in the aquifer. For more information concerning the application of the principle of superposition in variable-rate pumping tests, refer to the "Theis (1935) Solution for a Pumping Test in a Confined Aquifer" on page 54.

The Theis step-drawdown test solution predicts drawdown in a pumping well for any discharge rate Q and any time t. The solution can be written in the form of the Jacob-Rorabaugh equation to predict drawdown in the pumping well at a specified value of time:

$$s_w = B(r_e, t_p) Q + C Q^P$$

where t_p is the specified prediction time. AQTESOLV for Windows allows you to enter the prediction time t_p to calculate the coefficient $B(r_e, t_p)$ used in the prediction equation.



Solution Assumptions

- aquifer has infinite areal extent
- aquifer is homogeneous, isotropic and of uniform thickness
- pumping well is fully penetrating
- flow to pumping well is horizontal when pumping well is fully penetrating
- aquifer is confined
- flow is unsteady
- water is released instantaneously from storage with decline of hydraulic head
- diameter of pumping well is very small so that storage in the well can be neglected

Data Requirements

- pumping and observation well locations
- pumping rate(s)
- observation well measurements (time and displacement)

Solution Options

- variable pumping rates
- multiple pumping wells
- multiple observation wells

Visual Curve Matching Tips

- Choose **Visual** from the **Match** menu to perform visual curve matching using the procedure described in "Visual Matching With Type Curve Solutions" on page 165.

- Use **Active Type Curves** for more effective visual matching with variable-rate pumping tests (see "Active Type Curves" on page 167).
- Use **Parameter Tweaking** to perform visual curve matching and sensitivity analysis (see "Tweak Tab (Match>Toolbox)" on page 169).

References

- Jacob, C.E., 1947. Drawdown test to determine effective radius of artesian well, Trans. Amer. Soc. of Civil Engrs., vol. 112, paper 2321, pp. 1047-1064.
- Ramey, H.J., 1982. Well-loss function and the skin effect: A review. In: Narasimhan, T.N. (ed.) Recent trends in hydrogeology, Geol. Soc. Am., special paper 189, pp. 265-271.
- Rorabaugh, M.J., 1953. Graphical and theoretical analysis of step-drawdown test of artesian well, Proc. Amer. Soc. Civil Engrs., vol. 79, separate no. 362, 23 pp.
- Theis, C.V., 1935. The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage, Am. Geophys. Union Trans., vol. 16, pp. 519-524.

Tutorial

Perform one of the following tutorials to learn how to use the Theis solution:

1. Guided Tour (see "Analyzing a Pumping Test" on page 7)
2. Theis (1935) solution for a pumping test in a confined aquifer (see "Tutorial" on page 56)

Please visit <http://www.aqtesolv.com/examples/> for additional tutorials and sample data sets.

Hantush (1962) Solution for a Pumping Test in a Wedge-Shaped Confined Aquifer

Hantush (1962) derived an equation which predicts water-level displacement in a wedge-shaped confined aquifer in response to pumping:

$$s = \frac{Q}{4\pi T} e^{r/a \cos \theta} \int_u^{\infty} \frac{e^{-y-r^2/4a^2y}}{y} dy$$

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

$$b = b_0 e^{-2(x-x_0)/a}$$

Ordinarily, the slope on the base of the confined aquifer varies exponentially in the x-coordinate direction and is constant in the y-coordinate direction. The slope orientation angle θ measures the orientation of the slope in relation to the x-coordinate axis and is measured counterclockwise from the positive x-coordinate axis to the vector oriented in the updip direction of the slope. The parameter a is a constant defining the variation in thickness of the wedge-shaped aquifer.

The solution assumes that the change in aquifer thickness as a function of distance meets the following criterion:

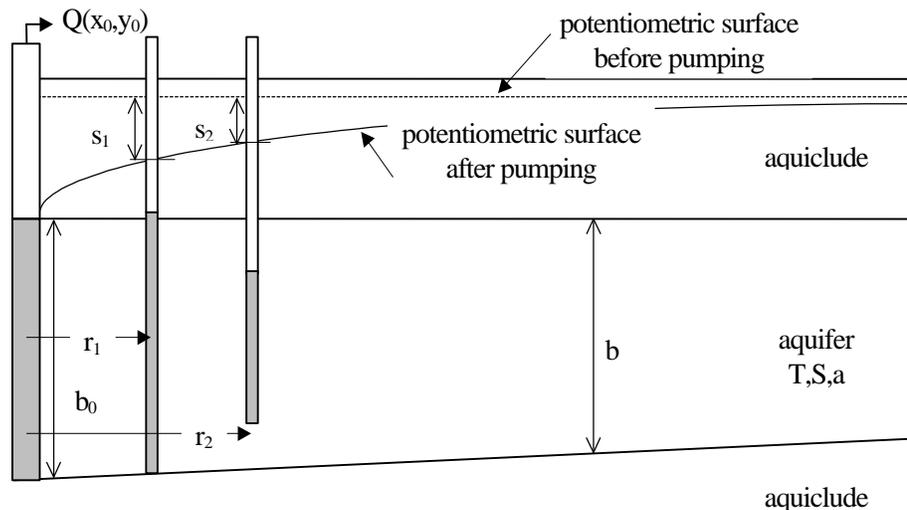
$$\frac{db}{dx} < 0.20$$

and that the duration of pumping does not exceed the following limitation:

$$t < \frac{r_0^2 S_s}{20K} \quad \text{where } r_0 = \frac{a}{2} \ln \left(\frac{a}{10b_0} \right)$$

Hydrogeologists commonly refer to the exponential integral in the drawdown equation as the *Hantush well function* (see "Hantush-Jacob (1955) Solution for a Pumping Test in a Leaky Aquifer" on page 119). Refer to the "List of Symbols" on page 157 for a description of the parameters and variables contained in the equations for this solution.

AQTESOLV for Windows allows you to analyze both constant- and variable-rate pumping tests using the Hantush wedge-shaped aquifer solution. For tests with a variable discharge rate, the program uses the principle of superposition to compute drawdown in the aquifer. For more information concerning the application of the principle of superposition in variable-rate pumping tests, refer to the "Theis (1935) Solution for a Pumping Test in a Confined Aquifer" on page 54.



Solution Assumptions

- aquifer has infinite areal extent
- aquifer is homogeneous and isotropic
- pumping well is fully penetrating
- flow to pumping well is horizontal
- aquifer is confined
- flow is unsteady
- water is released instantaneously from storage with decline of hydraulic head

- diameter of pumping well is very small so that storage in the well can be neglected
- the thickness of the aquifer varies exponentially in the direction of flow
- the rate of change in aquifer thickness in the direction of flow does not exceed 0.20
- the influence of pumping has not extended beyond the section of the aquifer at which the tangents of the maximum angles of dip of the confining beds are greater than 0.20

Data Requirements

- pumping and observation well locations
- pumping rate(s)
- observation well measurements (time and displacement)

Solution Options

- variable pumping rates
- multiple observation wells

Visual Curve Matching Tips

- Choose **Visual** from the **Match** menu to perform visual curve matching using the procedure described in "Visual Matching With Type Curve Solutions" on page 165.
- Use **Active Type Curves** for more effective visual matching with variable-rate pumping tests (see "Active Type Curves" on page 167).
- Select values of r/a from the **Family** and **Curve** lists on the toolbar.
- Use **Parameter Tweaking** to perform visual curve matching and sensitivity analysis (see "Tweak Tab (Match>Toolbox)" on page 169).

Reference

Hantush, M.S., 1962. Flow of ground water in sands of nonuniform thickness; 3. Flow to wells, Jour. Geophys. Res., vol. 67, no. 4, pp. 1527-1534.

Tutorial

Perform the tutorial for the Hantush-Jacob (1955) solution for pumping test in a leaky aquifer (see "Tutorial" on page 122) to learn how to use this solution.

Please visit <http://www.aqtesolv.com/examples/> for additional tutorials and sample data sets.

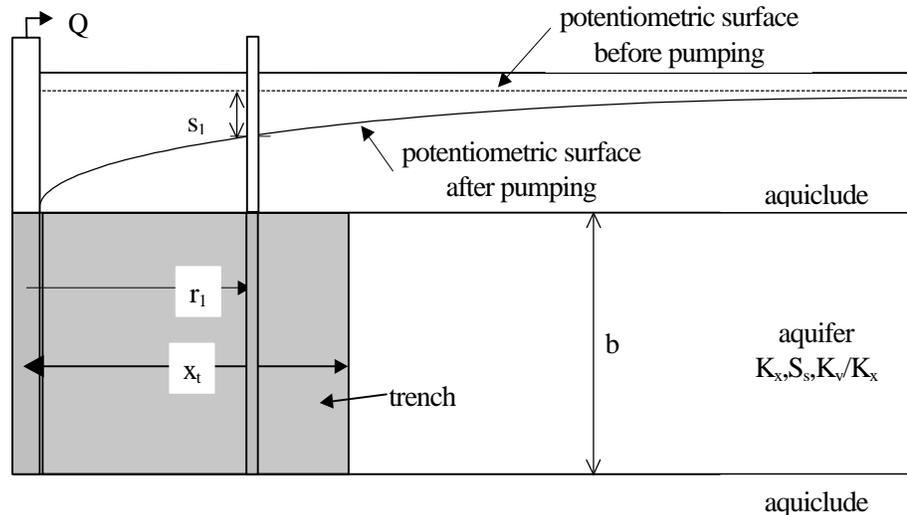
Murdoch (1994) Solution for Flow to a Trench

Murdoch (1994) presented a method for analyzing transient flow to an interceptor trench based on the analytical solutions by Gringarten and Witherspoon (1972) and Gringarten, Ramey and Raghavan (1974) for flow to a well in a confined infinite

radial system intersecting a single uniform-flux plane vertical fracture (see "Please visit <http://www.aqtesolv.com/examples/> for additional tutorials and sample data sets.

Gringarten-Witherspoon (1972) Solution for a Pumping Test in a Fractured Aquifer with a Plane Vertical Fracture" on page 146).

In this solution, the trench parallels the x axis of the coordinate system and has a length of $L (=2x_t)$. Refer to the "List of Symbols" on page 157 for a description of the parameters and variables contained in the equations.



Assumptions

- aquifer has infinite areal extent
- aquifer has uniform thickness
- aquifer potentiometric surface is initially horizontal
- interceptor trench and observation wells are fully penetrating
- confined aquifer represented by anisotropic system with a single interceptor trench
- flow is unsteady
- water is released instantaneously from storage with decline of hydraulic head

Data Requirements

- interceptor trench and observation well locations
- pumping rate(s)
- observation well measurements (time and displacement)
- saturated thickness of aquifer
- length of trench

Solution Options

- variable pumping rate

- multiple pumping wells
- multiple observation wells

Visual Curve Matching Tips

- Choose **Visual** from the **Match** menu to perform visual curve matching using the procedure described in "Visual Matching With Type Curve Solutions" on page 165.
- Use **Active Type Curves** for more effective visual matching with variable-rate pumping tests (see "Active Type Curves" on page 167).
- Choose **Linear Flow** from the **View** menu to help identify the presence of linear flow conditions (see "Linear Flow Plot" on page 42).
- Select values of K_y/K_x from the **Family** and **Curve** lists on the toolbar.
- Use **Parameter Tweaking** to perform visual curve matching and sensitivity analysis (see "Tweak Tab (Match>Toolbox)" on page 169).

Reference

Murdoch, L.C., 1994. Transient analyses of an interceptor trench, Water Resources Research, vol. 30, no. 11, pp. 3023-3031.

Tutorial

Perform the tutorial for the Gringarten-Witherspoon (1972) solution for pumping test in a fractured aquifer with a single vertical fracture (see "Tutorial" on page 148) to learn how to use this solution.

Instead of entering fracture data for this solution, enter data for the trench as follows:

1. Choose **Aquifer Data...** from the **Edit** menu. In the **Trench** tab, enter the length of the trench.
2. Choose **Pumping Well>Edit...** from the **Edit** menu. In the **General** tab, enter well coordinates at the center of the trench. In the **Rates** tab, enter the pumping rate(s) for the trench.

Please visit <http://www.aqtesolv.com/examples/> for additional tutorials and sample data sets.

Cooper-Bredehoeft-Papadopoulos (1967) Solution for a Slug Test in a Confined Aquifer

Cooper et al. (1967) derived an analytical solution describing the water-level response due to the instantaneous injection or withdrawal of water from a well in a confined aquifer. The equation for the Laplace transform solution is as follows:

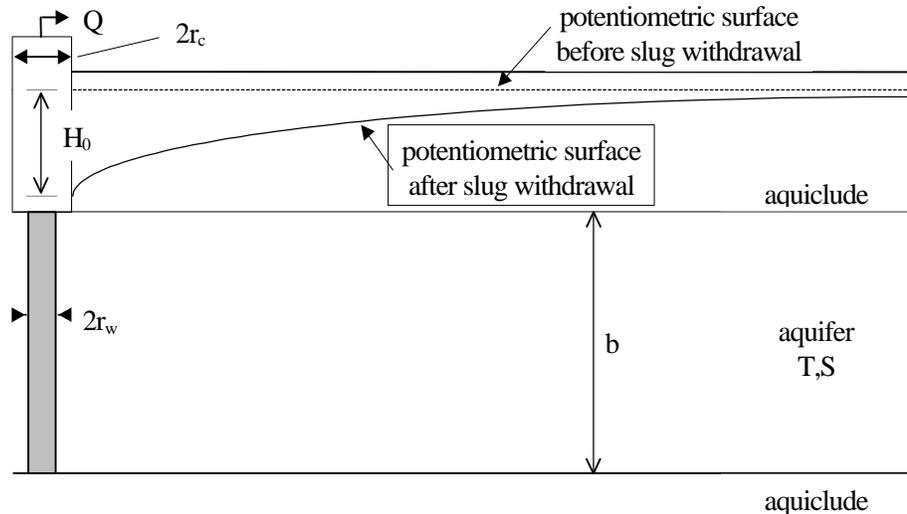
$$\bar{h} = \frac{r_w S s_0 K_0(rq)}{Tq[r_w q K_0(r_w q) + 2\alpha K_1(r_w q)]}$$

$$q = (pS / T)^{1/2}$$

$$\alpha = \frac{r_w^2 S}{r_c^2}$$

Refer to the "List of Symbols" on page 157 for a description of the parameters and variables contained in the equations for this solution.

By matching type curves of the Cooper-Bredehoeft-Papadopoulos slug test solution to data plotted on semi-logarithmic axes, it is possible to determine values of T and S for a confined aquifer and the value of the well radius (r_w).



Note that the well radius (r_w) may be larger or smaller than the casing radius (r_c).

Assumptions

- aquifer has infinite areal extent
- aquifer is homogeneous, isotropic and of uniform thickness
- aquifer potentiometric surface is initially horizontal
- a volume of water, V, is injected into or discharged from the well instantaneously
- test well is fully penetrating
- flow to test well is horizontal
- aquifer is confined
- flow is unsteady
- water is released instantaneously from storage with decline of hydraulic head

Data Requirements

- test well measurements (time and displacement)
- initial displacement
- casing radius and wellbore radius for test well

- saturated thickness of aquifer
- screen length
- total depth of well penetration
- porosity of gravel pack (optional)
- hydraulic conductivity anisotropy ratio (optional)

Visual Curve Matching Tips

- Choose **Visual** from the **Match** menu to perform visual curve matching using the procedure described in "Visual Matching With Type Curve Solutions" on page 165.
- Select values of S from the **Family** and **Curve** lists on the toolbar.
- Use **Parameter Tweaking** to perform visual curve matching and sensitivity analysis (see "Tweak Tab (Match>Toolbox)" on page 169).

Reference

Cooper, H.H., J.D. Bredehoeft and S.S. Papadopoulos, 1967. Response of a finite-diameter well to an instantaneous charge of water, Water Resources Research, vol. 3, no. 1, pp. 263-269.

Tutorial

The Guided Tour (see "Analyzing a Slug Test" on page 11) contains a tutorial for the Cooper-Bredehoeft-Papadopoulos slug test solution.

Please visit <http://www.aqtesolv.com/examples/> for additional tutorials and sample data sets.

Bouwer-Rice (1976) Solution for a Slug Test in a Confined Aquifer

For information concerning this solution, refer to "Bouwer-Rice (1976) Solution for a Slug Test in an Unconfined Aquifer" on page 107.

Hvorslev (1951) Solution for a Slug Test in a Confined Aquifer

Hvorslev (1951) developed an empirical relationship describing the water-level response in a confined aquifer due to the instantaneous injection or withdrawal of water from a well:

$$\ln(s_0) - \ln(s_t) = \frac{2KLt}{r_{ce}^2 \ln(L/2r_{we} + \sqrt{1 + (L/2r_{we})^2})}$$

$$r_{ce} = \sqrt{r_c^2 + n(r_w^2 - r_c^2)}$$

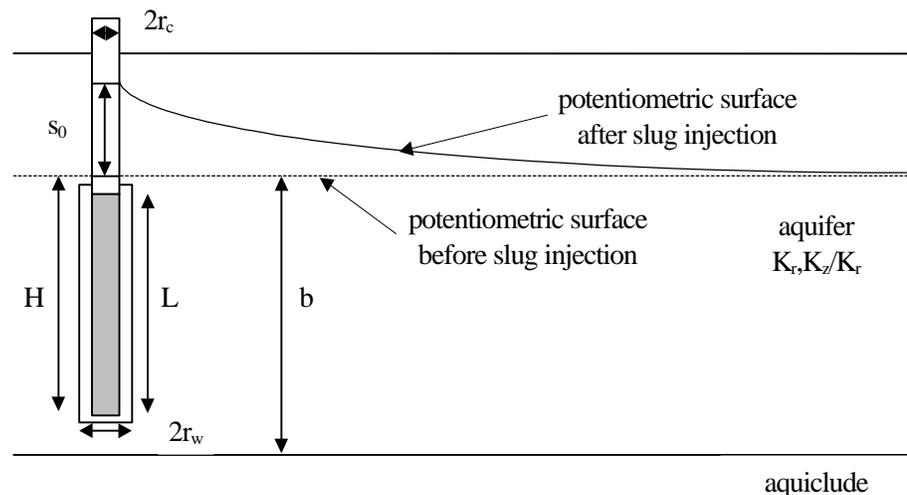
$$r_{we} = r_w \sqrt{\frac{K_z}{K_r}}$$

The Hvorslev (1951) solution assumes that the confined aquifer has infinite extent, both horizontally and vertically. For this reason, the solution by Bouwer and Rice solution may be more appropriate when the thickness of the aquifer is known.

Bouwer and Rice (1976) recommend computing an equivalent casing radius (r_{ce}) to correct for the porosity of the gravel pack when the height of the static water column in the well is less than the screen length (i.e., the screen is partially submerged). AQTESOLV for Windows computes the equivalent casing radius using the value of porosity (n) specified in the data set; a porosity equal to zero (0.0) results in no correction to the casing radius.

Butler (1998) recommends matching the Hvorslev solution to slug test data within a normalized head range (designated as $s/s_0(0)$ or $H/H_0(0)$) of 0.15 to 0.25. To display the recommended head range during visual curve matching, see "Visual Curve Matching Tips" on page 81.

Refer to the "List of Symbols" on page 157 for a description of the parameters and variables contained in the equations.



Assumptions

- aquifer has infinite areal and vertical extent
- aquifer is homogeneous
- aquifer potentiometric surface is initially horizontal
- a volume of water, V , is injected into or discharged from the well instantaneously
- aquifer is confined or unconfined
- flow is steady

Data Requirements

- test well measurements (time and displacement)
- initial displacement
- casing radius and wellbore radius for test well

- saturated thickness of aquifer
- screen length
- total depth of well penetration below confining unit (confined aquifer) or water table (unconfined aquifer)
- porosity of gravel pack (optional)
- hydraulic conductivity anisotropy ratio (optional)

Visual Curve Matching Tips

- Choose **Visual** from the **Match** menu to perform visual curve matching (see "Visual Matching With Straight-Line Solutions" on page 165).
- For this solution, **visual curve matching** is often more effective than automatic matching because you are interested in matching the straight line to a specific range of data that meet the assumptions of the solution. To achieve the same effect with **automatic curve matching**, it would require the judicious application of weights to ignore observations outside the desired range (see "Observations Tab" on page 36).
- Choose **Options** from the **View** menu and select the **Recommended Head Range** option in the **Plots** tab to superimpose on the plot the head range recommended by Butler (1998) to obtain the most reliable matching results for solutions (assuming a steady-state representation of flow for a slug test).
- Use **Parameter Tweaking** to perform visual curve matching and sensitivity analysis (see "Tweak Tab (Match>Toolbox)" on page 169).

References

- Bouwer, H. and R.C. Rice, 1976. A slug test method for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells, *Water Resources Research*, vol. 12, no. 3, pp. 423-428.
- Hvorslev, M.J., 1951. Time Lag and Soil Permeability in Ground-Water Observations, *Bull. No. 36, Waterways Exper. Sta. Corps of Engrs, U.S. Army, Vicksburg, Mississippi*, pp. 1-50.

Tutorial

Performing curve matching with the Hvorslev solution is essentially identical to the Bouwer-Rice method. Please refer to the Guided Tour (see "Analyzing a Slug Test" on page 11) which contains a tutorial for the Bouwer-Rice solution.

Please visit <http://www.aqtesolv.com/examples/> for additional tutorials and sample data sets.

Hyder et al. (1994) Solution for a Slug Test in a Confined Aquifer (KGS Model)

Hyder et al. (1994) derived an analytical solution, also known as the KGS Model, describing the water-level response due to the instantaneous injection or withdrawal

of water from a partially penetrating well in a confined aquifer. The equation for the Laplace transform solution is as follows:

$$\bar{h} = \frac{(\gamma/2)\Omega}{[1 + (\gamma/2)p\Omega]}$$

$$\alpha = \frac{2r_w^2 S_{s2} L}{r_c^2}$$

$$\gamma = K_{r2} / K_{r1}$$

$$\Omega = \int_{\zeta}^{\zeta+1} \{F_c^{-1}[F_c(\omega)f_1]\} d\eta$$

$$f_1 = \frac{[\Delta_2 K_0(v_1) - \Delta_1 I_0(v_1)]}{v_1 [\Delta_2 K_1(v_1) + \Delta_1 I_1(v_1)]}$$

$$\eta = z / L$$

$$\zeta = d / L$$

$$v_i = (\psi_i^2 \omega^2 + R_i p)^{1/2}$$

$$\psi_i = (A_i / a^2)^{1/2}$$

$$A_i = K_{zi} / K_{ri}$$

$$a = L / r_w$$

$$R_1 = \gamma \alpha / 2\lambda$$

$$R_2 = \alpha / 2$$

$$\lambda = S_{s2} / S_{s1}$$

$$\Delta_1 = K_0(v_1 \xi_{sk}) K_1(v_2 \xi_{sk}) - \frac{N}{\gamma} K_0(v_2 \xi_{sk}) K_1(v_1 \xi_{sk})$$

$$\Delta_2 = I_0(v_1 \xi_{sk}) K_1(v_2 \xi_{sk}) + \frac{N}{\gamma} K_0(v_2 \xi_{sk}) I_1(v_1 \xi_{sk})$$

$$N = v_1 / v_2$$

$$\xi_{sk} = r_{sk} / r_w$$

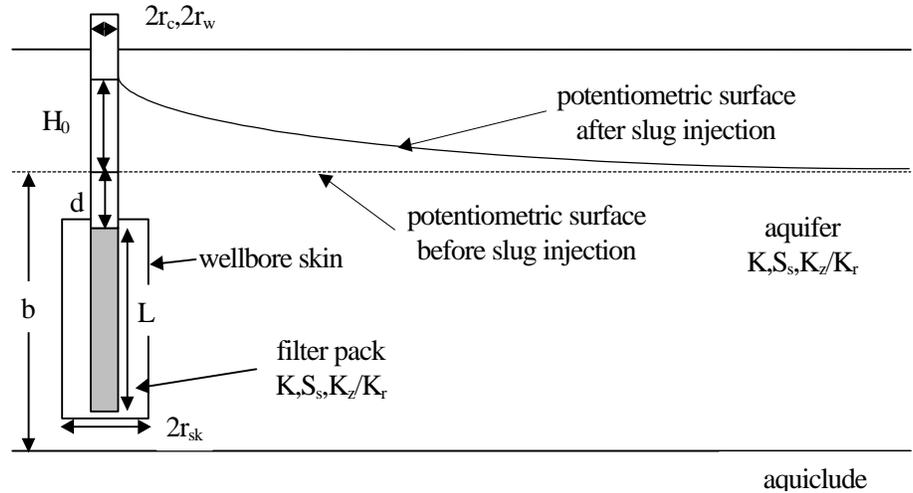
$F_c(\omega)$ = finite Fourier cosine transform of $B(z)$

F_c^{-1} = inverse finite Fourier cosine transform

$$B(z) = \begin{cases} 0, & z < d, z > L + d \\ 1, & \text{otherwise} \end{cases}$$

Refer to the "List of Symbols" on page 157 for a description of the parameters and variables contained in the equations for this solution.

By matching type curves of the KGS Model slug test solution to data plotted on semi-logarithmic axes, it is possible to determine values of K , S_s , S_s and K_z/K_r , K_z/K_r for the confined aquifer and K , S_s , S_s and K_z/K_r , K_z/K_r for the filter pack.



Assumptions

- aquifer has infinite areal extent
- aquifer is homogeneous and of uniform thickness
- aquifer potentiometric surface is initially horizontal
- a volume of water, V , is injected into or discharged from the well instantaneously
- aquifer is confined
- flow is unsteady
- water is released instantaneously from storage with decline of hydraulic head

Data Requirements

- test well measurements (time and displacement)
- initial displacement
- casing radius, effective well radius and outer radius of well skin for test well
- saturated thickness of aquifer
- screen length
- total depth of well penetration

Visual Curve Matching Tips

- Choose **Visual** from the **Match** menu to perform visual curve matching using the procedure described in "Visual Matching With Type Curve Solutions" on page 165.

- Select values of S_s , K_z/K_r , S_s' and K_z/K_r' , S_s , K_z/K_r , S_s' and K_z/K_r' from the **Family** and **Curve** lists on the toolbar.
- Use **Parameter Tweaking** to perform visual curve matching and sensitivity analysis (see "Tweak Tab (Match>Toolbox)" on page 169).

Reference

Hyder, Z, J.J. Butler, Jr., C.D. McElwee and W. Liu, 1994. Slug tests in partially penetrating wells, *Water Resources Research*, vol. 30, no. 11, pp. 2945-2957.

Tutorial

Perform the tutorial for the Hyder et al. (1994) solution for a slug test in an unconfined aquifer (see "Tutorial" on page 111) to learn how to use this solution.

Please visit <http://www.aqtesolv.com/examples/> for additional tutorials and sample data sets.

Butler (1998) Solution for a Slug Test in a High-K Confined Aquifer

Butler (1998) proposed a model for a slug test in a confined aquifer that includes inertial effects based on the models of McElwee et al. (1992) and Zlotnik and McGuire (1998). The solution accounts for the oscillatory water-level response sometimes observed in aquifers of high hydraulic conductivity:

$$w_D(t_D) = \begin{cases} e^{-C_D t_D} \left(\cos(\omega_D t_D) + \frac{C_D}{\omega_D} \sin(\omega_D t_D) \right), & C_D < 1 \\ e^{-t_D} (1 + t_D), & C_D = 1 \\ - \left(\frac{1}{\omega_D^+ - \omega_D^-} \right) \left(\omega_D^- e^{\omega_D^+ t_D} - \omega_D^+ e^{\omega_D^- t_D} \right), & C_D > 1 \end{cases}$$

$$w_D = s / H_0$$

$$t_D = t \sqrt{g / L_e}$$

$$C_D = \sqrt{g / L_e} \frac{r_c^2 \log(1 / (2\psi) + (1 + (1/\psi))^2)^{1/2}}{4K_r L}$$

$$\omega_D = \sqrt{1 - C_D^2}$$

$$\omega_D^\pm = -C_D \pm \omega_D$$

$$\psi = \frac{\sqrt{K_z / K_r}}{L / r_w}$$

Note from the definition of the dimensionless damping factor, $C_D C(D)$, that the solution adopts the Hvorslev (1951) model of flow in a confined aquifer (see "Hvorslev (1951) Solution for a Slug Test in a Confined Aquifer" on page 79). The

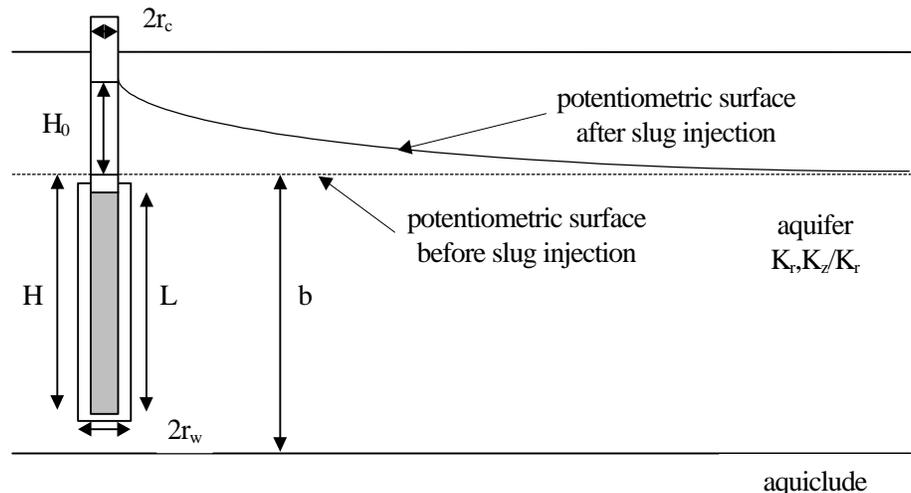
Butler slug test solution is said to be critically damped when the dimensionless damping factor is equal to 1, underdamped when this parameter is less than 1, and overdamped when it is greater than 1. Note that Butler (1998) defines a dimensionless damping factor having a critically damped value equal to 2 (see "Plots Tab (View>Options)" on page 44 to change the critically damped value). Refer to the "List of Symbols" on page 157 for a description of other parameters and variables contained in the equations for this solution.

Butler (2002) modified the definition of dimensionless damping factor to include frictional well loss:

$$C_D = \sqrt{g/L_e} \left(\frac{r_c^2 \log(1/(2\psi) + (1 + (1/\psi))^2)^{1/2}}{4K_r L} + \frac{4\nu \left(\ell + \frac{r_c^4 L}{r_w^4} \right)}{r_c^2 g} \right)$$

where ℓ is the length of the water column above the top of the well screen [L]. Butler (2002) showed that frictional well loss is important in small-diameter wells.

By matching a family of dimensionless damping factor (C_D) type curves for the Butler slug test solution to a plot of data on linear axes, it is possible to determine value of K_r in a confined aquifer.



Note that the well radius (r_w) may be less than, greater than or equal to the casing radius (r_c).

Assumptions

- aquifer has infinite areal extent
- aquifer is homogeneous and of uniform thickness
- aquifer potentiometric surface is initially horizontal
- a volume of water, V , is injected into or discharged from the well instantaneously
- test well is fully or partially penetrating

- flow to test well is horizontal
- aquifer is confined
- flow is steady

Data Requirements

- test well measurements (time and displacement)
- static water column height in well
- initial displacement
- casing radius and effective well radius for test well
- saturated thickness of aquifer
- screen length
- total depth of well penetration below upper confining unit
- porosity of gravel pack (optional)
- hydraulic conductivity anisotropy ratio (optional)

Visual Curve Matching Tips

- Choose **Visual** from the **Match** menu to perform visual curve matching using the procedure described in "Visual Matching With Oscillatory (Damped Sinusoidal) Solutions" on page 166.
- Use the **Active Type Curves** option for more effective visual matching (see "Active Type Curves" on page 167).
- Select values of C(D) from the **Family** and **Curve** lists on the toolbar.
- Use **Parameter Tweaking** to perform visual curve matching and sensitivity analysis (see "Tweak Tab (Match>Toolbox)" on page 169).
- See "Plots Tab (View>Options)" on page 44 to change the critical damping factor assumed for values of C(D).

References

- Butler, J.J., Jr., 1998. The Design, Performance, and Analysis of Slug Tests, Lewis Publishers, Boca Raton, 252p.
- Butler, J.J., Jr., 2002. A simple correction for slug tests in small-diameter wells, *Ground Water*, vol. 40, no. 3, pp. 303-307.
- McElwee, C.D., Butler, J.J., Jr. and G.C. Bohling, 1992. Nonlinear analysis of slug tests in highly permeable aquifers using a Hvorslev-type approach, Kansas Geol. Survey Open-File Report 92-39.
- Zlotnik, V.A. and V.L. McGuire, 1998. Multi-level slug tests in highly permeable formations: 1. Modifications of the Springer-Gelhar (SG) model, *Jour. of Hydrol.*, no. 204, pp. 271-282.

Tutorial

Performing curve matching with the Butler solution is essentially identical to the Springer-Gelhar method (see "Tutorial" on page 116 for the Springer-Gelhar solution).

Unconfined Aquifer Solutions

Choose **Solution...** from the **Match** menu to choose a solution for analyzing a pumping test or slug test in an unconfined aquifer.

Solutions for Pumping Tests in Unconfined Aquifers

1. Theis (1935) type curve solution
2. Cooper-Jacob (1946) straight line solution
3. Neuman (1974) type curve solution
4. Quick Neuman type curve solution
5. Streltsova (1974) type curve solution for piezometers
6. Moench (1997) type solution for a large-diameter pumping well

Solutions for Slug Tests in Unconfined Aquifers

1. Bouwer-Rice (1976) straight-line solution
2. Hvorslev (1951) straight-line solution
3. Hyder et al. (1994) type curve solution (KGS Model)
4. Springer-Gelhar (1991) type curve solution

Theis (1935) Solution for a Pumping Test in an Unconfined Aquifer

The Theis (1935) solution (see “Theis (1935) Solution” on page 54) is applicable to unconfined aquifers through the correction of drawdown data as follows:

$$s' = s - (s^2 / 2b)$$

where s' is corrected displacement, s is observed displacement and b is saturated thickness of the aquifer. This correction only applies to pumping tests in which water is withdrawn from an unconfined aquifer; it is not appropriate for injection tests.

The corrected displacement (s') predicted by this equation reaches a maximum of one-half the aquifer saturated thickness ($0.5b$) when the observed displacement is equal to the aquifer saturated thickness ($s = b$). Of course, complete dewatering of the aquifer ($s = b$) is not a realistic condition; however, in some cases, the displacement predicted with this correction equation along a type curve may exceed the saturated thickness of the aquifer.

Assumptions

- aquifer has infinite areal extent
- aquifer is homogeneous, isotropic and of uniform thickness
- pumping well is fully penetrating
- flow to pumping well is horizontal
- aquifer is unconfined

- flow is unsteady
- water is released instantaneously from storage with decline of hydraulic head
- diameter of pumping well is very small so that storage in the well can be neglected
- no delayed gravity response in aquifer
- flow velocity is proportional to tangent of the hydraulic gradient instead of the sine (which is actually the case)
- flow is horizontal and uniform in a vertical section through the axis of the well
- displacement is small relative to saturated thickness of aquifer

Data Requirements

- pumping and observation well locations
- pumping rate(s)
- observation well measurements (time and displacement)
- aquifer saturated thickness

Solution Options

- variable pumping rates
- multiple pumping wells
- multiple observation wells

Visual Curve Matching Tips

- Choose **Visual** from the **Match** menu to perform visual curve matching using the procedure described in "Visual Matching With Type Curve Solutions" on page 165.
- Use **Active Type Curves** for more effective visual matching with variable-rate pumping tests (see "Active Type Curves" on page 167).
- Select values of Kz/Kr from the **Family** and **Curve** lists on the toolbar (only affects partially penetrating wells).
- Use **Parameter Tweaking** to perform visual curve matching and sensitivity analysis (see "Tweak Tab (Match>Toolbox)" on page 169).

References

- Theis, C.V., 1935. The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage, *Am. Geophys. Union Trans.*, vol. 16, pp. 519-524.
- Kruseman, G.P. and N.A. DeRidder, 1990. Analysis and Evaluation of Pumping Test Data (2nd ed.), Publication 47, Intern. Inst. for Land Reclamation and Improvement, Wageningen, The Netherlands, 370p.

Tutorial

Perform one of the following tutorials to learn how to use the Theis solution:

1. Guided Tour (see "Analyzing a Pumping Test" on page 7)
2. Theis (1935) solution for a pumping test in a confined aquifer (see "Tutorial" on page 56)

Please visit <http://www.aqtesolv.com/examples/> for additional tutorials and sample data sets.

Cooper-Jacob (1946) Solution for a Pumping Test in an Unconfined Aquifer

The Cooper-Jacob (1946) solution (see "Cooper-Jacob (1946) Solution" on page 59) is applicable to unconfined aquifers through the correction of drawdown data as follows:

$$s' = s - (s^2 / 2b)$$

where s' is corrected displacement, s is observed displacement and b is saturated thickness of the aquifer. This correction only applies to pumping tests in which water is withdrawn from an unconfined aquifer; it is not appropriate for injection tests.

The corrected displacement (s') predicted by this equation reaches a maximum of one-half the aquifer saturated thickness ($0.5b$) when the observed displacement is equal to the aquifer saturated thickness ($s = b$). Of course, complete dewatering of the aquifer ($s = b$) is not a realistic condition; however, in some cases, the displacement predicted with this correction equation along a type curve may exceed the saturated thickness of the aquifer.

Assumptions

- aquifer has infinite areal extent
- aquifer is homogeneous, isotropic and of uniform thickness
- pumping well is fully penetrating
- flow to pumping well is horizontal
- aquifer is unconfined
- flow is unsteady
- water is released instantaneously from storage with decline of hydraulic head
- diameter of pumping well is very small so that storage in the well can be neglected
- values of u are small (i.e., r is small and t is large)
- no delayed gravity response in aquifer
- flow velocity is proportional to tangent of the hydraulic gradient instead of the sine (which is actually the case)
- flow is horizontal and uniform in a vertical section through the axis of the well

- displacement is small relative to saturated thickness of aquifer

Data Requirements

- pumping and observation well locations
- pumping rate(s)
- observation well measurements (time and displacement)
- aquifer saturated thickness

Solution Options

- variable pumping rates
- multiple observation wells

Visual Curve Matching Tips

- Choose **Visual** from the **Match** menu to perform visual curve matching using the procedure described in "Visual Matching With Straight-Line Solutions" on page 165.
- Display the **Valid Time** when the critical value of u criterion is satisfied (see "Plots Tab (View>Options)" on page 44).
- Use **Parameter Tweaking** to perform visual curve matching and sensitivity analysis (see "Tweak Tab (Match>Toolbox)" on page 169).

References

Cooper, H.H. and C.E. Jacob, 1946. A generalized graphical method for evaluating formation constants and summarizing well field history, Am. Geophys. Union Trans., vol. 27, pp. 526-534.

Kruseman, G.P. and N.A. DeRidder, 1990. Analysis and Evaluation of Pumping Test Data (2nd ed.), Publication 47, Intern. Inst. for Land Reclamation and Improvement, Wageningen, The Netherlands, 370p.

Tutorial

Perform the tutorial for the Cooper-Jacob (1946) solution for a pumping test in a confined aquifer (see "Tutorial" on page 61) to learn how to use this solution.

Please visit <http://www.aqtesolv.com/examples/> for additional tutorials and sample data sets.

Neuman (1974) Solution for a Pumping Test in an Unconfined Aquifer

Neuman (1974) derived an analytical solution for unsteady flow to a partially penetrating well in an unconfined aquifer with delayed gravity response:

$$s = \frac{Q}{4\pi T} \int_0^{\infty} 4y J_0(y\sqrt{\beta}) \left[u_0(y) + \sum_{n=1}^{\infty} u_n(y) \right] dy$$

$$\beta = \frac{r^2 K_z}{b^2 K_r}$$

$$\sigma = \frac{S}{S_y}$$

For a partially penetrating pumping well, the drawdown in a piezometer is found using the following equations:

$$u_o(y) = \frac{\{1 - \exp[-t_s \beta (y^2 - \gamma_0^2)]\} \cosh(\gamma_0 z_D)}{\{y^2 + (1 + \sigma) \gamma_0^2 - (y^2 - \gamma_0^2)^2 / \sigma\} \cosh(\gamma_0)} \cdot \frac{\sinh[\gamma_0(1 - d_D)] - \sinh[\gamma_0(1 - l_D)]}{(1_D - d_D) \sin(\gamma_0)}$$

$$u_n(y) = \frac{\{1 - \exp[-t_s \beta (y^2 + \gamma_n^2)]\} \cos(\gamma_n z_D)}{\{y^2 - (1 + \sigma) \gamma_n^2 - (y^2 + \gamma_n^2)^2 / \sigma\} \cos(\gamma_n)} \cdot \frac{\sin[\gamma_n(1 - d_D)] - \sin[\gamma_n(1 - l_D)]}{(1_D - d_D) \sin(\gamma_n)}$$

For a partially penetrating pumping well, the drawdown in a partially penetrating observation well is found using the following equations:

$$u_o(y) = \frac{\{1 - \exp[-t_s \beta (y^2 - \gamma_0^2)]\} \{ \sinh(\gamma_0 z_{2D}) - \sinh(\gamma_0 z_{1D}) \}}{\{y^2 + (1 + \sigma) \gamma_0^2 - (y^2 - \gamma_0^2)^2 / \sigma\} \cosh(\gamma_0)} \cdot \frac{\sinh[\gamma_0(1 - d_D)] - \sinh[\gamma_0(1 - l_D)]}{(z_{2D} - z_{1D}) \gamma_0 (1_D - d_D) \sin(\gamma_0)}$$

$$u_n(y) = \frac{\{1 - \exp[-t_s \beta (y^2 + \gamma_n^2)]\} \{ \sin(\gamma_n z_{2D}) - \sin(\gamma_n z_{1D}) \}}{\{y^2 - (1 + \sigma) \gamma_n^2 - (y^2 + \gamma_n^2)^2 / \sigma\} \cos(\gamma_n)} \cdot \frac{\sin[\gamma_n(1 - d_D)] - \sin[\gamma_n(1 - l_D)]}{(z_{2D} - z_{1D}) \gamma_n (1_D - d_D) \sin(\gamma_n)}$$

The gamma terms are the roots of the following equations:

$$\sigma \gamma_0 \sinh(\gamma_0) - (y^2 - \gamma_0^2) \cosh(\gamma_0) = 0, \gamma_0^2 < y^2$$

and

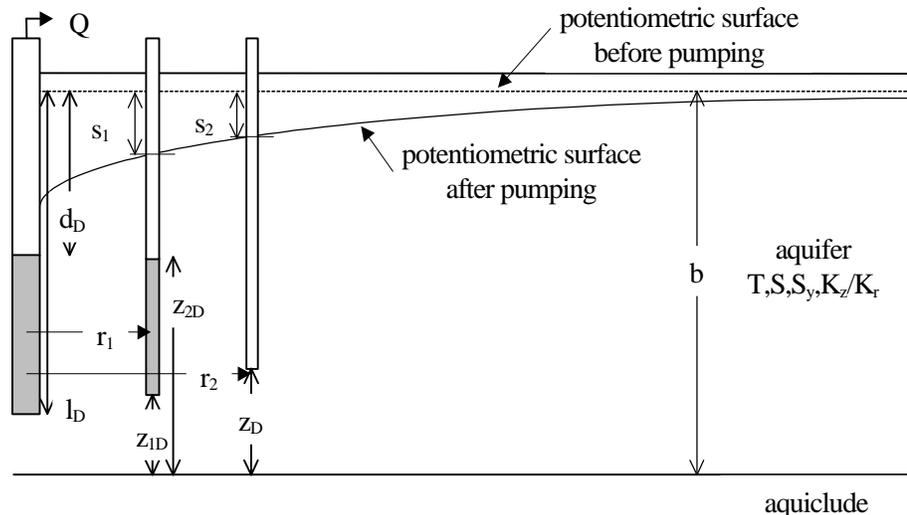
$$\sigma \gamma_n \sin(\gamma_n) + (y^2 + \gamma_n^2) \cos(\gamma_n) = 0, (2n - 1) / (\pi / 2) < \gamma_n < n\pi, n \geq 1$$

Refer to the "List of Symbols" on page 157 for a description of the parameters and variables contained in the equations.

AQTESOLV for Windows allows you to analyze both constant- and variable-rate pumping tests using the Neuman solution. For tests with a variable discharge rate, the program uses the principle of superposition to compute drawdown in the aquifer. For more information concerning the application of the principle of superposition in variable-rate pumping tests, refer to the "Theis (1935) Solution for a Pumping Test in a Confined Aquifer" on page 54.

The Neuman solution supports observation wells and piezometers. Use this solution to estimate values of transmissivity, elastic storage coefficient, specific yield and

β beta (or $K_z/K_r K_z/K_r$ for a data set containing more than one pair of pumping and observation wells) in an unconfined aquifer.



Entering partial penetration data for observation wells or piezometers

The equations of Neuman (1974) for a partially penetrating observation well or a piezometer use elevations measured from the base of the unconfined aquifer (z_{1D} , z_{2D} , z_D); however, when entering partial penetration data for observation wells and piezometers into AQTESOLV for Windows, input depths measured from the potentiometric surface before pumping (static water table).

Assumptions

- aquifer has infinite areal extent
- aquifer is homogeneous and has uniform thickness
- aquifer potentiometric surface is initially horizontal
- aquifer is unconfined
- flow is unsteady
- diameter of pumping well is very small so that storage in the well can be neglected

Data Requirements

- pumping and observation well locations
- pumping rate(s)
- observation well measurements (time and displacement)
- aquifer saturated thickness
- partial penetration depths (optional)

Solution Options

- variable pumping rates
- multiple pumping wells

- multiple observation wells
- partially penetrating wells

Visual Curve Matching Tips

In practice, one uses two sets of type curves to analyze a pumping test in an unconfined aquifer with the Neuman solution. Type A curves match early time data and Type B curves match late time data:

$$s_A = \frac{Q}{4\pi T} w(u_A, \beta)$$

$$s_B = \frac{Q}{4\pi T} w(u_B, \beta)$$

To analyze a pumping test using the Neuman type curve method, one plots drawdown as a function of time on double logarithmic axes. By matching two families of type curves drawn by plotting $w(u_A, \beta)$ as a function of $1/u_A$ and $w(u_B, \beta)$ as a function of $1/u_B$, one can estimate the values of transmissivity, storage coefficient, specific yield and β by visual analysis.

Procedure for Visual Curve Matching

1. Match **Type A** curves to early drawdown data to estimate T, S and β .
2. Match **Type B** curves to late drawdown data to estimate T, S_Y and β .
3. Choose **Toolbox...** from the **Match** menu and click the **Options** tab. Select the **Match early data (Type A)** or **Match late data (Type B)** option. Click **OK**.
4. Choose **Visual** from the **Match** menu to invoke visual curve matching.
5. Select values of the β parameter from **Curve** list on the toolbar.
6. Click and hold the left mouse button down to drag the Neuman type curves to a new position on the screen. Release the left mouse button when you have finished moving the curves.

Partial Penetration Type Curves

AQTESOLV for Windows stores Type A and Type B curves for fully penetrating wells. If your data set contains partially penetrating wells, however, you must compute new Type A and Type B curves for the partial penetration depths of the pumping and observation wells. AQTESOLV for Windows automatically prompts you when new partial penetration type curves are required for your data set.

Computing Curves

Choose **Calculate** in the **Partial Penetration Curves** dialog box to compute partial penetration curves using partial penetration data for the pumping and observation wells. AQTESOLV for Windows will save the partial penetration curves with the data set.

Retrieving Curves From Disk

Choose **Retrieve from disk** from the **Partial Penetration Curves** dialog box to open a disk file containing partial penetration type curves. The format of the file is compatible with DOS versions of AQTESOLV.

Saving Curves on Disk

After computing partial penetration type curves, AQTESOLV for Windows prompts you to save the type curve data on disk. The format of the file created by AQTESOLV for Windows is compatible with DOS versions of AQTESOLV.

References

Neuman, S.P., 1974. Effect of partial penetration on flow in unconfined aquifers considering delayed gravity response, *Water Resources Research*, vol. 10, no. 2, pp. 303-312.

Moench, A.F., 1993. Computation of type curves for flow to partially penetrating wells in water-table aquifers, *Ground Water*, vol. 31, no. 6, pp. 966-971.

Moench, A.F., 1996. Flow to a well in a water-table aquifer: an improved Laplace transform solution, *Ground Water*, vol. 34, no. 4, pp. 593-596.

Tutorial

In this tutorial, you will use the Neuman and Quick Neuman type curve solutions to analyze a constant rate pumping test in an unconfined aquifer. This tutorial shows you how to use visual and automatic curve matching to match Neuman type curves to drawdown data measured during the test.

Please visit <http://www.aqtesolv.com/examples/> for additional tutorials and sample data sets.

Open a New Data Set

Open a new data set by choosing **New** from the **File** menu. In the **New Data Set** dialog box, choose **Tutorial** in the list box and click **OK** to initialize the new data set with default values. AQTESOLV for Windows opens a new window with an Error Log view that reports any errors identified in the data set.

Enter Data for Pumping Test

Choose **Units...** from the **Edit** menu to select units of measurement for the data set.

1. Select **ft** (feet) for **Length**, **min** (minutes) for **Time**, **gal/min** (gallons-per-minute) for **Pumping Rate** and **ft/min** (feet/minute) for **Hyd. Conductivity**.
2. Click **OK**.

Choose **Annotations...** from the **Edit** menu to edit the data set title.

1. In the **Title** tab, enter **Fairborn, Ohio** for the **Title**.
2. Click **OK**.

Choose **Aquifer Data...** from the **Edit** menu to edit aquifer data.

1. In the **General** tab, enter **78.0** for the value of **Saturated Thickness**.

2. Click **OK**.

Choose **Pumping Well>Edit...** from the **Edit** menu to edit pumping well data.

1. In the **Rate** tab, enter values of **0.0** and **1080.0** for time and rate, respectively, where time is in minutes and rate is in gallons-per-minute.
2. Click **OK**.

Choose **Obs. Well>Edit...** from the **Edit** menu to edit data for the observation well.

1. In the **General** tab, enter a value of **73.0** for the **X-Coordinate** location of the well.
2. In the **Observations** tab, click the **Import** button to import observation well measurements from a delimited text file using the **Observation Data Import Wizard**. In Step 1 of the **Import Wizard**, enter **FAIRBORN.DAT** for the name of the import file. The file **FAIRBORN.DAT** contains time and displacement data arranged in two columns separated by a tab delimiter. Click **Next**.
3. In Step 2 of the **Import Wizard**, enter data describing the structure of the import file. The **Import Wizard** automatically determines that the import file contains 2 columns of data. Enter **1** for the **Elapsed Time** column and **2** for the **Displacement** column. Click **Next**.
4. In Step 3 of the **Import Wizard**, choose transformation and filter options for the data contained in the import file. Retain the default settings, and click **Finish**.
5. After **AQTESOLV** for Windows has finished importing the data, a message box displays the number of observations imported from the file. Click **OK**.
6. Click **OK**.

After you have completed the previous data entry steps, the **Error Log** displayed in the active window should show that the data set contains no errors. Now you are ready to display the data, choose a solution and estimate aquifer properties.

Save Data Set

Choose **Save As...** from the **File** menu to save the data you have entered into the current data set.

1. Enter **NEUMAN1.AQT** for the file name.
2. Click **OK** to save the data set.

Change View in Window

Choose **Displacement-Time** from the **View** menu to display a plot of displacement vs. time in the active window. The window displays a plot of the observation well data on semi-log axes.

Choose Quick Neuman Solution

Change the aquifer model and solution by choosing **Solution...** from the **Match** menu to choose a solution for analyzing a pumping test in an unconfined aquifer.

1. Choose the **Unconfined Quick Neuman** solution.
2. Click **OK**.

After you have selected the Quick Neuman solution for a pumping test in an unconfined aquifer, AQTESOLV for Windows updates the window by plotting the data on double logarithmic axes, superimposing a Neuman type curve on the plot, and displaying values of transmissivity (T), storage coefficient (S), specific yield (Sy) and beta in the legend.

The Quick Neuman implementation of the Neuman solution, rather than the full Neuman solution, is ideal for most situations. Computations with Quick Neuman are much faster than Neuman with virtually no loss in accuracy. Therefore, you should use Quick Neuman for initial estimation followed by Neuman to refine the estimates obtained with Quick Neuman.

Perform Visual Matching with Quick Neuman

Visually match the Quick Neuman solution to the data as follows:

1. Click **Match Early Data** on the toolbar to toggle the match early data (Type A) option and simultaneously invoke visual curve matching.
2. Select the value of the β beta parameter from **Curve** list on the toolbar. Choose a curve with a shape that matches the early data.
3. To begin interactively moving the Type A curve, move the mouse cursor over the plot, click the left mouse button and hold it down.
4. As you move the mouse, the type curve also moves. AQTESOLV for Windows updates the values of T and S in the legend as you move the Type A curve.
5. When you have finished matching the Type A curve to the early data, release the left mouse button to end visual curve matching and redraw the complete type curve.
6. Click **Match Late Data** on the toolbar to toggle the match late data (Type B) option and simultaneously invoke visual curve matching.
7. Follow the procedure for Type A curve matching to fit a Type B curve to the late data. As you move the Type B curve, AQTESOLV for Windows updates the values of T and Sy in the legend.

You should obtain a match using a value of 0.06 for beta. If necessary, repeat the preceding steps to finish matching the Type A and B curves.

Perform Automatic Matching with Quick Neuman

Choose **Automatic...** from the **Match** menu to perform automatic matching using the Neuman type curve solution.

1. Click **Estimate** to begin automatic estimation.
2. As the automatic estimation procedure completes iterations, a progress window displays the changes in the residual sum of squares (RSS) criterion and the values of the aquifer properties. After the automatic estimation procedure finishes, AQTESOLV for Windows displays a message box containing residual summary statistics. Click **OK** to close the message box.
3. Click the **Close** button to close the progress window and click **OK** to finish.

The plot shown in the active window displays the values of transmissivity (T=24.04), storage coefficient (S=0.0.002111), specific yield (Sy=0.1061) and beta (=0.04458) determined by automatic estimation.

Choose Neuman Solution

Change the aquifer model and solution by choosing **Solution...** from the **Match** menu to choose a solution for analyzing a pumping test in an unconfined aquifer.

1. Choose the **Unconfined Neuman (1974)** solution.
2. Click **OK**.

Compared to the Quick Neuman implementation of the Neuman solution, the full Neuman implementation is computationally more intensive and therefore requires greater time to plot the type curve. In all other respects, working with the Neuman solution for visual and automatic curve matching is identical to Quick Neuman.

Save Data Set

Choose **Save** from the **File** menu to save your work in the **NEUMAN1.AQT** data set.

Quick Neuman Solution for a Pumping Test in an Unconfined Aquifer

The Quick Neuman solution option provided by AQTESOLV for Windows computes Neuman type curves using a two-stage interpolation technique. QuickNeuman yields essentially the same results as the Neuman solution option, only much more quickly. Therefore, Quick Neuman is a viable alternative for performing automatic curve matching prior to using Neuman (see "Neuman (1974) Solution for a Pumping Test in an Unconfined Aquifer" on page 90).

Assumptions

- aquifer has infinite areal extent
- aquifer is homogeneous and has uniform thickness
- aquifer potentiometric surface is initially horizontal
- aquifer is unconfined
- flow is unsteady
- diameter of pumping well is very small so that storage in the well can be neglected

Data Requirements

- pumping and observation well locations
- pumping rate(s)
- observation well measurements (time and displacement)
- aquifer saturated thickness
- partial penetration depths (optional)

Solution Options

- variable pumping rates
- multiple pumping wells
- multiple observation wells

- partially penetrating wells

Visual Curve Matching Tips

Refer to the "Visual Curve Matching Tips" on page 93 for the Neuman (1974) solution.

Reference

Neuman, S.P., 1974. Effect of partial penetration on flow in unconfined aquifers considering delayed gravity response, *Water Resources Research*, vol. 10, no. 2, pp. 303-312.

Tutorial

To learn how to use the Quick Neuman solution, perform the tutorial for the Neuman (1974) Solution for a Pumping Test in an Unconfined Aquifer.

Please visit <http://www.aqtesolv.com/examples/> for additional tutorials and sample data sets.

Streltsova (1974) Solution for a Pumping Test in an Unconfined Aquifer

Streltsova (1974) derived an analytical solution for the water-level response in a piezometer due to unsteady flow to a pumping well in an unconfined aquifer with delayed gravity response:

$$s = \frac{Q}{4\pi T(l_D - d_D)} \sum_{n=-\infty}^{\infty} (-1)^n \int_{d_D}^{l_D} \left(\frac{1}{R_1(n)} \operatorname{erfc} \frac{R_1(n)}{2\sqrt{\tau}} - \frac{1}{R_2(n)} \operatorname{erfc} \frac{R_2(n)}{2\sqrt{\tau}} \right) dy$$

$$R_1(n) = \sqrt{\beta + \left(1 - z_D - \frac{2n}{(l_D - d_D)} - y \right)^2}$$

$$R_2(n) = \sqrt{\beta + \left(1 - z_D - \frac{2n}{(l_D - d_D)} + y \right)^2}$$

$$\beta = \frac{r^2 K_z}{b^2 K_r}$$

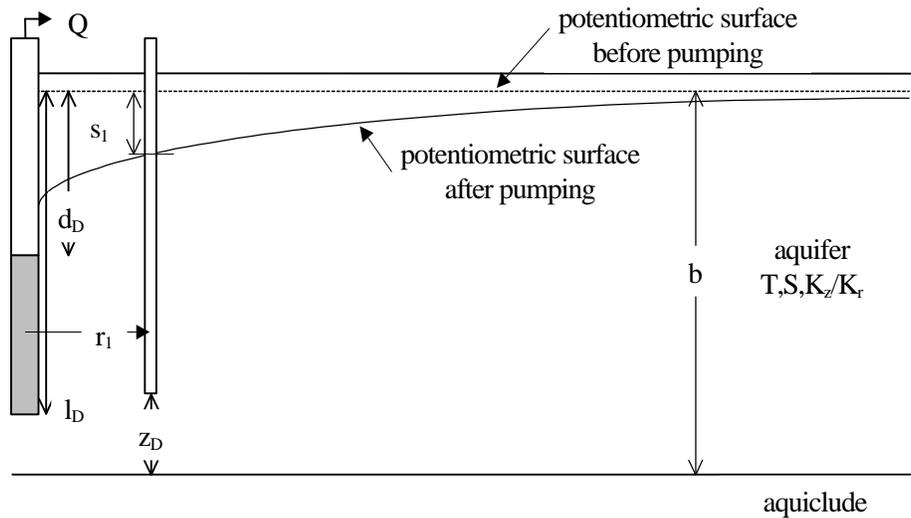
$$\tau = \frac{tK_z}{Sb}$$

Refer to the "List of Symbols" on page 157 for a description of the parameters and variables contained in the equations.

AQTESOLV for Windows allows you to analyze both constant- and variable-rate pumping tests using the Streltsova solution. For tests with a variable discharge rate, the program uses the principle of superposition to compute drawdown in the aquifer. For more information concerning the application of the principle of superposition in variable-rate pumping tests, refer to the "Theis (1935) Solution for a Pumping Test in a Confined Aquifer" on page 54.

The Streltsova solution only supports piezometers, not observation wells. Use this solution to estimate values of transmissivity, elastic storage coefficient and β (or

K_z/K_r for a data set containing more than one pumping well/piezometer pair) in an unconfined aquifer.



Entering piezometer data

The equations of Streltsova (1974) for a piezometer use elevations measured from the base of the unconfined aquifer (z_D); however, when entering partial penetration data for into AQTESOLV for Windows, input depth measured from the potentiometric surface before pumping (static water table).

Assumptions

- aquifer has infinite areal extent
- aquifer is homogeneous and has uniform thickness
- aquifer potentiometric surface is initially horizontal
- aquifer is unconfined
- flow is unsteady
- diameter of pumping well is very small so that storage in the well can be neglected

Data Requirements

- pumping and observation well locations
- pumping rate(s)
- piezometer measurements (time and displacement)
- aquifer saturated thickness
- piezometer depth (solution only supports piezometers)

Solution Options

- variable pumping rates
- multiple pumping wells
- multiple piezometers
- partial penetration (in a piezometer only)

Visual Curve Matching Tips

- Choose **Visual** from the **Match** menu to perform visual curve matching using the procedure described in "Visual Matching With Type Curve Solutions" on page 165.
- Use **Active Type Curves** for more effective visual matching with variable-rate pumping tests (see "Active Type Curves" on page 167).
- Select values of β from the **Family** and **Curve** lists on the toolbar.
- Use **Parameter Tweaking** to perform visual curve matching and sensitivity analysis (see "Tweak Tab (Match>Toolbox)" on page 169).

Reference

Streltsova, T.D., 1974. Drawdown in compressible unconfined aquifer, Jour. of the Hyd. Div., Proc. of the Am. Soc. of Civil Eng., vol. 100, no. HY11, pp. 1601-1616.

Tutorial

In this tutorial, you will use the Streltsova solution to analyze the constant rate pumping test data set created and saved in the tutorial for the Neuman unconfined aquifer solution. You will change the observation well to a piezometer and use visual curve matching to match a Streltsova type curve to the drawdown data.

Please visit <http://www.aqtesolv.com/examples/> for additional tutorials and sample data sets.

Open Data Set

Choose **Open...** from the **File** menu to open a dialog box for opening a data set stored on disk. You will open the data set created and saved in the tutorial for the Neuman (1974) solution.

1. Enter **NEUMAN1.AQT** for the name of the data set.
2. Click **OK** to open the data set.

Change View in Window

If necessary, choose **Error Log** from the **View** menu to display an Error Log report in the active window.

Edit Observation Well Data in Data Set

Choose **Obs. Well>Edit...** from the **Edit** menu to edit data for the observation well.

1. In the **Construction** tab, click **Piezometer** to change the observation well to a piezometer.
2. Enter **39.0** for the **Piezometer Depth**.
3. Click **OK**.

After you have completed the previous data entry steps, the **Error Log** displayed in the active window should show that the data set contains no errors. Now you are ready to display the data, choose a solution and estimate aquifer properties.

Save Data Set

Choose **Save As...** from the **File** menu to save the modified data you have entered into the data set.

1. Enter **STRELT1.AQT** for the name of the file.
2. Click **OK** to save the data set.

Change View in Window

Choose **Displacement-Time** from the **View** menu to display a plot of displacement vs. time in the active window.

Choose Streltsova Solution

Change the aquifer model and solution by choosing **Solution...** from the **Match** menu to choose a solution for analyzing a pumping test in an unconfined aquifer.

1. Choose the **Unconfined Streltsova (1974)** solution.
2. Click **OK**.

After you have selected the Streltsova solution for a pumping test in an unconfined aquifer, AQTESOLV for Windows updates the window by plotting the data on double logarithmic axes, superimposing a Streltsova type curve on the plot, and displaying values of transmissivity (T), storage coefficient (S) and beta in the legend.

Display Type Curve Family

Choose **Options...** from the **View** menu and click the **Plots** tab. Check the **Curve Family** option to superimpose a family of type curves for the Streltsova solution on the plot. The legend shows the values of the beta parameter for the two additional curves displayed with this option.

Click the **Family** tab to customize the curve family.

Perform Visual Matching with Streltsova

Choose **Visual** from the **Match** menu to perform visual curve matching with the Streltsova type curve solution.

1. To begin interactively moving the type curve, move the mouse cursor over the plot, click the left mouse button, and hold it down.
2. As you move the mouse, the type curve also moves. AQTESOLV for Windows updates the values of the aquifer properties, T and S, in the legend as you move the type curve.
3. When you have finished matching the type curve to the piezometer data, release the left mouse button to end visual curve matching.

Choose **Toolbox...** from the **Match** menu and click the **Parameters** tab to change the value of beta used to compute the Streltsova type curve.

1. Enter **0.12** for the value of **beta**.
2. Click **OK**.

Repeat the steps for moving the type curve to match the Streltsova solution to the data.

When you finish matching the type curve, you will discover that the Streltsova solution for a piezometer does not reproduce the results obtained in the tutorial for the Neuman solution for fully penetrating wells.

Save Data Set

Choose **Save** from the **File** menu to save your work in the **STRELT1.AQT** data set.

Moench (1997) Solution for a Pumping Test in an Unconfined Aquifer

Moench (1997) derived an analytical solution for unsteady flow to a partially penetrating large-diameter well in an unconfined aquifer with delayed gravity response. The Laplace transform solution for dimensionless drawdown in the pumped well is as follows:

$$\bar{h}_{wD} = \frac{2(A + S_w)}{p(1_D - d_D)[1 + pW_D(A + S_w)]}$$

The following equations are the Laplace transform solutions for dimensionless drawdown in a piezometer:

$$\bar{h}_D = \frac{2E}{p(1_D - d_D)[1 + pW_D(A + S_w)]}$$

or an observation well:

$$\bar{h}'_D = \frac{2E'}{p(1_D - d_D)[1 + pW_D(A + S_w)]}$$

where

$$A = \frac{2}{(1_D - d_D)} \sum_{n=0}^{\infty} \frac{K_0(q_n)}{\epsilon_n q_n K_1(q_n)} \frac{\{\sin[\epsilon_n(1 - d_D)] - \sin[\epsilon_n(1 - l_D)]\}^2}{[\epsilon_n + 0.5 \sin(2\epsilon_n)]}$$

$$E = 2 \sum_{n=0}^{\infty} \frac{K_0(q_n r_D) \cos(\epsilon_n z_D) \sin[\epsilon_n(1 - d_D)] - \sin[\epsilon_n(1 - l_D)]}{q_n K_1(q_n) [\epsilon_n + 0.5 \sin(2\epsilon_n)]}$$

$$E' = 2 \sum_{n=0}^{\infty} \left\{ \frac{K_0(q_n r_D) [\sin(\epsilon_n z_{2D}) - \sin(\epsilon_n z_{1D})]}{(z_{2D} - z_{1D}) \epsilon_n q_n K_1(q_n) [\epsilon_n + 0.5 \sin(2\epsilon_n)]} \right\}$$

$$\{\sin[\epsilon_n(1 - d_D)] - \sin[\epsilon_n(1 - l_D)]\}$$

$$W_D = \frac{\pi r_c^2}{2\pi r_w^2 S_s (1 - d)}$$

$$\bar{q}_n = \sqrt{(\epsilon_n^2 \beta_w + p)}$$

$$\bar{q}_n r_D = \sqrt{(\epsilon_n^2 \beta + p r_D^2)}$$

$$\beta_w = \frac{r_w^2 K_z}{b^2 K_r}$$

$$\beta = \frac{r^2 K_z}{b^2 K_r}$$

$$r_D = \frac{r}{r_w}$$

$$\sigma = \frac{S}{S_y}$$

$$\gamma = \alpha_1 b S_y / K_z$$

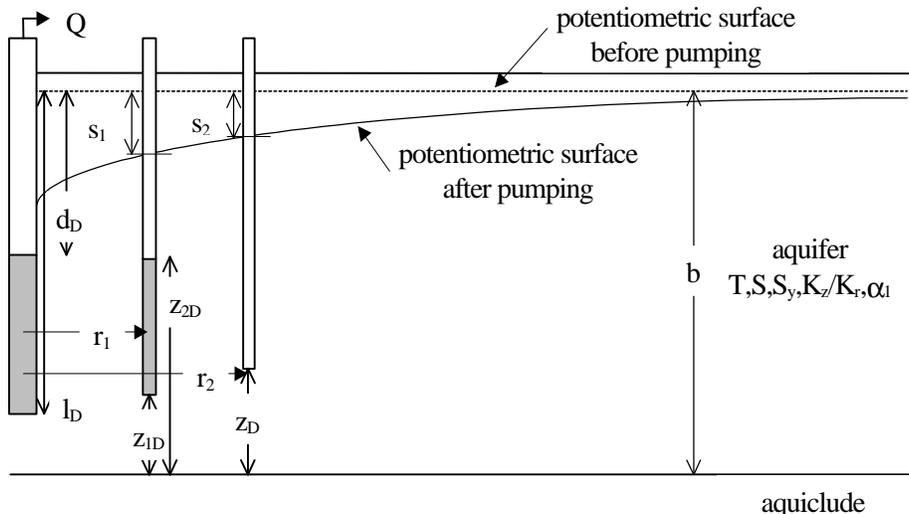
and ϵ_n are the roots of

$$\epsilon_n \tan(\epsilon_n) = \frac{p}{(\sigma \beta_w + p / \gamma)}$$

The parameter α_1 is a fitting parameter for drainage from the unsaturated zone and has units of inverse time (T^{-1}). A large value of α_1 effectively eliminates this parameter from the solution. Refer to the "List of Symbols" on page 157 for a description of the parameters and variables contained in the equations.

AQTESOLV for Windows allows you to analyze both constant- and variable-rate pumping tests using the Moench solution. For tests with a variable discharge rate, the program uses the principle of superposition to compute drawdown in the aquifer. For more information concerning the application of the principle of superposition in variable-rate pumping tests, refer to the "Theis (1935) Solution for a Pumping Test in a Confined Aquifer" on page 54.

The Moench solution supports observation wells and piezometers. Use this solution to estimate values of transmissivity, elastic storage coefficient, specific yield and β (or K_z/K_r for a data set containing more than one pair of pumping and observation wells), well radius, wellbore skin factor, and α_1 in an unconfined aquifer.



Entering partial penetration data for observation wells or piezometers

The equations of Moench (1997) for a partially penetrating observation well or piezometer use elevations measured from the base of the unconfined aquifer (z_{1D} , z_{2D} , z_D); however, when entering partial penetration data for observation wells and piezometers into AQTESOLV for Windows, input depths measured from the potentiometric surface before pumping (static water table).

Assumptions

- aquifer has infinite areal extent

- aquifer is homogeneous and has uniform thickness
- aquifer potentiometric surface is initially horizontal
- aquifer is unconfined
- flow is unsteady

Data Requirements

- pumping and observation well locations
- pumping rate(s)
- observation well measurements (time and displacement)
- aquifer saturated thickness
- partial penetration depths (optional)
- casing radius and wellbore radius for pumping well(s)

Solution Options

- large-diameter pumping wells
- variable pumping rates
- multiple pumping wells
- multiple observation wells
- partially penetrating wells

Visual Curve Matching Tips

- Choose **Visual** from the **Match** menu to perform visual curve matching using the procedure described in "Visual Matching With Type Curve Solutions" on page 165.
- Use **Active Type Curves** for more effective visual matching with variable-rate pumping tests (see "Active Type Curves" on page 167).
- Choose **Radial Flow** from the **View** menu to help identify the presence of wellbore storage (see "Radial Flow Plot" on page 42).
- Select values of β from the **Family** and **Curve** lists on the toolbar.
- Choose **Toolbox...** from the **Match** menu and click the **Options** tab to select visual curve matching options. Use **Match early data (Type A)** to match T and S. **Match late data (Type B)** lets you match T and S_{yy} . Check **Active type curves** to use active instead of static type curves.
- Use **Parameter Tweaking** to perform visual curve matching and sensitivity analysis (see "Tweak Tab (Match>Toolbox)" on page 169).

Reference

Moench, A.F., 1997. Flow to a well of finite diameter in a homogeneous, anisotropic water table aquifer, *Water Resources Research*, vol. 33, no. 6, pp. 1397-1407.

Tutorial

In this tutorial, you will use the Moench solution to analyze the constant rate pumping test data set created and saved in the tutorial for the Neuman unconfined aquifer solution. In this tutorial you will add large-diameter well data and use automatic curve matching to match a Moench type curve to the drawdown data.

Please visit <http://www.aqtesolv.com/examples/> for additional tutorials and sample data sets.

Open Data Set

Choose **Open...** from the **File** menu to open a data set stored on disk. You will open the data set created and saved in the tutorial for the Neuman (1974) solution.

1. Enter **NEUMAN1.AQT** for the name of the data set.
2. Click **OK** to open the data set.

Change View in Window

If necessary, choose **Error Log** from the **View** menu to display an Error Log report in the active window.

Add Large-Diameter Well Data to Data Set

Choose **Pumping Well>Edit...** from the **Edit** menu to edit data for the pumping well.

1. In the **Construction** tab, enter **1.0** for both **Wellbore Radius** and **Casing Radius**.
2. Click **OK**.

To analyze pumping tests using large-diameter well solutions, you must enter values for the wellbore radius and casing radius of the pumping well(s). If the values of either of these two variables is 0.0, AQTESOLV for Windows assumes the pumping well radius is infinitesimal; if you enter 0.0 for either value, AQTESOLV for Windows will not allow you to select any of the large-diameter well solutions contained in the program.

After you have completed the previous data entry steps, the **Error Log** displayed in the active window should show that the data set contains no errors. Now you are ready to display the data, choose a solution and estimate aquifer properties.

Save Data Set

Choose **Save As...** from the **File** menu to save the modified data you have entered into the data set.

1. Enter **MOENCHU1.AQT** for the name of the file.
2. Click **OK**.

Change View in Window

Choose **Displacement-Time** from the **View** menu to display a plot of displacement vs. time in the active window.

Choose Moench Solution

Change the aquifer model and solution by choosing **Solution...** from the **Match** menu to choose a solution for analyzing a pumping test in an unconfined aquifer.

1. Choose the **Unconfined Moench (1997)** solution.

2. Click **OK**.

After you have selected the Moench solution for a pumping test in an unconfined aquifer, AQTESOLV for Windows updates the window by plotting the data on double logarithmic axes, superimposing a Moench type curve on the plot, and displaying values of transmissivity (T), storage coefficient (S), specific yield (Sy), beta, wellbore skin factor (Sw), well radius (Rw) and alpha in the legend.

Due to the large number of parameters in the Moench unconfined aquifer solution, it is not practical to develop type curves for traditional visual analysis. Therefore, AQTESOLV for Windows provides you with the ability to match the Moench solution to your data by manually changing values of the seven parameters in the solution until you achieve a satisfactory match or by using automatic estimation.

Edit Parameters Prior to Estimation

Choose **Automatic...** from the **Match** menu and click the **Parameters** tab to edit parameter values and constraints and to enable/disable estimation of parameters during automatic estimation.

1. Enter a value of **0.0** for **Sw** and set **Estimation** to **Inactive**.
2. Enter a value of **1.0** for **Rw** and set **Estimation** to **Inactive**.
3. Set **Estimation** of **alpha** to **Inactive**. A large value of **alpha** (e.g., 1.0E+30) effectively removes this fitting parameter from the computation of the type curve.
4. Click **OK**.

Perform Automatic Matching with Moench

Choose **Automatic...** from the **Match** menu to open a dialog box for performing automatic matching of the Moench type curve solution to the observation well data.

1. Click **Estimate** to begin automatic estimation.
2. As the automatic estimation procedure completes iterations, a progress window displays the changes in the residual sum of squares (RSS) criterion and the values of the aquifer properties. After the automatic estimation procedure finishes, AQTESOLV for Windows displays a message box containing residual summary statistics. Click **OK** to close the message box.
3. Click the **Close** button to close the progress window and click **OK** to finish.

The plot shown in the active window displays the values of transmissivity (T=24.33), storage coefficient (S=0.001758), specific yield (Sy=0.1019) and beta (=0.04463) determined by automatic estimation. The changes in the parameters from those estimated using the Neuman solution indicate only a small wellbore storage effect in this example. To view the effect of wellbore storage on the type curve, choose **Unconfined...** from the **Solution** menu and select the Neuman (1974) solution.

Save Data Set

Choose **Save** from the **File** menu to save your work in the **MOENCHU1.AQT** data set.

Bouwer-Rice (1976) Solution for a Slug Test in an Unconfined Aquifer

Bouwer and Rice (1976) developed an empirical relationship describing the water-level response in an unconfined aquifer due to the instantaneous injection or withdrawal of water from a well:

$$\ln(s_0) - \ln(s_t) = \frac{2KLt}{r_{ce}^2 \ln(r_e / r_{we})}$$

$$r_{ce} = \sqrt{r_c^2 + n(r_w^2 - r_c^2)}$$

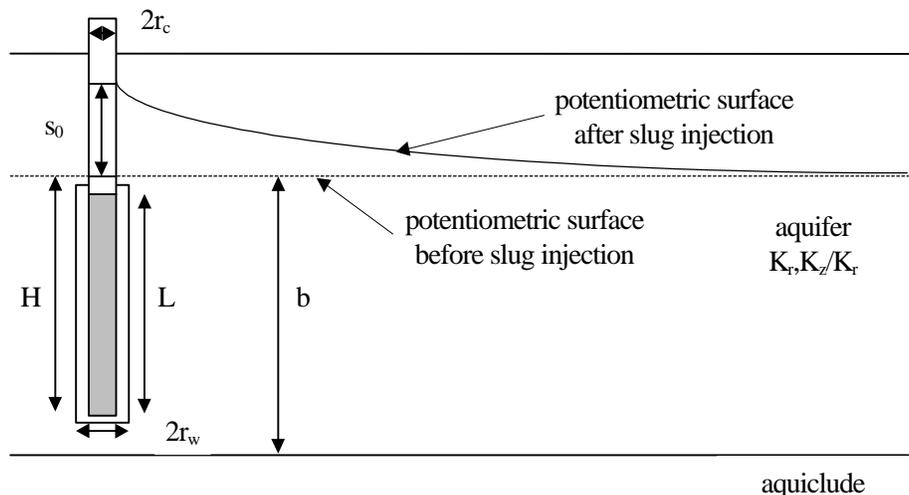
$$r_{we} = r_w \sqrt{\frac{K_z}{K_r}}$$

Bouwer and Rice (1976) recommend computing an equivalent casing radius (r_{ce}) to correct for the porosity of the gravel pack when the height of the static water column in the well is less than the screen length (i.e., the screen is partially submerged). AQTESOLV for Windows computes the equivalent casing radius using the value of porosity (n) specified in the data set; a porosity equal to zero (0.0) results in no correction to the casing radius.

Zlotnik (1994) advises the use of an equivalent wellbore radius (r_{we}) if the aquifer is anisotropic in a vertical plane and the well is partially penetrating. AQTESOLV for Windows automatically computes the equivalent wellbore radius using the value of anisotropy ratio (K_z/K_r) specified in the data set; an anisotropy ratio equal to unity (1.0) results in no correction to the well radius.

Butler (1998) recommends matching the Bouwer-Rice solution to slug test data within a normalized head range (designated as $s/s_0(0)$ or $H/H_0(0)$) of 0.2 to 0.3. To display the recommended head range during visual curve matching, see "Visual Curve Matching Tips" on page 108.

Refer to the "List of Symbols" on page 157 for a description of the parameters and variables contained in the equations.



Assumptions

- aquifer has infinite areal extent
- aquifer is homogeneous and of uniform thickness
- aquifer potentiometric surface is initially horizontal
- a volume of water, V , is injected into or discharged from the well instantaneously
- aquifer is confined or unconfined
- flow is steady

Data Requirements

- test well measurements (time and displacement)
- initial displacement
- casing radius and wellbore radius for test well
- saturated thickness of aquifer
- screen length
- total depth of well penetration below confining unit (confined aquifer) or water table (unconfined aquifer)
- porosity of gravel pack (optional)
- hydraulic conductivity anisotropy ratio (optional)

Visual Curve Matching Tips

- Choose **Visual** from the **Match** menu to perform visual curve matching (see "Visual Matching With Straight-Line Solutions" on page 165).
- For this solution, **visual curve matching** is often more effective than automatic matching because you are interested in matching the straight line to a specific range of data that meet the assumptions of the solution. To achieve the same effect with **automatic curve matching**, it would require the judicious application of weights to ignore observations outside the desired range (see "Observations Tab" on page 36).
- Choose **Options** from the **View** menu and select the **Recommended Head Range** option in the **Plots** tab to superimpose on the plot the head range recommended by Butler (1998) to obtain the most reliable matching results for solutions (assuming a steady-state representation of flow for a slug test).

References

Bouwer, H., 1989. The Bouwer and Rice slug test--an update, *Ground Water*, vol. 27, no. 3, pp. 304-309.

Bouwer, H. and R.C. Rice, 1976. A slug test method for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells, *Water Resources Research*, vol. 12, no. 3, pp. 423-428.

Zlotnik, V., 1994. Interpretation of slug and packer tests in anisotropic aquifers, *Ground Water*, vol. 32, no. 5, pp. 761-766.

Tutorial

The Guided Tour (see "Analyzing a Slug Test" on page 11) contains a tutorial for the Bouwer-Rice slug test solution.

Please visit <http://www.aqtesolv.com/examples/> for additional tutorials and sample data sets.

Hvorslev (1951) Solution for a Slug Test in an Unconfined Aquifer

For information concerning this solution, refer to "Hvorslev (1951) Solution for a Slug Test in a Confined Aquifer" on page 79.

Hyder et al. (1994) Solution for a Slug Test in an Unconfined Aquifer (KGS Model)

Hyder et al. (1994) derived an analytical solution, also known as the KGS Model, describing the water-level response due to the instantaneous injection or withdrawal of water from a partially penetrating well in an unconfined aquifer. The equation for the Laplace transform solution is as follows:

$$\bar{h} = \frac{(\gamma/2)\Omega^*}{[1 + (\gamma/2)p\Omega^*]}$$

$$\alpha = \frac{2r_w^2 S_{s2} L}{r_c^2}$$

$$\gamma = K_{r2} / K_{r1}$$

$$\Omega^* = \int_{\zeta}^{\zeta+1} \{F_s^{-1}[F_s(\omega^*)f_1]\} d\eta$$

$$f_1 = \frac{[\Delta_2 K_0(v_1) - \Delta_1 I_0(v_1)]}{v_1 [\Delta_2 K_1(v_1) + \Delta_1 I_1(v_1)]}$$

$$\eta = z / L$$

$$\zeta = d / L$$

$$v_i = (\psi_i^2 \omega^2 + R_i p)^{1/2}$$

$$\psi_i = (A_i / a^2)^{1/2}$$

$$A_i = K_{zi} / K_{ri}$$

$$a = L / r_w$$

$$R_i = \gamma \alpha / 2\lambda$$

$$R_2 = \alpha/2$$

$$\lambda = S_{s2}/S_{s1}$$

$$\Delta_1 = K_0(v_1\xi_{sk})K_1(v_2\xi_{sk}) - \frac{N}{\gamma} K_0(v_2\xi_{sk})K_1(v_1\xi_{sk})$$

$$\Delta_2 = I_0(v_1\xi_{sk})K_1(v_2\xi_{sk}) + \frac{N}{\gamma} K_0(v_2\xi_{sk})I_1(v_1\xi_{sk})$$

$$N = v_1/v_2$$

$$\xi_{sk} = r_{sk}/r_w$$

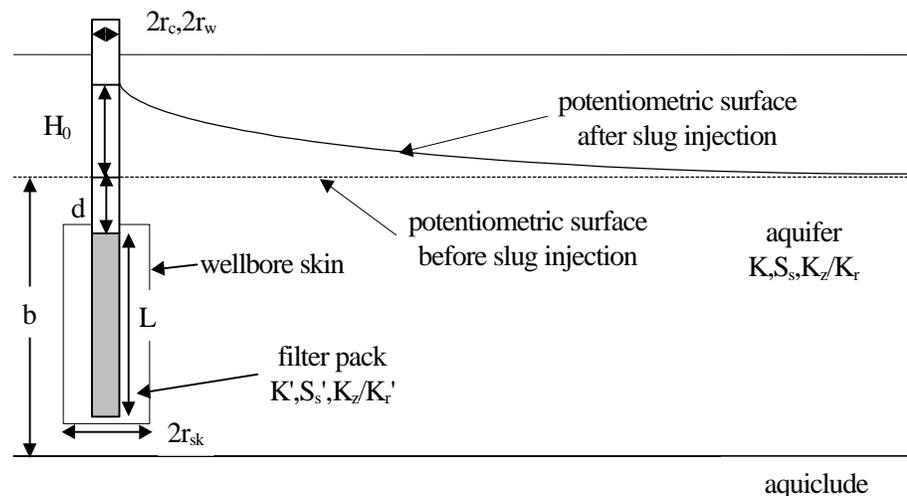
$F_s(\omega^*)$ = modified finite Fourier sine transform of $B(z)$

F_s^{-1} = inverse modified finite Fourier sine transform

$$B(z) = \begin{cases} 0, & z < d, z > L + d \\ 1, & \text{otherwise} \end{cases}$$

Refer to the "List of Symbols" on page 157 for a description of the parameters and variables contained in the equations for this solution.

By matching type curves of the KGS Model slug test solution to data plotted on semi-logarithmic axes, it is possible to determine values of K_r/K_r , S_s/S_s and $K_z/K_z/K_r$ for the unconfined aquifer and K_r'/K_r' , S_s'/S_s' and $K_z'/K_z'/K_r'$ for the filter pack.



Assumptions

- aquifer has infinite areal extent
- aquifer is homogeneous and of uniform thickness
- aquifer potentiometric surface is initially horizontal
- a volume of water, V , is injected into or discharged from the well instantaneously

- aquifer is unconfined
- flow is unsteady
- water is released instantaneously from storage with decline of hydraulic head

Data Requirements

- test well measurements (time and displacement)
- initial displacement
- casing radius, wellbore radius and well skin radius for test well
- saturated thickness of aquifer
- screen length
- total depth of well penetration below water table

Visual Curve Matching Tips

- Choose **Visual** from the **Match** menu to perform visual curve matching using the procedure described in "Visual Matching With Type Curve Solutions" on page 165.
- Select values of S_s , K_z/K_r , S_s' and $K_z/K_r'S_s$, K_z/K_r , S_s' and K_z/K_r' from the **Family** and **Curve** lists on the toolbar.
- Use **Parameter Tweaking** to perform visual curve matching and sensitivity analysis (see "Tweak Tab (Match>Toolbox)" on page 169).

Reference

Hyder, Z, J.J. Butler, Jr., C.D. McElwee and W. Liu, 1994. Slug tests in partially penetrating wells, Water Resources Research, vol. 30, no. 11, pp. 2945-2957.

Tutorial

In this tutorial, you will use the KGS Model to create and analyze a slug test. This tutorial shows you how to use visual and automatic curve matching to match the KGS Model to displacement data measured during the slug test.

Please visit <http://www.aqtesolv.com/examples/> for additional tutorials and sample data sets.

Open a New Data Set

Open a new data set by choosing **New** from the **File** menu. In the **New Data Set** dialog box, choose **Tutorial** in the list box and click **OK** to initialize the new data set with default values. AQTESOLV for Windows opens a new window with an Error Log view that reports any errors identified in the data set.

Enter Data for Slug Test

Choose **Units...** from the **Edit** menu to select units of measurement for the data set.

1. Select **m** (meters) for **Length**, **sec** (seconds) for **Time**, and **m/day** (meters-per-day) for **Hyd. Conductivity**.
2. Click **OK**.

Choose **Annotations...** from the **Edit** menu to edit the data set title.

1. In the **Title** tab, enter **Unconfined Slug Test** for the **Title**.
2. Click **OK**.

Choose **Slug Test Well...** from the **Edit** menu to edit slug test data.

1. In the **General** tab, enter **0.671** for **Initial Displacement**.
2. In the **Aquifer** tab, enter **47.87** for **Saturated Thickness**.
3. In the **Screen** tab, enter **1.52** for **Screen Length** and **18.29** for **Total Depth of Penetration**.
4. In the **Radius** tab, enter **0.064** for **Casing Radius** and **0.125** for **Wellbore Radius** and **Well Skin Radius**.
5. In the **Observations** tab, click the **Import** button to import observation well measurements from a delimited text file using the **Observation Data Import Wizard**. In Step 1 of the **Import Wizard**, enter **PRATT4-2.DAT** for the name of the import file. The file contains time and displacement data arranged in two columns separated by a tab delimiter. Click **Next**.
6. In Step 2 of the **Import Wizard**, enter data describing the structure of the import file. The **Import Wizard** automatically determines that the import file contains 2 columns of data. Enter **1** for the **Elapsed Time** column and **2** for the **Displacement** column. Click **Next**.
7. In Step 3 of the **Import Wizard**, choose transformation and filter options for the data contained in the import file. Retain the default settings, and click **Finish**.
8. After AQTESOLV for Windows has finished importing the data, a message box displays the number of observations imported from the file. Click **OK**.
9. Click **OK**.

After you have completed the previous data entry steps, the **Error Log** displayed in the active window should show that the data set contains no errors. Now you are ready to display the data, choose a solution and estimate aquifer properties.

Save Data Set

Choose **Save As...** from the **File** menu to save the data you have entered into the current data set.

1. Enter **KGS1.AQT** for the file name.
2. Click **OK** to save the data set.

Change View in Window

Choose **Displacement-Time** from the **View** menu to display a plot of displacement vs. time in the active window. The window displays a plot of the observation well data on semi-log axes.

Choose KGS Model Solution

Change the aquifer model and solution by choosing **Solution...** from the **Match** menu to choose a solution for analyzing a slug test in an unconfined aquifer.

1. Choose the **Unconfined KGS Model (1995)** solution.

2. Click **OK**.

After you have selected the KGS Model solution for a slug test in an unconfined aquifer, AQTESOLV for Windows updates the window by plotting the data on semi-log axes, superimposing a KGS Model type curve on the plot, and displaying values of radial hydraulic conductivity (K_r/K_r), specific storage (S_s/S_s) and hydraulic conductivity anisotropy ratio ($K_z/K_r K_z/K_r$) in the legend.

To analyze a slug test using the KGS Model type curve method, one plots relative displacement as a function of time on semi-log axes. By matching a family of type curves, one can estimate the values of hydraulic conductivity, specific storage and hydraulic conductivity anisotropy ratio of the aquifer by visual analysis.

Perform Visual Matching with KGS Model

Choose **Visual** from the **Match** menu to perform visual curve matching with the KGS Model solution.

1. To begin interactively moving the type curve, move the mouse cursor over the plot, click the left mouse button, and hold it down.
2. As you move the mouse, the type curve also moves. AQTESOLV for Windows updates the value of K_r in the legend as the type curve position changes. The values of S_s is fixed as you move the curve to the left and right on the plot.
3. When you have finished matching the type curve to the observation well data, release the left mouse button to end visual curve matching.

Choose **Toolbox...** from the **Match** menu to fine tune the match of the type curve to the data.

1. In the **Tweak** tab, select S_s from the **Parameter** list.
2. Check the **Apply changes automatically** option.
3. Move the button on the scroll bar to change the value of S_s . As you adjust the value, AQTESOLV for Windows updates the position of the type curve on the screen.
4. Repeat these steps for K_r to fine tune the position of the type curve.
5. Click **OK** when you have finished adjusting the parameters.

Perform Automatic Matching with KGS Model

Choose **Automatic...** from the **Match** menu to perform automatic matching using the KGS Model type curve solution.

1. In the **Parameters** tab, select **Inactive** for the **Estimation** of K_z/K_r (the default for this solution).
2. Click **Estimate** to begin automatic estimation.
3. As the automatic estimation procedure completes iterations, a progress window displays the changes in the residual sum of squares (RSS) criterion and the values of the aquifer properties. After the automatic estimation procedure finishes, AQTESOLV for Windows displays a message box containing residual summary statistics. Click **OK** to close the message box.
4. Click the **Close** button to close the progress window and click **OK** to finish.

The plot shown in the active window displays the values of transmissivity ($Kr=4.034$), storage coefficient ($Ss=0.0003834$) and hydraulic conductivity anisotropy ratio ($Kz/Kr=1.0$) determined by automatic estimation.

Save Data Set

Choose **Save** from the **File** menu to save your work in the **KGS1.AQT** data set.

Springer-Gelhar (1991) Solution for a Slug Test in a High-K Unconfined Aquifer

Springer and Gelhar (1991) with extensions by Zlotnik and McGuire (1998) present a slug test model that accounts for the oscillatory water-level response sometimes observed in unconfined aquifers of high hydraulic conductivity:

$$w_D(t_D) = \begin{cases} e^{-C_D t_D} \left(\cos(\omega_D t_D) + \frac{C_D}{\omega_D} \sin(\omega_D t_D) \right), & C_D < 1 \\ e^{-t_D} (1 + t_D), & C_D = 1 \\ - \left(\frac{1}{\omega_D^+ - \omega_D^-} \right) \left(\omega_D^- e^{\omega_D^+ t_D} - \omega_D^+ e^{\omega_D^- t_D} \right), & C_D > 1 \end{cases}$$

$$w_D = s / H_0$$

$$t_D = t \sqrt{g / L_e}$$

$$C_D = \sqrt{g / L_e} \frac{r_c^2 \log(r_e / r_{we})}{4K_r L}$$

$$\omega_D = \sqrt{1 - C_D^2}$$

$$\omega_D^\pm = -C_D \pm \omega_D$$

$$r_{we} = r_w \sqrt{\frac{K_z}{K_r}}$$

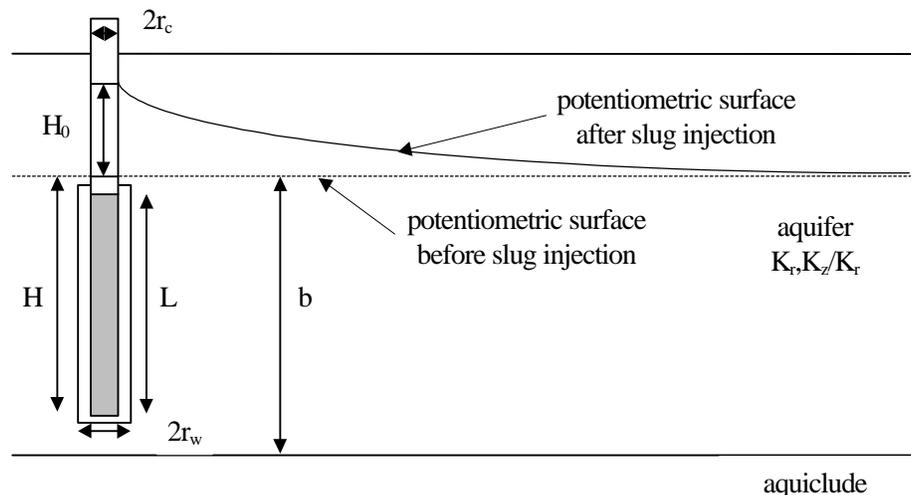
Note from the definition of the dimensionless damping factor, $C_D C(D)$, that the solution adopts the Bouwer-Rice (1976) model of flow in an unconfined aquifer (see "Bouwer-Rice (1976) Solution for a Slug Test in an Unconfined Aquifer" on page 107). The Springer-Gelhar solution is said to be critically damped when the dimensionless damping factor is equal to 1, underdamped when this parameter is less than 1, and overdamped when it is greater than 1. Note that Butler (1998) defines a dimensionless damping factor having a critically damped value equal to 2 (see "Plots Tab (View>Options)" on page 44 to change the critically damped value). Refer to the "List of Symbols" on page 157 for a description of other parameters and variables contained in the equations for this solution.

Butler (2002) modified the definition of dimensionless damping factor to include frictional well loss:

$$C_D = \sqrt{g/L_c} \left(\frac{r_c^2 \log(r_c/r_{we})}{4K_r L} + \frac{4\nu \left(\ell + \frac{r_c^4 L}{r_w^4 2} \right)}{r_c^2 g} \right)$$

where ℓ is the length of the water column above the top of the well screen [L].
Butler (2002) showed that frictional well loss is important in small-diameter wells.

By matching a family of dimensionless damping factor (C_D) type curves for the Springer-Gelhar solution to a plot of data on linear axes, it is possible to determine value of K_r in an unconfined aquifer.



Note that the well radius (r_w) may be less than, greater than or equal to the casing radius (r_c).

Assumptions

- aquifer has infinite areal extent
- aquifer is homogeneous and of uniform thickness
- aquifer potentiometric surface is initially horizontal
- a volume of water, V , is injected into or discharged from the well instantaneously
- test well is fully or partially penetrating
- flow to test well is horizontal
- aquifer is unconfined
- flow is steady

Data Requirements

- test well measurements (time and displacement)
- static water column height in well

- initial displacement
- casing radius and effective well radius for test well
- saturated thickness of aquifer
- screen length
- total depth of well penetration below water table
- porosity of gravel pack (optional)
- hydraulic conductivity anisotropy ratio (optional)

Visual Curve Matching Tips

- Choose **Visual** from the **Match** menu to perform visual curve matching using the procedure described in "Visual Matching With Oscillatory (Damped Sinusoidal) Solutions" on page 166.
- Use the **Active Type Curves** option for more effective visual matching (see "Active Type Curves" on page 167).
- Select values of C(D) from the **Family** and **Curve** lists on the toolbar.
- Use **Parameter Tweaking** to perform visual curve matching and sensitivity analysis (see "Tweak Tab (Match>Toolbox)" on page 169).
- See "Plots Tab (View>Options)" on page 44 to change the critical damping factor assumed for C(D).

References

- Bouwer, H. and R.C. Rice, 1976. A slug test method for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells, *Water Resources Research*, vol. 12, no. 3, pp. 423-428.
- Butler, J.J., Jr., 1998. The Design, Performance, and Analysis of Slug Tests, Lewis Publishers, Boca Raton, 252p.
- Butler, J.J., Jr., 2002. A simple correction for slug tests in small-diameter wells, *Ground Water*, vol. 40, no. 3, pp. 303-307.
- Springer, R.K. and L.W. Gelhar, 1991. Characterization of large-scale aquifer heterogeneity in glacial outwash by analysis of slug tests with oscillatory response, Cape Cod, Massachusetts, U.S. Geol. Surv. Water Res. Invest. Rep. 91-4034, pp. 36-40.
- Zlotnik, V.A. and V.L. McGuire, 1998. Multi-level slug tests in highly permeable formations: 1. Modifications of the Springer-Gelhar (SG) model, *Jour. of Hydrol.*, no. 204, pp. 271-282.

Tutorial

In this tutorial, you will use the Springer-Gelhar solution to create and analyze a slug test with oscillatory response. This tutorial shows you how to use visual and automatic curve matching to match the Springer-Gelhar solution to displacement data measured during the slug test.

Please visit <http://www.aqtesolv.com/examples/> for additional tutorials and sample data sets.

Open a New Data Set

Open a new data set by choosing **New** from the **File** menu. In the **New Data Set** dialog box, choose **Tutorial** in the list box and click **OK** to initialize the new data set with default values. AQTESOLV for Windows opens a new window with an Error Log view that reports any errors identified in the data set.

Enter Data for Slug Test

Choose **Units...** from the **Edit** menu to select units of measurement for the data set.

1. Select **m** (meters) for **Length**, **sec** (seconds) for **Time**, and **cm/sec** (centimeters-per-second) for **Hyd. Conductivity**.
2. Click **OK**.

Choose **Annotations...** from the **Edit** menu to edit the data set title.

1. In the **Title** tab, enter **Unconfined Slug Test with Oscillatory Response** for the **Title**.
2. Click **OK**.

Choose **Slug Test Well...** from the **Edit** menu to edit slug test data.

1. In the **General** tab, enter **-0.054** for **Initial Displacement** and **5.229** for **Static Water Column Height**.
2. In the **Aquifer** tab, enter **10.67** for **Saturated Thickness**.
3. In the **Screen** tab, enter **0.229** for **Screen Length** and **5.229** for **Total Depth of Penetration**.
4. In the **Radius** tab, enter **0.019** for **Casing Radius** and **0.017** for **Wellbore Radius** and **Well Skin Radius**.
5. In the **Observations** tab, click the **Import** button to import observation well measurements from a delimited text file using the **Observation Data Import Wizard**. In Step 1 of the **Import Wizard**, enter **SPRINGER1.DAT** for the name of the import file. The file contains time and displacement data arranged in two columns separated by a tab delimiter. Click **Next**.
6. In Step 2 of the **Import Wizard**, enter data describing the structure of the import file. The **Import Wizard** automatically determines that the import file contains 2 columns of data. Enter **1** for the **Elapsed Time** column and **2** for the **Displacement** column. Click **Next**.
7. In Step 3 of the **Import Wizard**, choose transformation and filter options for the data contained in the import file. Retain the default settings, and click **Finish**.
8. After AQTESOLV for Windows has finished importing the data, a message box displays the number of observations imported from the file. Click **OK**.
9. Click **OK**.

After you have completed the previous data entry steps, the **Error Log** displayed in the active window should show that the data set contains no errors. Now you are ready to display the data, choose a solution and estimate aquifer properties.

Save Data Set

Choose **Save As...** from the **File** menu to save the data you have entered into the current data set.

1. Enter **SPRINGER1.AQT** for the file name.
2. Click **OK** to save the data set.

Change View in Window

Choose **Displacement-Time** from the **View** menu to display a plot of displacement vs. time in the active window. The window displays a plot of the observation well data on semi-log axes.

Choose KGS Model Solution

Change the aquifer model and solution by choosing **Solution...** from the **Match** menu to choose a solution for analyzing a slug test in an unconfined aquifer.

1. Choose the **Unconfined Springer-Gelhar (1991) w/inertial effects** solution.
2. Click **OK**.

After you have selected the Springer-Gelhar solution for a slug test in an unconfined aquifer, AQTESOLV for Windows updates the window by plotting the data on semi-log axes, superimposing a Springer-Gelhar type curve on the plot, and displaying values of radial hydraulic conductivity (K_r) and dimensionless damping factor ($C_D(D)$) in the legend.

To analyze a slug test using the Springer-Gelhar type curve method, one plots relative displacement as a function of time on semi-log axes or linear. By matching a family of type curves, one can estimate the values of hydraulic conductivity and dimensionless damping factor by visual analysis.

Perform Visual Matching with Springer-Gelhar

Prior to performing visual curve matching with the Springer-Gelhar solution, choose **Toolbox...** from the **Match** menu and select the **Active type curves** option. Next, choose **Visual** from the **Match** menu to perform visual curve matching.

1. To begin interactively moving the type curve, move the mouse cursor over the plot, click the left mouse button, and hold it down.
2. As you move the mouse, the type curve also moves. Move the mouse up and down to adjust the amplitude of the curve and left and right to change the frequency. AQTESOLV for Windows updates the value of K_r and $C(D)$ in the legend as the type curve position changes.
3. When you have finished matching the type curve to the observation well data, release the left mouse button to end visual curve matching.

Perform Automatic Matching with Springer-Gelhar

Choose **Automatic...** from the **Match** menu to perform automatic matching using the Springer-Gelhar type curve solution.

1. Click **Estimate** to begin automatic estimation.
2. As the automatic estimation procedure completes iterations, a progress window displays the changes in the residual sum of squares (RSS) criterion and the values of the aquifer properties. After the automatic estimation procedure finishes, AQTESOLV for Windows displays a message box containing residual summary statistics. Click **OK** to close the message box.

- Click the **Close** button to close the progress window and click **OK** to finish.

The plot shown in the active window displays the values of transmissivity ($Kr=0.167$) and dimensionless damping factor ($C(D)=0.386$) determined by automatic estimation.

Save Data Set

Choose **Save** from the **File** menu to save your work in the **SPRINGER1.AQT** data set.

Leaky Aquifer Solutions

Choose **Solution...** from the **Match** menu to choose a solution for analyzing a pumping test in a leaky aquifer.

Solutions for Pumping Tests in Leaky Aquifers

- Hantush-Jacob (1955) type curve solution (no storage in aquitard)
- Hantush (1960) type curve solution (storage in aquitard, early time)
- Moench (1985) type curve solution (large-diameter well, storage in aquitard)
- Neuman-Witherspoon (1969) type curve solution (two-aquifer system, storage in aquitard)

No solutions are currently available for analyzing slug tests in a leaky aquifer; however, assuming leakage is negligible, you may use one of the slug test solutions for a confined aquifer.

Hantush-Jacob (1955) Solution for a Pumping Test in a Leaky Aquifer

Hantush and Jacob (1955) derived an analytical solution for predicting water-level changes in response to pumping in a leaky confined aquifer assuming steady flow (no storage) in the aquitard(s):

$$s = \frac{Q}{4\pi T} \int_u^{\infty} \frac{e^{-y-r^2/4B^2y}}{y} dy$$

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

$$B = \sqrt{\frac{Tb'}{K'}}$$

Hydrogeologists commonly refer to the integral expression in the drawdown equation as the *Hantush well function for leaky aquifers*, abbreviated as **w(u,r/B)**. Therefore, we can write the Hantush drawdown equation in compact notation as follows:

$$s = \frac{Q}{4\pi T} w(u, r/B)$$

Refer to the "List of Symbols" on page 157 for a description of the parameters and variables contained in the equations.

Hantush (1961a,b) derived equations for the effects of partial penetration in a leaky aquifer. For a piezometer, the partial penetration correction is as follows:

$$s = \frac{Q}{4\pi T} \left(w(u, r/B) + \frac{2b}{\pi(1-d)} \sum_{n=1}^{\infty} \frac{1}{n} \left[\sin\left(\frac{n\pi l}{b}\right) - \sin\left(\frac{n\pi d}{b}\right) \right] \cdot \cos\left(\frac{n\pi z}{b}\right) \cdot w\left(u, \sqrt{\left(r/B\right)^2 + \frac{K_z}{K_r} \left(\frac{n\pi r}{b}\right)^2} \right) \right)$$

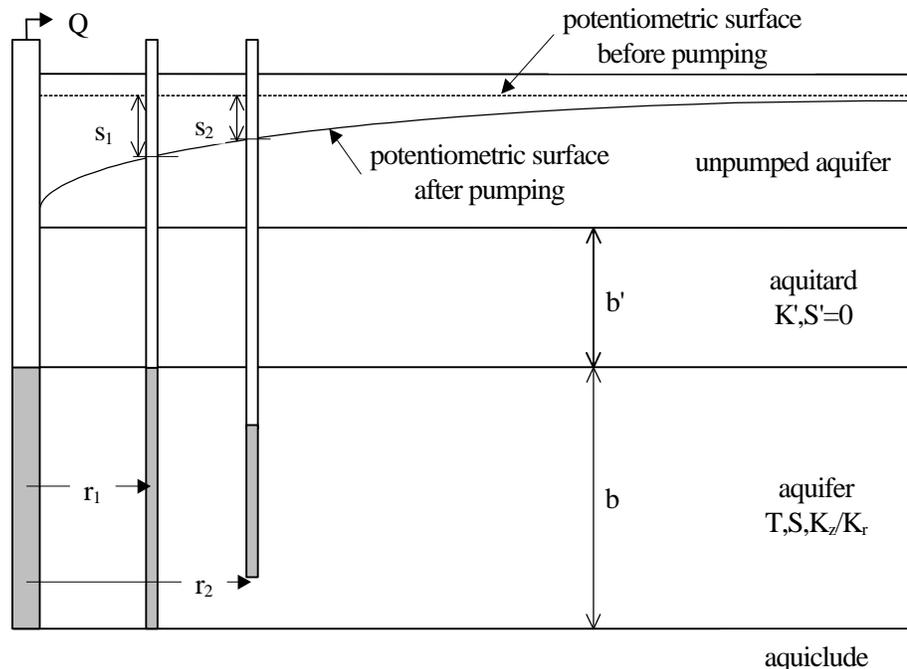
For an observation well, the following partial penetration correction applies:

$$s = \frac{Q}{4\pi T} \left(w(u, r/B) + \frac{2b^2}{\pi^2(1-d)(l'-d')} \sum_{n=1}^{\infty} \frac{1}{n^2} \left[\sin\left(\frac{n\pi l}{b}\right) - \sin\left(\frac{n\pi d}{b}\right) \right] \cdot \left[\sin\left(\frac{n\pi l'}{b}\right) - \sin\left(\frac{n\pi d'}{b}\right) \right] \cdot w\left(u, \sqrt{\left(r/B\right)^2 + \frac{K_z}{K_r} \left(\frac{n\pi r}{b}\right)^2} \right) \right)$$

where $w(u, r/B)$ is the Hantush well function for leaky aquifers.

AQTESOLV for Windows allows you to analyze both constant- and variable-rate pumping tests using the Hantush-Jacob solution. For tests with a variable discharge rate, the program uses the principle of superposition to compute drawdown in the aquifer. For more information concerning the application of the principle of superposition in variable-rate pumping tests, refer to the "Theis (1935) Solution for a Pumping Test in a Confined Aquifer" on page 54.

Use the Hantush-Jacob r/B solution to estimate values of transmissivity (T), storage coefficient (S), and r/B (or $1/B$ for a data set containing more than one pair of pumping and observation wells) in a leaky aquifer with no storage in the aquitard(s). For partially penetrating wells, the Hantush-Jacob r/B solution also estimates the values of hydraulic conductivity anisotropy ratio (K_z/K_r) and saturated thickness (b).



Assumptions

- aquifer has infinite areal extent
- aquifer is homogeneous, isotropic and of uniform thickness
- aquifer potentiometric surface is initially horizontal
- pumping well is fully or partially penetrating
- flow to pumping well is horizontal when pumping well is fully penetrating
- aquifer is leaky
- flow is unsteady
- water is released instantaneously from storage with decline of hydraulic head
- diameter of pumping well is very small so that storage in the well can be neglected
- confining bed(s) has infinite areal extent, uniform vertical hydraulic conductivity and uniform thickness
- confining bed(s) is overlain or underlain by an infinite constant-head plane source
- flow in the aquitard(s) is vertical

Data Requirements

- pumping and observation well locations
- pumping rate(s)
- observation well measurements (time and displacement)
- partial penetration depths (optional)
- saturated thickness (for partially penetrating wells)
- hydraulic conductivity anisotropy ratio (for partially penetrating wells)

Solution Options

- variable pumping rates
- multiple pumping wells
- multiple observation wells
- partially penetrating wells

Visual Curve Matching Tips

- Choose **Visual** from the **Match** menu to perform visual curve matching using the procedure described in "Visual Matching With Type Curve Solutions" on page 165.
- Use **Active Type Curves** for more effective visual matching with variable-rate pumping tests (see "Active Type Curves" on page 167).
- Select values of r/B from the **Family** and **Curve** lists on the toolbar.

- Use **Parameter Tweaking** to perform visual curve matching and sensitivity analysis (see "Tweak Tab (Match>Toolbox)" on page 169).

Reference

Hantush, M.S. and C.E. Jacob, 1955. Non-steady radial flow in an infinite leaky aquifer, Am. Geophys. Union Trans., vol. 36, pp. 95-100.

Hantush, M.S., 1961a. Drawdown around a partially penetrating well, Jour. of the Hyd. Div., Proc. of the Am. Soc. of Civil Eng., vol. 87, no. HY4, pp. 83-98.

Hantush, M.S., 1961b. Aquifer tests on partially penetrating wells, Jour. of the Hyd. Div., Proc. of the Am. Soc. of Civil Eng., vol. 87, no. HY5, pp. 171-194.

Tutorial

In this tutorial, you will use the Hantush-Jacob type curve solution to create and analyze a constant-rate pumping test. This tutorial shows you how to use automatic curve matching to match the Hantush-Jacob type curve to drawdown data measured during the pumping test.

Please visit <http://www.aqtesolv.com/examples/> for additional tutorials and sample data sets.

Open a New Data Set

Open a new data set by choosing **New** from the **File** menu. In the **New Data Set** dialog box, choose **Tutorial** in the list box and click **OK** to initialize the new data set with default values. AQTESOLV for Windows opens a new window with an Error Log view that reports any errors identified in the data set.

Enter Data for Pumping Test

Choose **Units...** from the **Edit** menu to select units of measurement for the data set.

1. Select **m** (meters) for **Length**, **min** (minutes) for **Time**, **L/sec** (liters-per-second) for **Pumping Rate** and **m/day** (meters/day) for **Hyd. Conductivity**.
2. Click **OK**.

Choose **Annotations...** from the **Edit** menu to edit the data set title.

1. In the **Title** tab, enter **Leaky Confined Pumping Test** for the **Title**.
2. Click **OK**.

Choose **Aquifer Data...** from the **Edit** menu to edit aquifer data.

1. In the **General** tab, enter **7.0** for the value of **Saturated Thickness**.
2. Click **OK**.

Choose **Pumping Well>Edit...** from the **Edit** menu to edit pumping well data.

1. In the **Rates** tab, enter values of **0.0** and **9.12** for time and rate, respectively, where time is in minutes and rate is in liters-per-second.
2. Click **OK**.

Choose **Obs. Well>Edit...** from the **Edit** menu to edit data for the observation well.

1. In the **General** tab, enter **H-30** for the **Observation Well Name**.

2. Enter a value of **30.0** for the **X-Coordinate** location of the well.
3. In the **Observations** tab, click the **Import** button to import observation well measurements from a delimited text file using the **Observation Data Import Wizard**. In Step 1 of the **Import Wizard**, enter **H30.DAT** for the name of the import file. The file H30.DAT contains time and displacement data arranged in two columns separated by a tab delimiter. Click **Next**.
4. In Step 2 of the **Import Wizard**, enter data describing the structure of the import file. The **Import Wizard** automatically determines that the import file contains 2 columns of data. Enter **1** for the **Elapsed Time** column and **2** for the **Displacement** column. Click **Next**.
5. In Step 3 of the **Import Wizard**, choose transformation and filter options for the data contained in the import file. Retain the default settings, and click **Finish**.
6. After AQTESOLV for Windows has finished importing the data, a message box displays the number of observations imported from the file. Click **OK**.
7. Click **OK**.

After you have completed the previous data entry steps, the **Error Log** displayed in the active window should show that the data set contains no errors. Now you are ready to display the data, choose a solution and estimate aquifer properties.

Save Data Set

Choose **Save As...** from the **File** menu to save the data you have entered into the current data set.

1. Enter **HANTUSH1.AQT** for the file name.
2. Click **OK** to save the data set.

Change View in Window

Choose **Displacement-Time** from the **View** menu to display a plot of displacement vs. time in the active window. The window displays a plot of the observation well data on semi-log axes.

Choose Hantush-Jacob Solution

Change the aquifer model and solution by choosing **Solution...** from the **Match** menu to choose a solution for analyzing a pumping test in a leaky aquifer.

1. Choose the **Leaky Hantush-Jacob (1955)** solution.
2. Click **OK**.

After you have selected the Hantush-Jacob solution for a pumping test in a leaky aquifer, AQTESOLV for Windows updates the window by plotting the data on double logarithmic axes, superimposing a Hantush-Jacob type curve on the plot, and displaying values of transmissivity (T), storage coefficient (S), leakage parameter (r/B), hydraulic conductivity anisotropy ratio ($K_z/K_r K_z/K_r$) and saturated thickness (b) in the legend.

To analyze a pumping test using the Hantush r/B type curve method, one plots drawdown as a function of time on double logarithmic axes. By matching a family of type curves drawn by plotting $w(u, r/B)$ as a function of $1/u$ and r/B , one can estimate the values of transmissivity and storage coefficient of the aquifer by visual analysis.

Perform Visual Matching with Hantush-Jacob

Choose **Visual** from the **Match** menu to perform visual curve matching with the Hantush-Jacob solution.

1. To begin interactively moving the type curve, move the mouse cursor over the plot, click the left mouse button, and hold it down.
2. As you move the mouse, the type curve also moves. AQTESOLV for Windows updates the values of the aquifer properties, T and S, in the legend as the type curve position changes.
3. When you have finished matching the type curve to the observation well data, release the left mouse button to end visual curve matching.
4. You can select different values of the **r/B** parameter from the **Curve** list on the toolbar. Change the value of r/B until you find a type curve that fits the data. Continue moving the curve until you obtain a suitable match.

Perform Automatic Matching with Hantush-Jacob

Choose **Automatic...** from the **Match** menu to perform automatic matching using the Hantush-Jacob type curve solution.

1. Click **Estimate** to begin automatic estimation.
2. As the automatic estimation procedure completes iterations, a progress window displays the changes in the residual sum of squares (RSS) criterion and the values of the aquifer properties. After the automatic estimation procedure finishes, AQTESOLV for Windows displays a message box containing residual summary statistics. Click **OK** to close the message box.
3. Click the **Close** button to close the progress window and click **OK** to finish.

The plot shown in the active window displays the values of transmissivity (T=415.6), storage coefficient (S=0.0001562) and dimensionless leakage parameter (r/B=0.03229) determined by automatic estimation.

Save Data Set

Choose **Save** from the **File** menu to save your work in the **HANTUSH1.AQT** data set.

Hantush (1960) Solution for a Pumping Test in a Leaky Aquifer

Hantush (1960) derived an analytical solution for predicting water-level displacements in response to pumping in a leaky confined aquifer assuming storage in the aquitard(s). The solution in AQTESOLV for Windows assumes for **small** values of time, i.e., when $t < b'S'/10K'$ and $t < b''S''/10K''$.

$$s = \frac{Q}{4\pi T} \int_u^{\infty} \frac{e^{-y}}{y} \operatorname{erfc} \frac{\beta\sqrt{u}}{\sqrt{y(y-u)}} dy$$

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

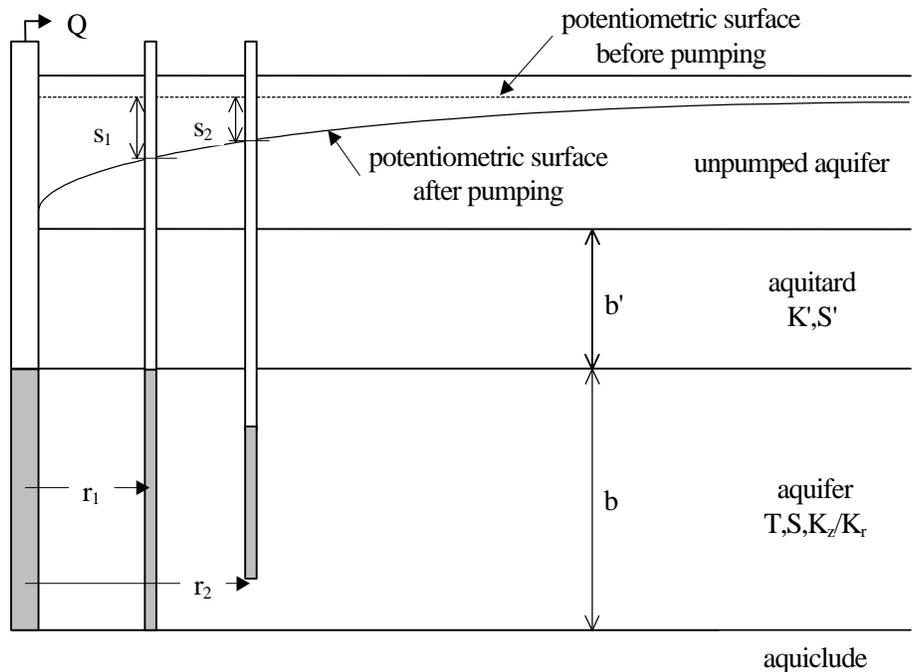
$$\beta = \frac{r}{4} \left[\sqrt{\frac{K'S'}{b'TS}} + \sqrt{\frac{K''S''}{b''TS}} \right]$$

Refer to the "List of Symbols" on page 157 for a description of the parameters and variables contained in the equations.

Refer to "Hantush-Jacob (1955) Solution for a Pumping Test in a Leaky Aquifer" on page 119 for partial penetration correction equations for this solution.

AQTESOLV for Windows allows you to analyze both constant- and variable-rate pumping tests using the Hantush solution. For tests with a variable discharge rate, the program uses the principle of superposition to compute drawdown in the aquifer. For more information concerning the application of the principle of superposition in variable-rate pumping tests, refer to the "Theis (1935) Solution for a Pumping Test in a Confined Aquifer" on page 54.

Use the Hantush solution to estimate values of transmissivity, storage coefficient, and β (or β/r) for a data set containing more than one pair of pumping and observation wells in a leaky aquifer with storage in the aquitard(s) for small values of time. For partially penetrating wells, the Hantush solution also estimates the values of hydraulic conductivity anisotropy ratio (K_z/K_r) and saturated thickness (b).



Assumptions

- aquifer has infinite areal extent
- aquifer is homogeneous, isotropic and of uniform thickness
- aquifer potentiometric surface is initially horizontal
- pumping well is fully or partially penetrating
- flow to pumping well is horizontal when pumping well is fully penetrating

- aquifer is leaky
- flow is unsteady
- water is released instantaneously from storage with decline of hydraulic head
- diameter of pumping well is very small so that storage in the well can be neglected
- confining bed(s) has infinite areal extent, uniform vertical hydraulic conductivity and storage coefficient, and uniform thickness
- confining bed(s) is overlain or underlain by an infinite constant-head plane source
- flow in the aquitard(s) is vertical

Data Requirements

- pumping and observation well locations
- pumping rate(s)
- observation well measurements (time and displacement)
- partial penetration depths (optional)
- saturated thickness (for partially penetrating wells)
- hydraulic conductivity anisotropy ratio (for partially penetrating wells)

Solution Options

- variable pumping rates
- multiple pumping wells
- multiple observation wells
- partially penetrating wells

Visual Curve Matching Tips

- Choose **Visual** from the **Match** menu to perform visual curve matching using the procedure described in "Visual Matching With Type Curve Solutions" on page 165.
- Use **Active Type Curves** for more effective visual matching with variable-rate pumping tests (see "Active Type Curves" on page 167).
- Select values of β from the **Family** and **Curve** lists on the toolbar.
- Use **Parameter Tweaking** to perform visual curve matching and sensitivity analysis (see "Tweak Tab (Match>Toolbox)" on page 169).

Reference

Hantush, M.S., 1960. Modification of the theory of leaky aquifers, Jour. of Geophys. Res., vol. 65, no. 11, pp. 3713-3725.

Tutorial

In this tutorial, you will use the Hantush solution to analyze the constant rate pumping test data set created and saved in the tutorial for the Hantush-Jacob leaky aquifer solution. In this tutorial, you will add an observation well to the data set and use automatic curve matching to match the Hantush type curve to drawdown data measured in two observation wells during a constant rate test.

Please visit <http://www.aqtesolv.com/examples/> for additional tutorials and sample data sets.

Open Data Set

Choose **Open...** from the **File** menu to open a data set stored on disk. You will open the data set created and saved in the tutorial for the Hantush-Jacob (1955) solution.

1. Enter **HANTUSH1.AQT** for the name of the data set.
2. Click **OK** to open the data set.

Change View in Window

Choose **Error Log** from the **View** menu to display an Error Log report in the active window.

Add Observation Well to Data Set

Choose **Obs. Well>Add...** from the **Edit** menu to add an observation well and edit observation well data.

1. In the **General** tab, enter **H-90** for the **Observation Well Name**.
2. Enter a value of **90.0** for the **X-Coordinate** location of the well.
3. In the **Observations** tab, click the **Import** button to import observation well measurements from a delimited text file using the **Observation Data Import Wizard**. In Step 1 of the **Import Wizard**, enter **H90.DAT** for the name of the import file. The file H90.DAT contains time and displacement data arranged in two columns separated by a tab delimiter. Click **Next**.
4. In Step 2 of the **Import Wizard**, enter data describing the structure of the import file. The **Import Wizard** automatically determines that the import file contains 2 columns of data. Enter **1** for the **Elapsed Time** column and **2** for the **Displacement** column. Click **Next**.
5. In Step 3 of the **Import Wizard**, choose transformation and filter options for the data contained in the import file. Retain the default settings, and click **Finish**.
6. After AQTESOLV for Windows has finished importing the data, a message box displays the number of observations imported from the file. Click **OK**.
7. Click **OK**.

After you have completed the previous data entry steps, the **Error Log** displayed in the active window should show that the data set contains no errors. Now you are ready to display the data, choose a solution and estimate aquifer properties.

Save Data Set

Choose **Save As...** from the **File** menu to save the data you have entered into the current data set.

1. Enter **HANTUSH2.AQT** for the file name.
2. Click **OK** to save the data set.

Change View in Window

Choose **Displacement-Time** from the **View** menu to display a plot of displacement vs. time in the active window. The window displays a plot of the observation well data on semi-log axes.

Choose Hantush Solution

Change the aquifer model and solution by choosing **Solution...** from the **Match** menu to choose a solution for analyzing a pumping test in a leaky aquifer.

1. Choose the **Leaky Hantush (1960)** solution.
2. Click **OK**.

After you have selected the Hantush solution for a pumping test in a leaky aquifer, AQTESOLV for Windows updates the window by plotting the data on double logarithmic axes, superimposing two Hantush type curves on the plot, and displaying values of transmissivity (T), storage coefficient (S) and leakage parameter (beta/r) in the legend.

AQTESOLV for Windows displays two type curves, one for each observation well, because the leakage parameter (beta) in the Hantush solution is a function of the radial distance, r, between the pumping and observation wells. The parameter displayed (beta/r) is independent of r.

Perform Automatic Matching with Hantush

Choose **Automatic...** from the **Match** menu to perform automatic matching using the Hantush type curve solution.

1. Click **Estimate** to begin automatic estimation.
2. As the automatic estimation procedure completes iterations, a progress window displays the changes in the residual sum of squares (RSS) criterion and the values of the aquifer properties. After the automatic estimation procedure finishes, AQTESOLV for Windows displays a message box containing residual summary statistics. Click **OK** to close the message box.
3. Click the **Close** button to close the progress window and click **OK** to finish.

The plot shown in the active window displays the values of transmissivity (T=348.2), storage coefficient (S=0.0001658) and leakage parameter (beta/r=0.0009434) determined by automatic estimation.

Save Data Set

Choose **Save** from the **File** menu to save your work in the **HANTUSH2.AQT** data set.

Moench (1985) Solution for a Pumping Test in a Leaky Aquifer

Moench (1985) derived an analytical solution for predicting water-level displacements in response to pumping in a leaky confined aquifer assuming storage in the aquitard(s) and wellbore skin. The solution also assumes that an aquitard is

overlain or underlain by either a constant head boundary (Case 1) or a no-flow boundary (Case 2).

The Laplace transform solution for dimensionless drawdown in the pumped well is as follows:

$$\bar{h}_{wD} = \frac{2[K_0(x) + xS_w K_1(x)]}{p\{pW_D[K_0(x) + xS_w K_1(x)] + xK_1(x)\}}$$

The following equation is the Laplace transform solution for dimensionless drawdown in an observation well:

$$\bar{h}_D = \frac{2K_0(r_D x)}{p\{pW_D[K_0(x) + xS_w K_1(x)] + xK_1(x)\}}$$

$$x = (p + \bar{q}_D)^{1/2}$$

$$\bar{q}_D = \gamma^2 m \coth(m) \text{ (Case 1)}$$

$$\bar{q}_D = \gamma^2 m \tanh(m) \text{ (Case 2)}$$

$$m = \frac{(\sigma p)^{1/2}}{\gamma}$$

$$\gamma = r_w \left(\frac{K'}{K b b'} \right)^{1/2}$$

$$\sigma = \frac{S'_s b'}{S_s b}$$

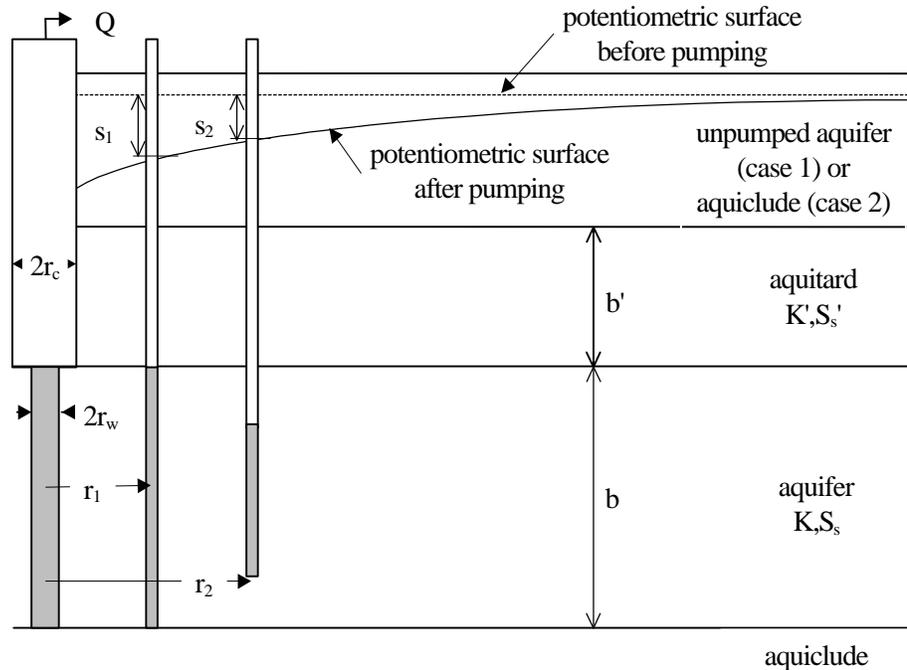
$$r_D = \frac{r}{r_w}$$

$$W_D = \frac{\pi r_c^2}{2\pi r_w^2 S_s b}$$

Refer to the "List of Symbols" on page 157 for a description of the parameters and variables contained in the equations.

AQTESOLV for Windows allows you to analyze both constant- and variable-rate pumping tests using the Moench solution. For tests with a variable discharge rate, the program uses the principle of superposition to compute drawdown in the aquifer. For more information concerning the application of the principle of superposition in variable-rate pumping tests, refer to the "Theis (1935) Solution for a Pumping Test in a Confined Aquifer" on page 54.

Use the Moench solution to estimate values of transmissivity, storage coefficient, r/B , β and r_w well radius (or $1/B$ and β/r for a data set containing more than one pair of pumping and observation wells) in a leaky aquifer with storage in the aquitard(s). If a data set contains more than one pumping well, AQTESOLV for Windows estimates the well radius for the first pumping well contained in the data set.



Assumptions

- aquifer has infinite areal extent
- aquifer is homogeneous, isotropic and of uniform thickness
- aquifer potentiometric surface is initially horizontal
- pumping well is fully penetrating
- flow to pumping well is horizontal
- aquifer is leaky
- flow is unsteady
- water is released instantaneously from storage with decline of hydraulic head
- confining bed(s) has infinite areal extent, uniform vertical hydraulic conductivity and storage coefficient, and uniform thickness
- confining bed(s) is overlain or underlain by an infinite constant-head plane source
- flow in the aquitard(s) is vertical

Data Requirements

- pumping and observation well locations
- pumping rate(s)
- observation well measurements (time and displacement)
- casing radius and wellbore radius for pumping well(s)

Solution Options

- large-diameter pumping wells
- variable pumping rate
- multiple pumping wells
- multiple observation wells

Visual Curve Matching Tips

- Choose **Visual** from the **Match** menu to perform visual curve matching using the procedure described in "Visual Matching With Type Curve Solutions" on page 165.
- Use **Active Type Curves** for more effective visual matching with variable-rate pumping tests (see "Active Type Curves" on page 167).
- Choose **Radial Flow** from the **View** menu to help identify the presence of wellbore storage (see "Radial Flow Plot" on page 42).
- Select values of r/B and β from the **Family** and **Curve** lists on the toolbar.
- Use **Parameter Tweaking** to perform visual curve matching and sensitivity analysis (see "Tweak Tab (Match>Toolbox)" on page 169).

Reference

Moench, A.F., 1985. Transient flow to a large-diameter well in an aquifer with storative semiconfining layers, *Water Resources Research*, vol. 21, no. 8, pp. 1121-1131.

Tutorial

In this tutorial, you will use the Moench solution to analyze the constant rate pumping test data set created and saved in the tutorial for the Hantush leaky aquifer solution. In this tutorial, you will use automatic curve matching to match the Moench type curve to drawdown data measured in two observation wells during a constant rate test.

Please visit <http://www.aqtesolv.com/examples/> for additional tutorials and sample data sets.

Open Data Set

Choose **Open...** from the **File** menu to open a data set stored on disk. You will open the data set created and saved in the tutorial for the Hantush (1960) solution.

1. Enter **HANTUSH2.AQT** for the name of the data set.
2. Click **OK** to open the data set.

Change View in Window

Choose **Error Log** from the **View** menu to display an Error Log report in the active window.

Add Large-Diameter Well Data to Data Set

Choose **Pumping Well>Edit...** from the **Edit** menu to edit pumping well data.

1. In the **Construction** tab, enter **0.00001** for both **Wellbore Radius** and **Casing Radius**.
2. Click **OK**.

To analyze pumping tests using large-diameter well solutions, you must enter values for the wellbore radius and casing radius of the pumping well(s). If the values of either of these two variables is 0.0, AQTESOLV for Windows assumes the pumping well radius is infinitesimal; if you enter 0.0 for either value, AQTESOLV for Windows will not allow you to select any of the large-diameter well solutions contained in the program.

After you have completed the previous data entry steps, the **Error Log** displayed in the active window should show that the data set contains no errors. Now you are ready to display the data, choose a solution and estimate aquifer properties.

Save Data Set

Choose **Save As...** from the **File** menu to save the data you have entered into the current data set.

1. Enter **MOENCHL1.AQT** for the file name.
2. Click **OK** to save the data set.

Change View in Window

Choose **Displacement-Time** from the **View** menu to display a plot of displacement vs. time in the active window. The window displays a plot of the observation well data on semi-log axes.

Choose Moench Solution

Change the aquifer model and solution by choosing **Solution...** from the **Match** menu to choose a solution for analyzing a pumping test in a leaky aquifer.

1. Choose the **Leaky Moench (1985) Case 1** solution.
2. Click **OK**.

After you have selected the Moench solution for a pumping test in a leaky aquifer, AQTESOLV for Windows updates the window by plotting the data on double logarithmic axes, superimposing two Moench type curves on the plot, and displaying values of transmissivity (T), storage coefficient (S) and leakage parameters (1/B and beta/r), wellbore skin (Sw) and wellbore radius (Rw) in the legend.

AQTESOLV for Windows displays two type curves, one for each observation well, because the leakage parameters (r/B and beta) in the Moench solution are a function of the radial distance, r, between the pumping and observation wells. The parameters displayed (1/B and beta/r) are independent of r.

Edit Parameters Prior to Estimation

Choose **Automatic...** from the **Match** menu and click the **Parameters** tab to edit parameter values and constraints and to enable/disable estimation of parameters during automatic estimation.

1. Enter a value of **0.0** for **Sw** and set **Estimation** to **Inactive**.
2. Enter a value of **0.00001** for **Rw** and set **Estimation** to **Inactive**.
3. Click **OK**.

Perform Automatic Matching with Moench

Choose **Automatic...** from the **Match** menu to perform automatic matching using the Moench type curve solution.

1. Click **Estimate** to begin automatic estimation.
2. As the automatic estimation procedure completes iterations, a progress window displays the changes in the residual sum of squares (RSS) criterion and the values of the aquifer properties. After the automatic estimation procedure finishes, AQTESOLV for Windows displays a message box containing residual summary statistics. Click **OK** to close the message box.
3. Click the **Close** button to close the progress window and click **OK** to finish.

The plot shown in the active window displays the values of transmissivity ($T=347.5$), storage coefficient ($S=0.0001704$) and leakage parameters ($1/B=0.001683$ and $\beta_1/r=0.0008894$) determined by automatic estimation.

Save Data Set

Choose **Save** from the **File** menu to save your work in the **MOENCHL1.AQT** data set.

Neuman-Witherspoon (1969) Solution for a Pumping Test in a Leaky Aquifer

Neuman and Witherspoon (1969) derived an analytical solution for the problem of flow to a well in a confined infinite radial system consisting of two aquifers separated by an aquitard. The well completely penetrates only one of the aquifers. The solution considers storage in the aquitard and drawdown in the unpumped aquifer.

The following equation predicts drawdown in the pumped aquifer:

$$s = \frac{Q}{4\pi T_0} \int_0^{\infty} (1 - e^{-y\bar{t}_{D1}}) \{ [1 + G(y)] J_0[\omega_1(y)] + [1 - G(y)] J_0[\omega_2(y)] \} \frac{dy}{y}$$

where:

$$\bar{t}_{D1} = t_{D1} (r/B_{11})^4 / (4\beta_{11})^2$$

$$r/B_{ij} = r \sqrt{K'_j / T_i b'_j}$$

$$\beta_{ij} = r / 4b_i \sqrt{K'_j S'_{sj} / K_i S_{si}}$$

$$G(y) = M(y) / F(y)$$

$$\omega_1^2(y) = \frac{1}{2} [N(y) + F(y)]$$

$$\omega_2^2(y) = \frac{1}{2} [N(y) - F(y)]$$

$$F^2(y) = M^2(y) + \left[\frac{2(r/B_{11})(r/B_{21})y}{\sin y} \right]^2$$

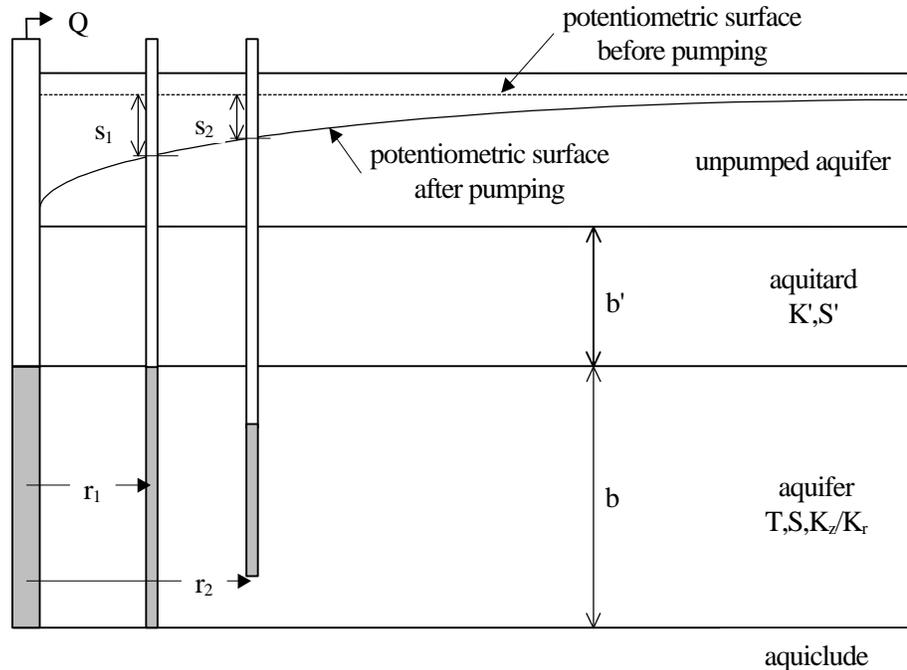
$$M(y) = \left[\frac{(r/B_{11})^4}{(4\beta_{11})^2} - \frac{(r/B_{21})^4}{(4\beta_{21})^2} \right] y^2 - \left[\left(\frac{r}{B_{11}} \right)^2 - \left(\frac{r}{B_{21}} \right)^2 \right] y \cot y$$

$$N(y) = \left[\frac{(r/B_{11})^4}{(4\beta_{11})^2} + \frac{(r/B_{21})^4}{(4\beta_{21})^2} \right] y^2 - \left[\left(\frac{r}{B_{11}} \right)^2 + \left(\frac{r}{B_{21}} \right)^2 \right] y \cot y$$

Refer to the "List of Symbols" on page 157 for a description of the parameters and variables contained in the equations.

AQTESOLV for Windows allows you to analyze both constant- and variable-rate pumping tests using the Neuman-Witherspoon solution. For tests with a variable discharge rate, the program uses the principle of superposition to compute drawdown in the aquifer. For more information concerning the application of the principle of superposition in variable-rate pumping tests, refer to the "Theis (1935) Solution for a Pumping Test in a Confined Aquifer" on page 54.

Use the Neuman-Witherspoon solution to estimate values of transmissivity, storage coefficient, r/B , β beta and r_w well radius (or $1/B$ and β/r beta/ r for a data set containing more than one pair of pumping and observation wells) in a leaky aquifer with storage in the aquitard(s).



Assumptions

- aquifer has infinite areal extent
- aquifers are homogeneous, isotropic and of uniform thickness

- aquifer potentiometric surface is initially horizontal
- pumping well is fully penetrating
- flow to pumping well is horizontal
- aquifer is leaky
- flow is unsteady
- water is released instantaneously from storage with decline of hydraulic head
- diameter of pumping well is very small so that storage in the well can be neglected
- confining bed has infinite areal extent, uniform vertical hydraulic conductivity and storage coefficient, and uniform thickness
- flow in the aquitard is vertical

Data Requirements

- pumping and observation well locations
- pumping rate(s)
- observation well measurements (time and displacement)

Solution Options

- variable pumping rate
- multiple pumping wells
- multiple observation wells

Visual Curve Matching Tips

- Choose **Visual** from the **Match** menu to perform visual curve matching using the procedure described in "Visual Matching With Type Curve Solutions" on page 165.
- Use **Active Type Curves** for more effective visual matching with variable-rate pumping tests (see "Active Type Curves" on page 167).
- Select values of r/B and β from the **Family** and **Curve** lists on the toolbar.
- Choose **Toolbox...** from the **Match** menu and click the **Options** tab to select visual curve matching options. Use **Match early data (Type A)** to match the properties of the pumped aquifer (T and S). **Match late data (Type B)** lets you match the unpumped aquifer properties (T' and S'). Check **Active type curves** to use active instead of static type curves.
- Use **Parameter Tweaking** to perform visual curve matching and sensitivity analysis (see "Tweak Tab (Match>Toolbox)" on page 169).

Reference

Neuman, S.P. and P.A. Witherspoon, 1969. Theory of flow in a confined two aquifer system, Water Resources Research, vol. 5, no. 4, pp. 803-816.

Tutorial

In this tutorial, you will perform sensitivity analysis with the Neuman-Witherspoon solution to evaluate the effect(s) of unpumped aquifer properties on drawdown in the pumped aquifer using the constant rate pumping test data set created and saved in the tutorial for the Moench leaky aquifer solution.

Please visit <http://www.aqtesolv.com/examples/> for additional tutorials and sample data sets.

Open Data Set

Choose **Open...** from the **File** menu to open a data set stored on disk. You will open the data set created and saved in the tutorial for the Moench (1985) solution.

1. Enter **MOENCHL1.AQT** for the name of the data set.
2. Click **OK** to open the data set.

Change View in Window

Choose **Displacement-Time** from the **View** menu to display a plot of displacement vs. time in the active window.

Choose Neuman-Witherspoon Solution

Change the aquifer model and solution by choosing **Solution...** from the **Match** menu to choose a solution for analyzing a pumping test in a leaky aquifer.

1. Choose the **Leaky Neuman-Witherspoon (1969)** solution.
2. Click **OK**.

After you have selected the Neuman-Witherspoon solution for a pumping test in a leaky aquifer, AQTESOLV for Windows updates the window by plotting the data on double logarithmic axes, superimposing two Neuman-Witherspoon type curves on the plot, and displaying in the legend values of transmissivity (T) and storage coefficient (S) for the pumped aquifer, leakage parameters ($1/B$ and $\beta\text{beta}/r$), and transmissivity (T') and storage coefficient (S') for the unpumped aquifer.

AQTESOLV for Windows displays two type curves, one for each observation well, because the leakage parameters (r/B and βbeta) in the Neuman-Witherspoon solution are each a function of the radial distance, r , between the pumping and observation wells. The parameters displayed ($1/B$ and $\beta\text{beta}/r$) is independent of r .

Change Format of X Axis

Choose **Format...** from the **View** menu and click the **X Axis** tab to format the x axis.

1. Change the **Maximum** value for the axis to 100000.
2. Click **OK**.

Perform Sensitivity Analysis with Neuman-Witherspoon

Choose **Toolbox...** from the **Match** menu and click the **Tweak** tab to perform sensitivity analysis using the Neuman-Witherspoon solution.

1. From the **Parameter** list, choose **T'** (transmissivity in the unpumped aquifer) as the parameter that you want to tweak.
2. Click the arrow buttons or the scroll bar to tweak the value of the parameter. Check **Apply changes automatically** to update the plot while you change the parameter.
3. For increasing values of **T'**, drawdown in the pumped aquifer as shown by the type curve approaches a constant value at large values of time. You can experiment with other parameters to see their effect on the solution.
4. Click **OK**.

Save Data Set

Choose **Save As...** from the **File** menu to save your work in a new data set.

1. Enter **NEUMANL1.AQT** for the file name.
2. Click **OK** to save the data set.

Fractured Aquifer Solutions

Choose **Solution...** from the **Match** menu to choose a solution for analyzing pumping tests in fractured aquifers.

Solutions for Pumping Tests in Fractured Aquifers

1. Moench (1984) type curve solution for a double-porosity fissured aquifer with slab-shaped matrix blocks
2. Moench (1984) type curve solution for a double-porosity fissured aquifer with spherical shaped matrix blocks
3. Gringarten-Witherspoon (1972) type curve solution for a fractured aquifer with a plane vertical fracture
4. Gringarten-Ramey (1974) type curve solution for a fractured aquifer with a plane horizontal fracture

No solutions are currently available in AQTESOLV for Windows for analyzing slug tests in a fractured aquifer; however, assuming negligible fracture flow effects, you may use one of the slug test solutions for a confined aquifer.

Moench (1984) Solution for a Pumping Test in a Fractured Aquifer with Slab-Shaped Blocks

Moench (1984) derived an analytical solution for predicting water-level displacements in response to pumping in a fractured aquifer assuming a double-porosity model with slab-shaped matrix blocks with fracture skin and wellbore skin.

The Laplace transform solution for dimensionless drawdown in the pumped well is as follows:

$$\bar{h}_{wD} = \frac{2[K_0(x) + xS_w K_1(x)]}{p\{pW_D [K_0(x) + xS_w K_1(x)] + xK_1(x)\}}$$

The follow equation is the Laplace transform solution for dimensionless drawdown in an observation well:

$$\bar{h}_D = \frac{2K_0(r_D x)}{p\{pW_D[K_0(x) + xS_w K_1(x)] + xK_1(x)\}}$$

$$x = (p + \bar{q}_D)^{1/2}$$

$$\bar{q}_D = \frac{\gamma^2 m \tanh(m)}{1 + S_f m \tanh(m)}$$

$$m = \frac{(\sigma p)^{1/2}}{\gamma}$$

$$\gamma = \frac{r_w}{b'} \left(\frac{K'}{K} \right)^{1/2}$$

$$\sigma = \frac{S'_s}{S_s}$$

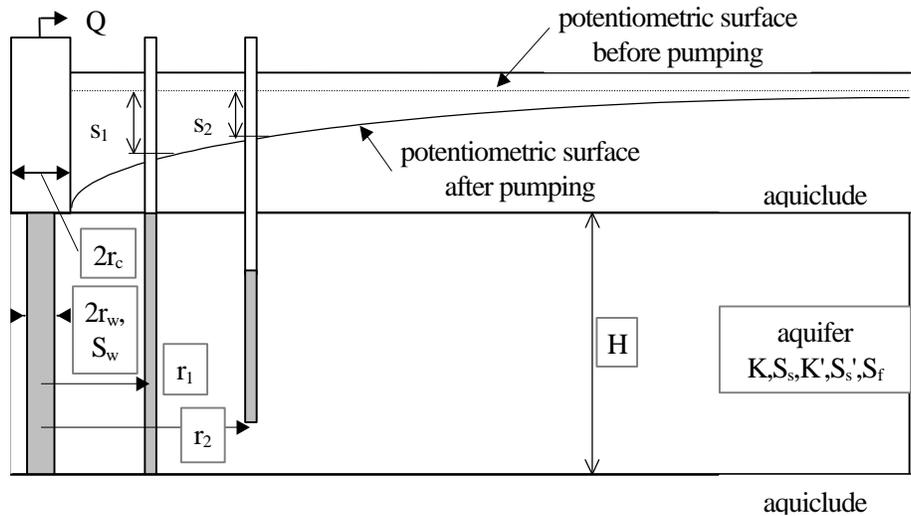
$$r_D = \frac{r}{r_w}$$

$$S_f = \frac{K' b_s}{K_s b'}$$

$$W_D = \frac{\pi r_c^2}{2\pi r_w^2 S_s H}$$

AQTESOLV for Windows allows you to analyze both constant- and variable-rate pumping tests using the Moench solution. For tests with a variable discharge rate, the program uses the principle of superposition to compute drawdown in the aquifer. For more information concerning the application of the principle of superposition in variable-rate pumping tests, refer to the "Theis (1935) Solution for a Pumping Test in a Confined Aquifer" on page 54.

Refer to the "List of Symbols" on page 157 for a description of the parameters and variables contained in the equations.



Assumptions

- aquifer has infinite areal extent
- aquifer has uniform thickness
- aquifer potentiometric surface is initially horizontal
- pumping and observation wells are fully penetrating
- fractured aquifer represented by double porosity system consisting of low-permeability, primary porosity blocks and high-permeability, secondary porosity fissures
- matrix consists of slab-shaped blocks
- flow is unsteady
- water is released instantaneously from storage with decline of hydraulic head

Data Requirements

- pumping and observation well locations
- pumping rate(s)
- observation well measurements (time and displacement)
- casing radius and wellbore radius for pumping well(s)
- saturated thickness of aquifer
- thickness of slab-shaped blocks

Solution Options

- large-diameter pumping wells
- variable pumping rate
- multiple pumping wells

- multiple observation wells

Visual Curve Matching Tips

- Choose **Visual** from the **Match** menu to perform visual curve matching using the procedure described in "Visual Matching With Type Curve Solutions" on page 165.
- Use **Active Type Curves** for more effective visual matching with variable-rate pumping tests (see "Active Type Curves" on page 167).
- Choose **Radial Flow** from the **View** menu to help identify the presence of wellbore storage (see "Radial Flow Plot" on page 42).
- Select values of Sw from the **Family** and **Curve** lists on the toolbar.
- Choose **Toolbox...** from the **Match** menu and click the **Options** tab to select visual curve matching options. Use **Match early data (Type A)** to match the properties of the fractures (K and Ss). **Match late data (Type B)** lets you match the matrix properties (K' and Ss'). Check **Active type curves** to use active instead of static type curves.
- Use **Parameter Tweaking** to perform visual curve matching and sensitivity analysis (see "Tweak Tab (Match>Toolbox)" on page 169).

Reference

Moench, A.F., 1984. Double-porosity models for a fissured groundwater reservoir with fracture skin, *Water Resources Research*, vol. 20, no. 7, pp. 831-846.

Tutorial

In this tutorial, you will use the Moench type curve solution for fractured aquifers to create and analyze a constant-rate pumping test. This tutorial shows you how to use automatic curve matching to match the Moench type curve to drawdown data measured during a pumping test.

Please visit <http://www.aqtesolv.com/examples/> for additional tutorials and sample data sets.

Open a New Data Set

Open a new data set by choosing **New** from the **File** menu. In the **New Data Set** dialog box, choose **Tutorial** in the list box and click **OK** to initialize the new data set with default values. AQTESOLV for Windows opens a new window with an Error Log view that reports any errors identified in the data set.

Enter Data for Pumping Test

Choose **Units...** from the **Edit** menu to select units of measurement for the data set.

1. Select **m** (meters) for **Length**, **min** (minutes) for **Time**, **L/sec** (liters-per-second) for **Pumping Rate** and **m/sec** (meters/second) for **Hyd. Conductivity**.
2. Click **OK**.

Choose **Annotations...** from the **Edit** menu to edit the data set title.

1. In the **Title** tab, enter **Nevada Test Site** for the **Title**.
2. Click **OK**.

Choose **Aquifer Data...** from the **Edit** menu to edit aquifer data.

1. In the **General** tab, enter **400.0** for the value of **Saturated Thickness**.
2. In the **Double Porosity** tab, enter **80.0** for the **Thickness of Slab Blocks**.
3. Click **OK**.

Choose **Pumping Well>Edit...** from the **Edit** menu to edit pumping well data.

1. In the **General** tab, enter **UE-25b#1** for the **Pumping Well Name**.
2. In the **Construction** tab, enter **0.11** for the **Wellbore Radius**.
3. Enter **0.11** for the **Casing Radius**.
4. In the **Rates** tab, enter values of **0.0** and **35.8** for time and rate, respectively, where time is in minutes and rate is in liters-per-second.
5. Click **OK**.

Choose **Obs. Well>Edit...** from the **Edit** menu to edit data for the observation well.

1. In the **General** tab, enter **UE-25a#1** for the **Observation Well Name**.
2. Enter a value of **110.0** for the **X-Coordinate** location of the well.
3. In the **Observations** tab, click **Import** to import observation well measurements from a delimited text file using the **Observation Data Import Wizard**. In Step 1 of the **Import Wizard**, enter **UE25A1.DAT** for the name of the import file. The file UE25A1.DAT contains time and displacement data arranged in two columns separated by a tab delimiter. Click **Next**.
4. In Step 2 of the **Import Wizard**, enter data describing the structure of the import file. The **Import Wizard** automatically determines that the import file contains 2 columns of data. Enter **1** for the **Elapsed Time** column and **2** for the **Displacement** column. Click **Next**.
5. In Step 3 of the **Import Wizard**, choose transformation and filter options for the data contained in the import file. Retain the default settings, and click **Finish**.
6. After AQTESOLV for Windows has finished importing the data, a message box displays the number of observations imported from the file. Click the **OK** button to close the message box.
7. Click **Select All** to select all of the observations in the spreadsheet.
8. Click **Math** to transform the selected data.
9. Select **Weights** for the **Data**, **Replace** for the **Operation** and **10.0** for the **Constant** to replace all measurement weights.
10. Click **OK**. Click **Yes** to confirm the transformation.
11. Click **OK**.

Choose **Obs. Well>Add...** from the **Edit** menu to add observation data for the pumping well.

1. In the **General** tab, enter **UE-25b#1** for the **Observation Well Name**.

2. In the **Observations** tab, click **Import** to import observation well measurements from a delimited text file using the **Observation Data Import Wizard**. In Step 1 of the **Import Wizard**, enter **UE25B1.DAT** for the name of the import file. The file UE25B1.DAT contains time and displacement data arranged in two columns separated by a tab delimiter. Click **Next**.
3. In Step 2 of the **Import Wizard**, enter data describing the structure of the import file. The **Import Wizard** automatically determines that the import file contains 2 columns of data. Enter **1** for the **Elapsed Time** column and **2** for the **Displacement** column. Click **Next**.
4. In Step 3 of the **Import Wizard**, choose transformation and filter options for the data contained in the import file. Retain the default settings, and click **Finish**.
5. After AQTESOLV for Windows has finished importing the data, a message box displays the number of observations imported from the file. Click the **OK** button to close the message box.
6. Click **OK**.

After you have completed the previous data entry steps, the **Error Log** displayed in the active window should show that the data set contains no errors. Now you are ready to display the data, choose a solution and estimate aquifer properties.

Save Data Set

Choose **Save As...** from the **File** menu to save the data you have entered into the current data set.

1. Enter **MOENCHF1.AQT** for the file name.
2. Click **OK** to save the data set.

Change View in Window

Choose **Displacement-Time** from the **View** menu to display a plot of displacement vs. time in the active window. The window displays a plot of the observation well data on semi-log axes.

Choose Moench Solution

Change the aquifer model and solution by choosing **Solution...** from the **Match** menu to choose a solution for analyzing a pumping test in a fractured aquifer.

1. Choose the **Fractured Moench (1984) w/ slab-shaped blocks** solution.
2. Click **OK**.

After you have selected the Moench solution for a pumping test in a fractured aquifer, AQTESOLV for Windows updates the window by plotting the data on double logarithmic axes, superimposing Moench type curves on the plot, and displaying values of fracture hydraulic conductivity (K), fracture specific storage (Ss), matrix hydraulic conductivity (K'), matrix specific storage (Ss'), wellbore skin (Sw) and fracture skin (Sf) in the legend.

Due to the large number of parameters in the Moench fractured aquifer solution, it is not practical to develop type curves for traditional visual analysis. Therefore, AQTESOLV for Windows provides you with the ability to match the Moench solution to your data by manually changing values of the six parameters in the solution until you achieve a satisfactory match.

Change View in Window

Choose **Composite** from the **View** menu to display a composite plot of displacement vs. time/radius squared in the active window. The window displays a plot of the observation well data on semi-log axes.

Edit Parameters Prior to Estimation

Choose **Automatic...** from the **Match** menu and click the **Parameters** tab to edit parameter values and constraints and to enable/disable estimation of parameters during automatic estimation.

1. Enter a value of **0.00005** for **K**.
2. Enter a value of **1.0E-6** for **Ss**.
3. Enter a value of **1.0E-6** for **K'**.
4. Enter a value of **0.0005** for **Ss'**.
5. Enter a value of **0.0** for **Sw** and set **Estimation** to **Inactive**.
6. Enter a value of **1.0** for **Sf** and set **Estimation** to **Inactive**.
7. Click **OK**.

Perform Automatic Matching with Moench

Choose **Automatic...** from the **Match** menu to perform automatic matching using the Moench type curve solution.

1. Click **Estimate** to begin automatic estimation.
2. As the automatic estimation procedure completes iterations, a progress window displays the changes in the residual sum of squares (RSS) criterion and the values of the aquifer properties. After the automatic estimation procedure finishes, AQTESOLV for Windows displays a message box containing residual summary statistics. Click **OK** to close the message box.
3. Click the **Close** button to close the progress window and click **OK** to finish.

The plot shown in the active window displays the values of fracture hydraulic conductivity ($K=1.083E-05$), fracture specific storage ($Ss=1.794E-06$), matrix hydraulic conductivity ($K'=2.235E-06$) and matrix specific storage ($Ss'=0.0004165$) determined by automatic estimation.

Save Data Set

Choose **Save** from the **File** menu to save your work in the **MOENCHF1.AQT** data set.

Moench (1984) Solution for a Pumping Test in a Fractured Aquifer with Spherical Shaped Blocks

Moench (1984) derived an analytical solution for predicting water-level displacements in response to pumping in a fractured aquifer assuming a double-porosity model with spherical shaped matrix blocks with fracture skin and wellbore skin.

The Laplace transform solution for dimensionless drawdown in the pumped well is as follows:

$$\bar{h}_{wD} = \frac{2[K_0(x) + xS_w K_1(x)]}{p\{pW_D[K_0(x) + xS_w K_1(x)] + xK_1(x)\}}$$

The following equation is the Laplace transform solution for dimensionless drawdown in an observation well:

$$\bar{h}_D = \frac{2K_0(r_D x)}{p\{pW_D[K_0(x) + xS_w K_1(x)] + xK_1(x)\}}$$

$$x = (p + \bar{q}_D)^{1/2}$$

$$\bar{q}_D = \frac{3\gamma^2[m \coth(m) - 1]}{1 + S_f[m \coth(m) - 1]}$$

$$m = \frac{(\sigma p)^{1/2}}{\gamma}$$

$$\gamma = \frac{r_w}{b'} \left(\frac{K'}{K} \right)^{1/2}$$

$$\sigma = \frac{S'_s}{S_s}$$

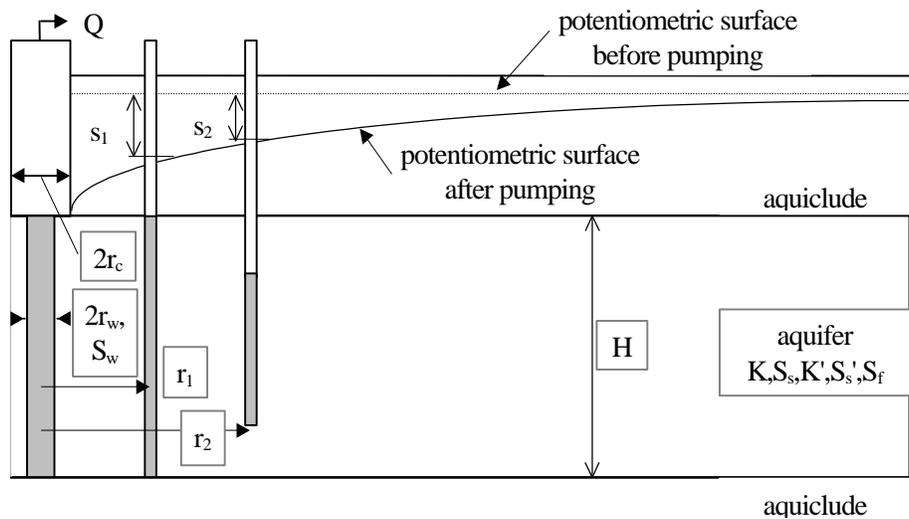
$$r_D = \frac{r}{r_w}$$

$$S_f = \frac{K'_s b_s}{K_s b'}$$

$$W_D = \frac{\pi r_c^2}{2\pi r_w^2 S_s H}$$

AQTESOLV for Windows allows you to analyze both constant- and variable-rate pumping tests using the Moench solution. For tests with a variable discharge rate, the program uses the principle of superposition to compute drawdown in the aquifer. For more information concerning the application of the principle of superposition in variable-rate pumping tests, refer to the "Theis (1935) Solution for a Pumping Test in a Confined Aquifer" on page 54.

Refer to the "List of Symbols" on page 157 for a description of the parameters and variables contained in the equations.



Assumptions

- aquifer has infinite areal extent
- aquifer has uniform thickness
- aquifer potentiometric surface is initially horizontal
- pumping and observation wells are fully penetrating
- fractured aquifer represented by double porosity system consisting of low-permeability, primary porosity blocks and high-permeability, secondary porosity fissures
- matrix consists of spherical blocks
- flow is unsteady
- water is released instantaneously from storage with decline of hydraulic head

Data Requirements

- pumping and observation well locations
- pumping rate(s)
- observation well measurements (time and displacement)
- casing radius and wellbore radius for pumping well(s)
- saturated thickness of aquifer
- diameter of spherical shaped blocks

Solution Options

- large-diameter pumping wells
- variable pumping rate
- multiple pumping wells

- multiple observation wells

Visual Curve Matching Tips

- Choose **Visual** from the **Match** menu to perform visual curve matching using the procedure described in "Visual Matching With Type Curve Solutions" on page 165.
- Use **Active Type Curves** for more effective visual matching with variable-rate pumping tests (see "Active Type Curves" on page 167).
- Choose **Radial Flow** from the **View** menu to help identify the presence of wellbore storage (see "Radial Flow Plot" on page 42).
- Select values of S_w from the **Family** and **Curve** lists on the toolbar.
- Choose **Toolbox...** from the **Match** menu and click the **Options** tab to select visual curve matching options. Use **Match early data (Type A)** to match the properties of the fractures (K and S_s). **Match late data (Type B)** lets you match the matrix properties (K' and S_s'). Check **Active type curves** to use active instead of static type curves.
- Use **Parameter Tweaking** to perform visual curve matching and sensitivity analysis (see "Tweak Tab (Match>Toolbox)" on page 169).

Reference

Moench, A.F., 1984. Double-porosity models for a fissured groundwater reservoir with fracture skin, *Water Resources Research*, vol. 20, no. 7, pp. 831-846.

Tutorial

Perform the tutorial for the Moench (1984) solution for a pumping test in a fractured aquifer with slab-shaped matrix blocks (see "Tutorial" on page 140) to learn how to use this solution.

Please visit <http://www.aqtesolv.com/examples/> for additional tutorials and sample data sets.

Gringarten-Witherspoon (1972) Solution for a Pumping Test in a Fractured Aquifer with a Plane Vertical Fracture

Gringarten and Witherspoon (1972) and Gringarten, Ramey and Raghavan (1974) presented an analytical solution for flow to a well in a confined infinite radial system intersecting a single uniform-flux plane vertical fracture. The solution assumes the well fully penetrates the aquifer and bisects the fracture.

The following equation predicts drawdown in the aquifer:

$$s = \frac{Q}{4\pi\sqrt{T_x T_y}} \frac{\sqrt{\pi}}{2} \int_0^{t_p} \left[\operatorname{erf} \frac{1-x_D}{2\sqrt{\tau}} + \operatorname{erf} \frac{1+x_D}{2\sqrt{\tau}} \right] e^{-\frac{y_D^2 T_x}{4\tau T_y}} \frac{d\tau}{\sqrt{\tau}}$$

where:

$$t_D = \frac{T_x t}{S x_f^2}$$

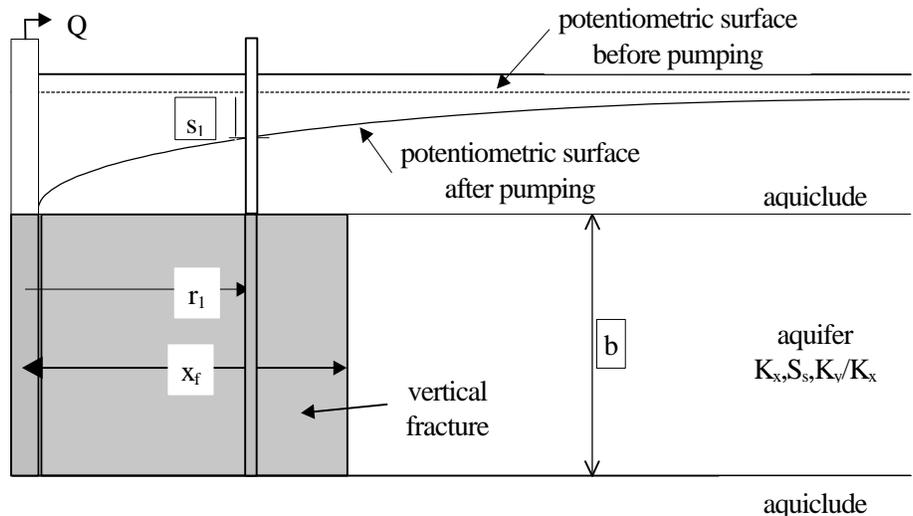
$$x_D = \frac{x}{x_f}$$

$$y_D = \frac{y}{x_f}$$

In this solution, the vertical fracture parallels the x axis of the coordinate system and has a length of $L_f (=2x_f)$.

AQTESOLV for Windows allows you to analyze both constant- and variable-rate pumping tests using the Gringarten-Witherspoon solution. For tests with a variable discharge rate, the program uses the principle of superposition to compute drawdown in the aquifer. For more information concerning the application of the principle of superposition in variable-rate pumping tests, refer to the "Theis (1935) Solution for a Pumping Test in a Confined Aquifer" on page 54.

Refer to the "List of Symbols" on page 157 for a description of the parameters and variables contained in the equations.



Assumptions

- aquifer has infinite areal extent
- aquifer has uniform thickness
- aquifer potentiometric surface is initially horizontal
- pumping and observation wells are fully penetrating
- fractured aquifer represented by anisotropic system with a single plane vertical fracture
- flow is unsteady
- water is released instantaneously from storage with decline of hydraulic head

- diameter of pumping well is very small so that storage in the well can be neglected

Data Requirements

- pumping and observation well locations
- pumping rate(s)
- observation well measurements (time and displacement)
- saturated thickness of aquifer
- length of vertical fracture

Solution Options

- variable pumping rate
- multiple pumping wells
- multiple observation wells

Visual Curve Matching Tips

- Choose **Visual** from the **Match** menu to perform visual curve matching using the procedure described in "Visual Matching With Type Curve Solutions" on page 165.
- Use **Active Type Curves** for more effective visual matching with variable-rate pumping tests (see "Active Type Curves" on page 167).
- Choose **Linear Flow** from the **View** menu to help identify the presence of linear flow conditions (see "Linear Flow Plot" on page 42).
- Select values of K_y/K_x from the **Family** and **Curve** lists on the toolbar.
- Use **Parameter Tweaking** to perform visual curve matching and sensitivity analysis (see "Tweak Tab (Match>Toolbox)" on page 169).

Reference

Gringarten, A.C. and P.A. Witherspoon, 1972. A method of analyzing pump test data from fractured aquifers, Int. Soc. Rock Mechanics and Int. Assoc. Eng. Geol., Proc. Symp. Rock Mechanics, Stuttgart, vol. 3-B, pp. 1-9.

Tutorial

In this tutorial, you will use automatic curve matching and the Gringarten-Witherspoon type curve solution for fractured aquifers to match drawdown data measured during a constant-rate pumping test.

Please visit <http://www.aqtesolv.com/examples/> for additional tutorials and sample data sets.

Open a New Data Set

Open a new data set by choosing **New** from the **File** menu. In the **New Data Set** dialog box, choose **Tutorial** in the list box and click **OK** to initialize the new data set

with default values. AQTESOLV for Windows opens a new window with an Error Log view that reports any errors identified in the data set.

Enter Data for Pumping Test

Choose **Units...** from the **Edit** menu to select units of measurement for the data set.

1. Select **ft** (feet) for **Length**, **min** (minutes) for **Time**, **consistent** for **Pumping Rate** and **consistent** for **Hyd. Conductivity**.
2. Click **OK**.

Choose **Annotations...** from the **Edit** menu to edit the data set title.

1. In the **Title** tab, enter **Vertical Fracture with Uniform Flux** for the **Title**.
2. Click **OK**.

Choose **Aquifer Data...** from the **Edit** menu to edit aquifer data.

1. In the **General** tab, enter **1.0** for the value of **Saturated Thickness**.
2. In the **Single Fracture** tab, enter **2.0** for the **Length of the Vertical Fracture**.
3. Click **OK**.

Choose **Pumping Well>Edit...** from the **Edit** menu to edit pumping well data.

1. In the **Rates** tab, enter values of **0.0** and **3.14159e-6** for time and rate, respectively, where time is in minutes and rate is in cubic feet per minute.
2. Click **OK**.

Choose **Obs. Well>Edit...** from the **Edit** menu to edit data for the observation well.

1. In the **General** tab, enter **r'=0.2** for the **Observation Well Name**.
2. Enter values of **0.2** for the **X-Coordinate** and **0.0** for the **Y-Coordinate** locations of the well.
3. In the **Observations** tab, enter the following measurements from the keyboard (set all weights equal to 1.0):

<i>Time</i>	<i>Displacement</i>
0.002	0.158498
0.008	0.317031
0.02	0.50129
0.08	0.999257
0.2	1.53935
0.8	2.65586
2	3.50752
8	4.85983
20	5.76918
80	7.152
200	8.06761
800	9.45359
2000	10.3698
8000	11.7561
20000	12.6724
80000	14.0588

200000	14.9751
800000	16.3615

TIPS

To save time, you can copy the values of time and displacement from the table shown above and paste them into AQTESOLV for Windows using the **Paste** button.

4. When you have finished entering the observations, click **OK**.

After you have completed the previous data entry steps, the **Error Log** displayed in the active window should show that the data set contains no errors. Now you are ready to display the data, choose a solution and estimate aquifer properties.

Save Data Set

Choose **Save As...** from the **File** menu to save the data you have entered into the current data set.

1. Enter **GRINV1.AQT** for the file name.
2. Click **OK** to save the data set.

Change View in Window

Choose **Displacement-Time** from the **View** menu to display a plot of displacement vs. time in the active window. The window displays a plot of the observation well data on semi-log axes.

Choose Gringarten-Witherspoon Solution

Change the aquifer model and solution by choosing **Solution...** from the **Match** menu to choose a solution for analyzing a pumping test in a fractured aquifer.

1. Choose the **Fractured Gringarten-Witherspoon (1972) w/ vertical fracture** solution.
2. Click **OK**.

After you have selected the Gringarten-Witherspoon solution for a pumping test in a fractured aquifer, AQTESOLV for Windows updates the window by superimposing a Gringarten-Witherspoon type curve on the plot and displaying values of hydraulic conductivity (K_x), specific storage (S_s), anisotropy ration (K_y/K_x) and fracture length (L_f) in the legend.

Perform Automatic Matching with Gringarten-Witherspoon

Choose **Automatic...** from the **Match** menu to perform automatic matching using the Gringarten-Witherspoon type curve solution.

1. In the **Estimation** tab, change the **Maximum** number of iterations to **100**.
2. In the **Parameters** tab, set **Estimation of K_y/K_x** to **Inactive**.
3. Click **Estimate** to begin automatic estimation.
4. As the automatic estimation procedure completes iterations, a progress window displays the changes in the residual sum of squares (RSS) criterion and the values of the aquifer properties. After the automatic estimation procedure finishes, AQTESOLV for Windows displays a message box containing residual summary statistics. Click **OK** to close the message box.

- Click the **Close** button to close the progress window and click **OK** to finish.

The plot shown in the active window displays the values of hydraulic conductivity ($K_x=2.5E-7$), specific storage ($S_s=2.5E-7$), anisotropy ratio ($K_y/K_x=1$) and fracture length ($L_f=2$) determined by automatic estimation.

Change View to Linear Flow Plot

Choose **Linear Flow** from the **View** menu to display a linear flow plot in the active window.

- Early-time data exhibiting a unit slope on this plot are indicative of linear flow conditions to a single fracture with infinite conductivity or uniform flux along the fracture.
- Choose **Visual** from the **Match** menu to match a line with unit slope to the early-time data.
- Click a point over the early-time data where you want to draw a line with unit slope.

Save Data Set

Choose **Save** from the **File** menu to save your work in the **GRINV1.AQT** data set.

Gringarten-Ramey (1974) Solution for a Pumping Test in a Fractured Aquifer with a Plane Horizontal Fracture

Gringarten and Ramey (1974) derived an analytical solution for flow to a well in a confined infinite radial system intersecting a single plane horizontal fracture. The solution assumes uniform flux along the fracture.

The following equation predicts drawdown in a piezometer:

$$s = \frac{Q}{4\pi\sqrt{K_r K_z}} \frac{2}{H_D} \int_0^{t_D} P \cdot Z \frac{d\tau}{\tau}$$

where:

$$t_D = \frac{K_r t}{S_s r_f^2}$$

$$P = e^{-\frac{r_D^2}{4\tau}} \int_0^1 I_0\left(\frac{r_D v}{2\tau}\right) e^{-\frac{v^2}{4\tau}} v dv$$

$$Z = 1 + 2 \sum_{n=1}^{\infty} e^{-\frac{n^2 \pi^2 \tau}{H_D^2}} \cos n\pi \frac{Z_f}{H} \cos n\pi \frac{Z}{H}$$

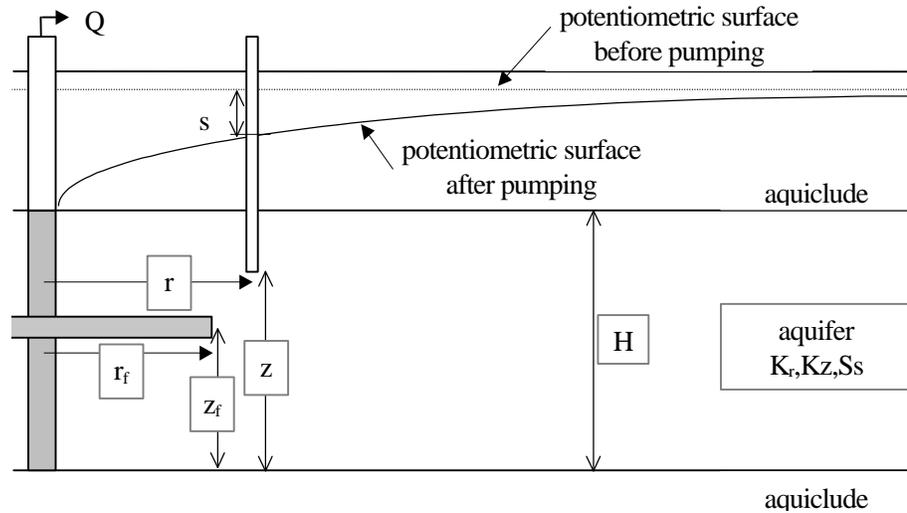
$$H_D = \frac{H}{r_f} \sqrt{K_r / K_z}$$

$$r_D = \frac{r}{r_f}$$

The Gringarten-Ramey solution only supports piezometers, not observation wells.

AQTESOLV for Windows allows you to analyze both constant- and variable-rate pumping tests using the Gringarten-Ramey solution. For tests with a variable discharge rate, the program uses the principle of superposition to compute drawdown in the aquifer. For more information concerning the application of the principle of superposition in variable-rate pumping tests, refer to the "Theis (1935) Solution for a Pumping Test in a Confined Aquifer" on page 54.

Refer to the "List of Symbols" on page 157 for a description of the parameters and variables contained in the equations.



Assumptions

- aquifer has infinite areal extent
- aquifer has uniform thickness
- aquifer potentiometric surface is initially horizontal
- pumping well is fully penetrating
- fractured aquifer represented by anisotropic system with a single plane horizontal fracture
- flow is unsteady
- water is released instantaneously from storage with decline of hydraulic head
- diameter of pumping well is very small so that storage in the well can be neglected

Data Requirements

- pumping and observation well locations
- pumping rate(s)
- piezometer measurements (time and displacement)
- saturated thickness of aquifer

- radius of horizontal fracture

Solution Options

- variable pumping rate
- multiple pumping wells
- multiple observation wells

Visual Curve Matching Tips

- Choose **Visual** from the **Match** menu to perform visual curve matching using the procedure described in "Visual Matching With Type Curve Solutions" on page 165.
- Use **Active Type Curves** for more effective visual matching with variable-rate pumping tests (see "Active Type Curves" on page 167).
- Choose **Linear Flow** from the **View** menu to help identify the presence of linear flow conditions (see "Linear Flow Plot" on page 42).
- Select values of Kz/Kr from the **Family** and **Curve** lists on the toolbar.
- Use **Parameter Tweaking** to perform visual curve matching and sensitivity analysis (see "Tweak Tab (Match>Toolbox)" on page 169).

Reference

Gringarten, A.C. and H.J. Ramey, 1974. Unsteady state pressure distributions created by a well with a single horizontal fracture, partial penetration or restricted entry, Soc. Petrol. Engrs. J., pp. 413-426.

Tutorial

In this tutorial, you will use automatic curve matching and the Gringarten-Ramey type curve solution for fractured aquifers to match drawdown data measured in the pumped well during a constant-rate pumping test.

Please visit <http://www.aqtesolv.com/examples/> for additional tutorials and sample data sets.

Open a New Data Set

Open a new data set by choosing **New** from the **File** menu. In the **New Data Set** dialog box, choose **Tutorial** in the list box and click **OK** to initialize the new data set with default values. AQTESOLV for Windows opens a new window with an Error Log view that reports any errors identified in the data set.

Enter Data for Pumping Test

Choose **Units...** from the **Edit** menu to select units of measurement for the data set.

1. Select **ft** (feet) for **Length**, **min** (minutes) for **Time**, **consistent** for **Pumping Rate** and **consistent** for **Hyd. Conductivity**.
2. Click **OK**.

Choose **Annotations...** from the **Edit** menu to edit the data set title.

1. In the **Title** tab, enter **Horizontal Fracture with Uniform Flux** for the **Title**.
2. Click **OK**.

Choose **Aquifer Data...** from the **Edit** menu to edit aquifer data.

1. In the **General** tab, enter **1.0** for the value of **Saturated Thickness**.
2. In the **Single Fracture** tab, enter **1.0** for the **Radius of the Horizontal Fracture** and **0.5** for the **Depth of the Horizontal Fracture**.
3. Click **OK**.

Choose **Pumping Well>Edit...** from the **Edit** menu to edit pumping well data.

1. In the **General** tab, enter values of **0.0** for the **X-Coordinate** and **0.0** for the **Y-Coordinate** locations of the well.
2. In the **Construction** tab, enter **0.001** and **0.001** for the **Casing Radius** and **Wellbore Radius**, respectively. For this solution, which assumes an infinitesimal well radius, we enter small values for the casing and wellbore radius to calculate displacement in the pumped well.
3. In the **Rates** tab, enter values of **0.0** and **3.14159e-6** for time and rate, respectively, where time is in minutes and rate is in cubic feet per minute.
4. Click **OK**.

Choose **Obs. Well>Edit...** from the **Edit** menu to edit observation data for the pumped well.

1. In the **General** tab, enter the same coordinate values as the pumped well, i.e., **0.0** for the **X-Coordinate** and **0.0** for the **Y-Coordinate**.
2. In the **Construction** tab, select the **Piezometer** option and enter a piezometer depth **z** of **0.5**.
3. In the **Observations** tab, click the **Import** button to import observation well measurements from a delimited text file using the **Observation Data Import Wizard**. In Step 1 of the **Import Wizard**, enter **GRINH1.DAT** for the name of the import file. The file GRINH1.DAT contains time and displacement data arranged in two columns separated by a tab delimiter. Click **Next**.
4. In Step 2 of the **Import Wizard**, enter data describing the structure of the import file. The **Import Wizard** automatically determines that the import file contains 2 columns of data. Enter **1** for the **Elapsed Time** column and **2** for the **Displacement** column. Click **Next**.
5. In Step 3 of the **Import Wizard**, choose transformation and filter options for the data contained in the import file. Retain the default settings, and click **Finish**.
6. After AQTESOLV for Windows has finished importing the data, a message box displays the number of observations imported from the file. Click **OK**.
7. Click **OK**.

After you have completed the previous data entry steps, the **Error Log** displayed in the active window should show that the data set contains no errors. Now you are ready to display the data, choose a solution and estimate aquifer properties.

Save Data Set

Choose **Save As...** from the **File** menu to save the data you have entered into the current data set.

1. Enter **GRINH1.AQT** for the file name.
2. Click **OK** to save the data set.

Change View in Window

Choose **Displacement-Time** from the **View** menu to display a plot of displacement vs. time in the active window. The window displays a plot of the observation well data on semi-log axes.

Choose Gringarten-Ramey Solution

Change the aquifer model and solution by choosing **Solution...** from the **Match** menu to choose a solution for analyzing a pumping test in a fractured aquifer.

1. Choose the **Fractured Gringarten-Ramey (1974) w/ horizontal fracture** solution.
2. Click **OK**.

After you have selected the Gringarten-Ramey solution for a pumping test in a fractured aquifer, AQTESOLV for Windows updates the window by superimposing a Gringarten-Ramey type curve on the plot and displaying values of hydraulic conductivity (K_r), specific storage (S_s), anisotropy ration (K_z/K_r) and fracture radius (R_f) in the legend.

Perform Automatic Matching with Gringarten-Ramey

Choose **Automatic...** from the **Match** menu to perform automatic matching using the Gringarten-Ramey type curve solution.

1. In the **Estimation** tab, change the **Maximum** number of iterations to **100**.
2. In the **Parameters** tab, change the **Minimum** and **Maximum** constraints for **Ss** to **1.0e-10** and **1.0e-4**, respectively.
3. Set **Estimation** of **Kz/Kr** to **Inactive**.
4. Click **Estimate** to begin automatic estimation.
5. As the automatic estimation procedure completes iterations, a progress window displays the changes in the residual sum of squares (RSS) criterion and the values of the aquifer properties. After the automatic estimation procedure finishes, AQTESOLV for Windows displays a message box containing residual summary statistics. Click **OK** to close the message box.
6. Click the **Close** button to close the progress window and click **OK** to finish.

The plot shown in the active window displays the values of hydraulic conductivity ($K_r=2.499E-7$), specific storage ($S_s=2.499E-7$), anisotropy ratio ($K_z/K_r=1$) and fracture radius ($R_f=1$) determined by automatic estimation.

Save Data Set

Choose **Save** from the **File** menu to save your work in the **GRINH1.AQT** data set.

List of Symbols

a = constant defining variation in thickness of wedge - shaped aquifer [L^{-1}]
 b = thickness of aquifer [L]
 b_0 = thickness of aquifer at pumping well [L]
 b_s = thickness of fracture skin [L]
 b' = thickness of aquitard overlying aquifer in leaky system or
 one - half thickness of blocks in fissured system [L]
 b'' = thickness of aquitard underlying aquifer [L]
 B = leakage factor [L^{-1}]
 $B(r_e, t)$ = linear head - loss coefficient [T/L^2]
 $B_1(r_w, t)$ = linear aquifer - loss coefficient [T/L^2]
 B_2 = linear well - loss coefficient [T/L^2]
 C = nonlinear well - loss coefficient [T^2/L^5]
 C_D = dimensionless damping factor
 d_D = vertical distance between top of perforations in pumping
 well and initial position of water table divided by initial
 saturated thickness of aquifer [L]
 H = static height of water in well measured from base of well
 to static water level [L]
 H_0 = initial displacement in well due to slug injection or extraction [L]
 J_0 = Bessel function of first kind, zero order
 J_1 = Bessel function of first kind, first order

K = hydraulic conductivity of fractures in fissured system [L/T]
 K_0 = modified Bessel function of second kind, zero order
 K_1 = modified Bessel function of second kind, first order
 K_r = radial (horizontal) hydraulic conductivity of aquifer [L/T]
 K_s = hydraulic conductivity of fracture skin [L/T]
 K_z = vertical hydraulic conductivity of aquifer [L/T]
 K' = hydraulic conductivity of aquitard overlying aquifer in
leaky system or block system in fissured system [L/T]
 K'' = hydraulic conductivity of aquitard underlying
aquifer [L/T]
 l_D = vertical distance between bottom of perforations in
pumping well and initial position of water table divided by
initial saturated thickness of aquifer [L]
 L = length of well screen [L]
 p = Laplace transform variable
 P = order of nonlinear well - losses [dimensionless]
 Q = pumping rate [L³ / T]
 r = radial distance [L]
 r_c = well casing radius [L]
 r_e = equivalent radius over which head loss occurs [L]
 r_w = well radius [L]

s = displacement [L]
 s_t = displacement at time t [L]
 s_0 = initial displacement in well [L]
 S = coefficient of storage of aquifer [dimensionless]
 S_f = fracture skin [dimensionless]
 S_s = specific storage of aquifer or fractures in fissured system [L^{-1}]
 S'_s = specific storage of aquitard in leaky system or blocks in fissured system [L^{-1}]
 S_w = wellbore skin [dimensionless]
 S_y = specific yield of aquifer [dimensionless]
 S' = coefficient of storage of aquitard overlying aquifer [dimensionless]
 S'' = coefficient of storage of aquitard underlying aquifer [dimensionless]
 t = time since pumping began [T]
 t_s = dimensionless time with respect to S_s equal to Tt / Sr^2 [T]
 t_y = dimensionless time with respect to S_y equal to $Tt / S_y r^2$ [T]
 T = transmissivity [L^2 / T]
 x_0 = x - coordinate location of pumping well [L]
 y = variable of integration
 y_0 = y - coordinate location of pumping well [L]
 Y_0 = Bessel function of second kind, zero order
 Y_1 = Bessel function of the second kind, first order
 z_D = vertical distance above bottom of aquifer divided by initial saturated thickness of aquifer [L]
 z_{1D} = vertical distance from bottom of aquifer to bottom of observation well perforations divided by initial saturated thickness of aquifer [L]
 z_{2D} = vertical distance from bottom of aquifer to top of observation well perforations divided by initial saturated thickness of aquifer [L]

Estimating Aquifer Coefficients

Overview

The **Match** menu provides two methods for estimating the hydraulic properties of aquifers from pumping tests and slug tests. Each method matches analytical solutions to data measured during an aquifer test.

- **Visual matching** is analogous to traditional graphical methods that rely on manually fitting type curves or straight lines to determine aquifer parameters.
- **Automatic matching** uses nonlinear least-squares parameter estimation to automatically fit analytical solutions to aquifer test data.

Whichever method you choose, AQTESOLV for Windows allows you to visualize the results of your analysis by plotting the solution and data. In addition, the automatic curve matching technique provides statistical measures of the "fit" of the solution to the data.

Automatic Curve Matching

Click  on the toolbar to perform automatic curve matching

Choose **Automatic...** from the **Match** menu to open a dialog for estimating hydraulic properties using automatic curve matching. The automatic parameter estimation procedure systematically adjusts the values of hydraulic properties to achieve the best statistical match between a solution (type curve) and the test data.

The automatic curve matching feature in AQTESOLV for Windows uses a nonlinear least squares procedure to match a type curve or straight-line solution to your data. The iterative procedure minimizes the "residuals" or errors between the computed and the observed drawdown or displacement.

Performing Automatic Estimation

1. Choose **Automatic...** from the **Match** menu.
2. Click **Estimate** to start automatic estimation.
3. A window appears that displays the progress of automatic estimation. Click **Abort** to halt the iterations.
4. When automatic estimation is complete, a message appears with convergence information and residual statistics.

TIPS

1. Prior to attempting automatic curve matching, perform visual curve matching to improve the initial estimates of the aquifer properties.
2. Generally, you should maintain the tolerances for RSS and parameter change at small values (e.g., 1×10^{-10} 1.0E-10); however, for certain solutions, changing the maximum number of iterations is helpful. For example, if automatic curve matching converges slowly, try increasing the maximum number of iterations.

TIPS FOR NEUMAN (1974) SOLUTION

1. Perform visual curve matching with Quick Neuman to determine initial estimates of hydraulic properties.
2. Perform automatic curve matching with Quick Neuman to refine the parameter estimates.
3. In most cases, the parameter estimates determined using Quick Neuman are sufficiently accurate; however, if desired, you can further refine the parameter estimates by changing the solution method to Neuman (1974) and performing automatic estimation.

Estimation Tab (Match>Automatic)

Choose **Automatic...** from the **Match** menu and click the **Estimation** tab to set options controlling parameter estimation.

Iterations

1. Enter the **Maximum** number of iterations to perform using automatic curve matching.
2. The automatic curve matching procedure terminates when the maximum number of iterations is reached (or when convergence criteria are met).

Convergence Criteria

1. Enter the **RSS** (residual sum of squares) convergence criterion. Automatic curve matching terminates when the residual sum of squares reaches this tolerance value.
2. Enter the **Parameter Change** (in percent) convergence criterion. Automatic curve matching terminates when the maximum percent change in parameter values reaches this tolerance value.
3. The automatic curve matching procedure terminates when either convergence criterion is met (or when the maximum number of iterations is reached).

Display Options

1. Check the **Intermediate updates** box if you want AQTESOLV for Windows to update the type curve position after each automatic curve matching iteration.
2. Check the **Activity indicator** box if you want AQTESOLV for Windows to display a flashing green lamp while automatic curve matching is in progress.

Parameters Tab (Match>Automatic)

Choose **Automatic...** from the **Match** menu and click the **Parameters** tab to enter values, minimum and maximum (lower and upper) bounds, and active/inactive status for aquifer parameters (see "Parameters Tab (Match>Toolbox)" on page 169).

Active Wells Tab (Match>Automatic)

Choose **Automatic...** from the **Match** menu and click the **Active Wells** tab to select observation wells to match during automatic estimation.

Observation Well To Match

1. Place a check next to observation wells that you want to match during automatic curve matching. Removing a check excludes the well from automatic estimation.
2. You must select at least one well in the list.

Options Tab (Match>Automatic)

Choose **Automatic...** from the **Match** menu and click the **Options** tab to configure options controlling partial penetration and multiple well calculations (see "Options Tab (Match>Toolbox)" on page 170).

How Automatic Curve Matching Works

AQTESOLV for Windows performs nonlinear weighted least-squares parameter estimation (automatic curve matching) using the Gauss-Newton linearization method. To improve the convergence of the method from poor initial guesses for the unknown parameters, AQTESOLV for Windows includes the Marquardt correction factor (Marquardt, 1963).

In the Gauss-Newton method of parameter estimation, the parameter corrections necessary to minimize the difference between observed and estimated values of the response variable can be expressed as a Taylor series expanded about the current estimated value as follows:

$$y_i = \hat{y} + \frac{\partial y}{\partial b} \Delta b + \frac{\partial^2 y}{2! \partial b^2} (\Delta b)^2 + \frac{\partial^3 y}{3! \partial b^3} (\Delta b)^3 \dots$$

where:

- y_i = ith observed value of response variable
- \hat{y}_i = estimate of the ith value of response variable
- Δb = parameter correction, $\hat{b}^1 - \hat{b}^0$
- \hat{b}^1 = updated estimate of the unknown parameter
- \hat{b}^0 = current estimate of the unknown parameter

The previous equation can be linearized by truncating the Taylor series after the first derivative as follows:

$$y_i \approx \hat{y}_i + \frac{\partial y}{\partial b} \Delta b$$

Thus, for p unknown parameters, the general linearized equation for computing parameter corrections is written as follows:

$$y_i \approx \hat{y}_i + \sum_{k=1}^p \frac{\partial y_i}{\partial b_k} \Delta b_k$$

The previous equation is written for each observed value of the response variable. The partial derivatives of the response variable with respect to the unknown parameters are known as sensitivity coefficients. The resulting system of linearized equations is solved iteratively until convergence is obtained. The objective function for this minimization problem is the sum of the squared residuals given by the following expression:

$$RSS = \sum_{i=1}^n (y_i - \hat{y}_i)^2$$

where n is the total number of observed values of the response variable. In matrix form, the Gauss-Newton method computes parameter correction as follows:

$$\Delta B = (X^T X)^{-1} X^T \Delta Y$$

where:

- $\Delta B = p \times 1$ vector of parameter corrections
- $X = n \times p$ matrix of sensitivity coefficients
- $X^T = p \times n$ transpose of X
- $X^T X = p \times p$ variance - covariance matrix
- $\Delta Y = n \times 1$ vector of residuals $(y_i - \hat{y}_i)$

To improve the conditioning of the variance-covariance matrix, AQTESOLV for Windows adds the Marquardt correction factor to the previous equation:

$$\Delta B = (X^T X + I \cdot \lambda)^{-1} X^T \Delta Y$$

where:

- $I =$ Marquardt correction factor
- $I =$ identity matrix

The Marquardt correction factor is added when parameter corrections computed by the Gauss-Newton method fail to reduce the residual sum of squares (RSS). Iterations performed with the Marquardt correction factor start with a sufficiently small value of λ ; larger values of λ are added until the RSS is reduced. The parameter estimation algorithm terminates when the RSS is minimized.

Weighted least-squares estimation is accomplished as follows:

$$\Delta B = (X^T W X)^{-1} X^T W \Delta Y$$

where:

- $W = n \times n$ nonsingular symmetric matrix obtained from $w^T w$
- $w = n \times n$ diagonal matrix of weights

Thus, in this implementation of the weighted least-squares algorithm, a larger weight assigned to a measurement results in greater influence by that measurement in the parameter estimation procedure.

Visual Curve Matching

Click  on the toolbar to perform *visual curve matching*

Choose **Visual** from the **Match** menu to perform visual curve matching. By selecting this option, you can interactively match pumping test and slug test solutions to your data or perform diagnostic analyses to evaluate specific flow conditions and regimes.

With **displacement vs. time, composite** or **residual drawdown** plots, use the **Visual** option to match pumping test and slug test solutions to aquifer test data.

With **diagnostic** plots (**radial flow, linear flow, bilinear flow** or **spherical flow**), use the **Visual** option to identify periods of specific flow conditions such as radial flow, wellbore storage, fracture flow or spherical flow.

AQTESOLV for Windows also provides an option for performing visual curve matching with **derivative vs. time** plots.

Visual Matching (Displacement-Time, Composite and Residual Drawdown Plots)

On **displacement vs. time, composite** or **residual drawdown** plots, choose **Visual** from the **Match** menu to match analytical solutions for pumping tests and slug tests to aquifer test data.

The procedure for visual curve matching differs according to whether you are matching a **type curve solution** (e.g., Theis), a **straight-line solution** (e.g., Cooper-Jacob or Bouwer-Rice) or a **damped sinusoidal solution** (e.g., Springer-Gelhar).

You also can match curves to displacement data and derivative data at the same time on a **Displacement-Time** or **Composite** plot (see "Plots Tab (View>Options)" on page 44).

Visual Matching With Type Curve Solutions

1. Choose **Visual** from the **Match** menu.
2. Click and hold the left mouse button down within the plot area.
3. Move the mouse to match the type curve to your data. As you move the type curve, AQTESOLV for Windows automatically updates the plot legend to reflect changes in parameter values.
4. Release the left mouse button when you have finished matching the type curve.

Visual Matching With Straight-Line Solutions

1. Choose **Visual** from the **Match** menu.
2. Move the mouse to a point located on the new line you wish to match to your data.
3. Click and hold down the left mouse button to anchor the new line at this point.
4. Move the mouse to match a new straight line to your data. As you move the mouse, AQTESOLV for Windows drags a straight line between the anchor point and the position of the mouse.

5. Release the left mouse button when you have finished matching a new straight line. AQTESOLV for Windows automatically updates the plot legend to reflect changes in parameter values.

Visual Matching With Oscillatory (Damped Sinusoidal) Solutions

1. Choose **Visual** from the **Match** menu.
2. Click **Active Type Curves** on the toolbar (recommended).
3. Click and hold the left mouse button down within the plot area.
4. Move the mouse up and down to adjust the amplitude of the solution.
5. Move the mouse left and right to adjust the period of the curve.
6. Release the left mouse button when you have finished matching the curve. AQTESOLV for Windows automatically updates the plot legend to reflect changes in parameter values.

Visual Matching (Diagnostic Plots)

Data exhibiting a unit slope on certain diagnostic plots are indicative of particular flow conditions such as wellbore storage, fracture flow and spherical flow. Use visual curve matching with the diagnostic plots to identify these flow conditions by testing for the presence of a unit slope.

Visual Matching With Radial Flow Plots

1. Early-time data on log-log axes exhibiting a **unit slope** are indicative of **wellbore storage**.
2. Choose **Log Axes** from the **View** menu.
3. Choose **Visual** from the **Match** menu to match a line with a fixed unit slope to the early-time data.
4. Click a point over the data where you want to position the line with a fixed unit slope.

Visual Matching With Linear Flow Plots

1. Early-time data on log-log axes exhibiting a **unit slope** are indicative of **linear flow conditions** to a single fracture with infinite conductivity or uniform flux along the fracture.
2. Choose **Log Axes** from the **View** menu.
3. Choose **Visual** from the **Match** menu to match a line with a fixed unit slope to the early-time data.
4. Click a point over the data where you want to position the line with a fixed unit slope.

Visual Matching With Bilinear Flow Plots

1. Early-time data on log-log axes exhibiting a **unit slope** are indicative of **bilinear flow conditions** to a single fracture with finite conductivity.

2. Choose **Log Axes** from the **View** menu.
3. Choose **Visual** from the **Match** menu to match a line with a fixed unit slope to the early-time data.
4. Click a point over the data where you want to position the line with a fixed unit slope.

Visual Matching With Spherical Flow Plots

1. Early-time data on log-log axes exhibiting a **unit slope** are indicative of **spherical flow conditions**.
2. Choose **Log Axes** from the **View** menu.
3. Choose **Visual** from the **Match** menu to match a line with a fixed unit slope to the early-time data.
4. Click a point over the data where you want to position the line with a fixed unit slope.

Visual Matching (Derivative Plots)

Perform visual curve matching with derivative plots using the visual curve matching tools feature.

1. Choose **Toolbox...** from the **Match** menu and click the **Tweak** tab.
2. Select an aquifer parameter to adjust from the **Parameter** list.
3. Change the value of the selected aquifer parameter using the scroll bar control.
4. Click the **Apply** button to update type curve plots.
5. Check the **Apply changes automatically** box to update type curve plots automatically for each change.

Alternatively, you can match curves to displacement data and derivative data at the same time on a **Displacement-Time** or **Composite** plot (see "Plots Tab (View>Options)" on page 44).

Active Type Curves

Click  on the toolbar to perform visual curve matching with active type curves

AQTESOLV for Windows lets you perform visual curve matching with static or active type curves.

The **Active Type Curves** feature is an enhanced method of performing visual curve matching introduced by AQTESOLV for Windows. With active type curves, AQTESOLV for Windows automatically refreshes the complete type curve as you perform visual curve matching.

1. Choose **Toolbox...** from the **Match** menu and click the **Options** tab to check the **Active type curves** box.
2. The **Active Curves** button on the toolbar toggles the active type curves feature and simultaneously initiates visual curve matching.

TIPS

Apply **Active Type Curves** for effective visual curve matching in the following situations:

1. For **pumping tests** with variable pumping rates or solutions with early- and late-time response such as delayed gravity response or double porosity effects (see "Matching Early/Late Data" on page 168)
2. For **slug tests** with oscillatory response (i.e., solutions with inertial effects in high-K aquifers)

Matching Early/Late Data

Click **A** or **B** on the toolbar to perform visual curve matching to **early data (Type A)** or **late data (Type B)**

Certain aquifer test solutions involve aquifer parameters that only affect early and late data. AQTESOLV for Windows lets you choose the range of data to match during visual curve matching.

The **Active Type Curves** feature is an enhanced method of performing visual curve matching introduced by AQTESOLV for Windows. With active type curves, AQTESOLV for Windows automatically refreshes the complete type curve as you perform visual curve matching.

For example, the Neuman (1974) solution for a pumping test in an unconfined aquifer involves matching Type A curves to early data and Type B curves to late data. The final match of the Type A curve determines the values of T, S and β beta and the Type B curve determines T, S_y and β beta.

Match early data

1. Choose **Toolbox...** from the **Match** menu and click the **Options** tab to select the **Match early data (Type A)** option.
2. The **Match Early Data** button on the toolbar toggles the match early data (Type A) option and simultaneously invokes visual curve matching.

Match late data

1. Choose **Toolbox...** from the **Match** menu and click the **Options** tab to select the **Match late data (Type B)** option.
2. The **Match Late Data** button on the toolbar toggles the match late data (Type B) option and simultaneously invokes visual curve matching.

Solutions that allow you to perform visual matching to early and late data include the following:

1. Neuman (1974) pumping test solution for unconfined aquifers,
2. Quick Neuman pumping test solution for unconfined aquifers,
3. Neuman-Witherspoon (1969) pumping test solution for leaky aquifers,
4. Moench (1984) pumping test solution for fractured aquifers with slab-shaped blocks, and
5. Moench (1984) pumping test solution for fractured aquifers with spherical blocks.

Matching Type Curve Families

If type curve families are available for the active solution, you can select the aquifer parameter for the type curve family and its value from **Family** and **Curve** lists on the toolbar.

Selecting New Type Curve From Family

1. Select an aquifer parameter for a type curve family from those available in the **Family** list on the toolbar.
2. Select a value for the aquifer parameter from the **Curve** list on the toolbar.
3. To change the values shown in the **Curve** list, choose **Options...** from the **View** menu and click the **Family** tab.
4. The controls for the **Family** and **Curve** lists appear inactive when type curve families are not available for the active solution.

Toolbox for Curve Matching

Click  on the toolbar to activate curve matching tools and options

Choose **Toolbox...** from the **Match** menu to view a suite of curve matching tools and options. The toolbox allows you to tweak individual aquifer parameters, perform sensitivity analysis, edit parameters and select visual curve matching/solution options.

Tweak Tab (Match>Toolbox)

Choose **Toolbox...** from the **Match** menu and click the **Tweak** tab to adjust the values of individual aquifer parameters. This tool provides a useful option for visual curve matching and also for sensitivity analysis.

Tweak Parameters

1. Select an aquifer parameter to adjust from the **Parameter** list.
2. Change the value of the selected aquifer parameter using the scroll bar control.
3. Click the **Apply** button to update type curve plots.
4. Check the **Apply changes automatically** box to update type curve plots automatically for each change.

Parameters Tab (Match>Toolbox)

Choose **Toolbox...** from the **Match** menu and click the **Parameters** tab to enter values, minimum and maximum (lower and upper) bounds, and active/inactive status for aquifer parameters.

Parameter Column

1. The **Parameter** column lists the aquifer parameters estimated for the active solution.
2. Units for each parameter (if any) are shown with the parameter symbol.

Value Column

1. The **Value** column contains current estimates of the aquifer parameters in the solution.
2. Enter new values to change the starting guesses used by the automatic curve matching procedure for each aquifer parameter.

Minimum Column

1. The **Minimum** column contains the minimum (lower) bounds used to constrain the aquifer parameters during automatic curve matching.
2. Enter new values to change the feasibility ranges for each aquifer parameter. The automatic curve matching procedure constrains the estimated value of each aquifer parameter to the feasibility range defined by the **Minimum** and **Maximum** bounds.

Maximum Column

1. The **Maximum** column contains the maximum (upper) bounds used to constrain the aquifer parameters during automatic curve matching.
2. Enter new values to change the feasibility ranges for each aquifer parameter. The automatic curve matching procedure constrains the estimated value of each aquifer parameter to the feasibility range defined by the **Minimum** and **Maximum** bounds.

Estimation Column

1. The **Estimation** column identifies the estimation status (active or inactive) for each aquifer parameter.
2. Choose whether the aquifer parameters are free to change (active) or not (inactive) during automatic curve matching.

Restoring a Set of Parameter Values

1. Click **Automatic** to set parameter estimates to values determined most recently from automatic curve matching.
2. Click **Visual** to set parameter values to their visual curve matching estimates.
3. Click **Current** to reset the parameters to their current values.

Options Tab (Match>Toolbox)

Choose **Toolbox...** from the **Match** menu and click the **Options** tab to configure visual matching and solution options.

Visual Matching

1. Check the **Active type curves** box to perform visual curve matching with active type curves.
2. Check the **Use standard axes** box to perform visual curve matching using standard axes for the active solution. For example, with this option selected, AQTESOLV for Windows will automatically switch to standard log-log axes when you invoke visual curve matching using the Theis solution.
3. Select the **Match early data (Type A)** option to perform visual matching to early data.
4. Select the **Match late data (Type B)** option to perform visual matching to late data.

5. The **Match Early Data** and **Match Late Data** buttons on the toolbar toggle the options for matching early (Type A) or late (Type B) data and simultaneously invoke visual curve matching.

Solution

1. Check the **Partial penetration** box if you want AQTESOLV for Windows to include partial penetration in the calculations for the active solution.

This option appears inactive (grayed out) if all wells in the data set are fully penetrating or if the active solution does not support partial penetration.

2. Check the **Multiple wells** box if you want AQTESOLV for Windows to include multiple pumping wells (including image wells) in the calculations for the active solution.

This option appears inactive (grayed out) if the data set only includes one pumping well or if the active solution does not support multiple pumping wells.

3. Select a **convergence level** to optimize speed and accuracy for the active solution. Choose a lower level for faster computations during preliminary estimation and a higher level, if necessary, for higher accuracy in research applications and final results.

The list of options appears inactive (grayed out) if the active solution method only has one convergence setting.

Obtaining Output

Overview

AQTESOLV for Windows has many options for obtaining output from the program. First, you can print plots and reports on output devices connected to your computer. Second, you can export data from the program to files for use by other software. Finally, you can copy plots and reports to the clipboard.

Printing Options

The **File** menu provides options for obtaining printer output from AQTESOLV for Windows. The options allow you to print plots and reports, preview the printed appearance of plots and reports prior to printing, and configure a printer connected to your computer.

Click  on the toolbar to open the Print dialog box

Print

Choose **Print...** from the **File** menu to open a dialog box for printing the plot or report in the active window. Click the **Setup...** button to select a specific printer.

Click  on the toolbar for Print Preview

Print Preview

Choose **Print Preview** from the **File** menu to preview the appearance of a plot or report prior to printing. While previewing, click the **Print...** button to print the plot or report or click the **Close** button to end print preview without printing.

Print Setup

Choose **Print Setup...** from the **File** menu to open a dialog box for choosing the specific printer connected to your computer, selecting paper size and orientation, and setting printer options.

Page Setup

Choose **Page Setup...** from the **File** menu to configure the printing of report headers and footers.

Margins Tab (File>Page Setup)

Enter values (in inches) for the margins of printed pages of reports and plots.

Print Tab (File>Page Setup)

Select options to customize the printing of plots and reports.

Troubleshooting (Printing)

Y-Axis Label Printed Horizontally

If you encounter difficulties printing the y-axis label of a plot, perform each of the following steps in succession to remedy the problem.

1. Choose **Print Setup...** from the **File** menu and check that the settings are correct. Make sure you are using the correct driver for your printer.
2. Choose **Print Setup...** from the **File** menu and go to **Properties**. Select **print graphics in raster mode** option, if available.
3. Choose **Print Setup...** from the **File** menu and go to **Properties**. Select **print True Type fonts as graphics** option, if available.
4. Choose **Page Setup...** from the **File** menu and click **Print** tab to override font rotation for the y-axis label.

Plot Legend Exceeds Page Size

If the legend beneath a plot exceeds the page size, choose **Format...** from the **View** menu and click the Legend tab to perform one or more of the following remedies to decrease the size of the legend.

1. Click the **Font...** button to select a smaller font size.
2. In the group of **Printer Options**, deactivate one or more of the text blocks displayed in the legend (e.g., **title**, **project info**, **aquifer data** or **well data**).

Plot or Report Output Is Compressed

If the output for a plot or report appears compressed on the output device, attempt the following remedies.

1. Choose **Print Setup...** from the **File** menu and go to **Properties**. Select **print graphics in raster mode** option, if available.
2. Choose **Print Setup...** from the **File** menu and go to **Properties**. Select **print True Type fonts as graphics** option, if available.

Export Options

Choose **Export...** from the **File** menu to select options for exporting data. These options allow you to create files that you can use in other Windows applications.

Export Plot Data

1. Choose **Export...** from the **File** menu.

2. Select **X-Y Plot Data** and click **OK** to export data displayed in the active view to a file.
3. Enter a file name for the exported data and click **OK**.

Export Type Curve

1. Choose **Export...** from the **File** menu.
2. Select **Type Curve** and click **OK** to export type curve data displayed in the active view to a file.
3. Enter a file name for the exported type curve and click **OK**.

Export Windows Metafile

1. Choose **Export...** from the **File** menu.
2. Select **Windows Metafile** or **Enhanced Metafile** and click **OK** to export the active plot or report to a file in Windows metafile format.
3. Enter a file name for the metafile and click **OK**.

Export Grid File

1. Choose **Export...** from the **File** menu.
2. Select **Grid File** and click **OK** to launch the **Grid Wizard** for preparing a grid file in Surfer for Windows format.
3. Follow the steps in the **Grid Wizard** to prepare the grid file and optionally create and display a contour plot using Surfer for Windows (see "Contouring" on page 49).

Clipboard Functions

You can use the Windows clipboard to cut, copy and paste data by right-clicking the mouse and selecting from available options in a context menu.

Copy

Choose **Copy** from the **Edit** menu to copy the current view (plot or report) to the clipboard in Windows metafile format. Use the **Paste** command in another Windows application to insert AQTESOLV for Windows plots and reports into different documents.

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Glossary of Terms

Aquiclude

A saturated geologic unit that is incapable of transmitting significant quantities of water under ordinary hydraulic gradients.

Aquifer

A saturated permeable geologic unit that can transmit significant quantities of water under ordinary hydraulic gradients.

Aquitard

A saturated geologic unit that transmits water in quantities insufficient for economic use.

Casing Radius

Radius of unperforated portion of well casing.

Client Name

A user-supplied character string (up to 30 characters) storing the name of the client which sponsored the aquifer test. Used for reports and plots.

Coefficient of Permeability

See Hydraulic Conductivity.

Company Name

A user-supplied character string (up to 30 characters) storing the name of the company which conducted the aquifer test. Used for reports and plots.

Confined Aquifer

An aquifer with upper and lower boundaries consisting of aquicludes.

Date of Test

A user-supplied character string (up to 30 characters) storing the date of an aquifer test. Used for reports and plots.

Discrete Fractured Aquifer

An aquifer consisting of low-permeability, primary porosity matrix and discrete high-permeability, secondary porosity fissures (e.g., a single vertical or horizontal plane fracture).

Displacement

Change in water level relative to static condition.

Double-Porosity Fractured Aquifer

An aquifer represented by a double porosity system consisting of low-permeability, primary porosity blocks and high-permeability, secondary porosity fissures.

Drawdown

Change in water level relative to static condition due to pumping or slug withdrawal during an aquifer test.

Fracture Skin

A thin, low-permeability material coating the surface of fractures (e.g., mineral deposit) that restricts flow of water.

Fractured Aquifer

See Discrete Fractured Aquifer or Double-Porosity Fractured Aquifer.

Hydraulic Conductivity

The volume of water moving through a unit area of aquifer perpendicular to the direction of flow in unit time under a unit hydraulic gradient.

Leaky Aquifer

An aquifer with upper and lower boundaries of one aquitard and one aquiclude or two aquitards.

Location of Test

A user-supplied character string (up to 30 characters) storing the location of the aquifer test. Used for reports and plots.

Measurement Weight

Use weights to assign the relative weight of each measurement for use during automatic curve matching. In typical cases, assign weights of 1.0 or 0.0 to include or exclude measurements during automatic curve matching.

Observation Well Name

A user-supplied character string (up to 30 characters) storing the name of the observation well used in the aquifer test. Used for reports and plots.

Permeability

See Hydraulic Conductivity.

Piezometer

An open-ended pipe installed in an aquifer to measure hydraulic head at a specific depth.

Porosity

The ratio of void volume to total volume in an unconsolidated material.

Project Number

A user-supplied character string (up to 30 characters) storing the company's number or ID of the aquifer test project. Used for reports and plots.

Residual

The difference between simulated and observed displacement.

Residual Drawdown

See Residual Displacement.

Residual Displacement

Water-level displacement measured from static condition in an observation well after pumping has stopped during the recovery phase of a pumping test.

Saturated Thickness

Vertical distance measured from the top of an aquifer (confining layer or water table) to the base of the aquifer.

Semiconfined Aquifer

See Leaky Aquifer.

Semiconfined Aquifer

See Leaky Aquifer.

Specific Storage

The volume of water released from storage by a unit volume of confined aquifer per unit decline in hydraulic head.

Specific Yield

The volume of water released from storage per unit surface area of an unconfined aquifer per unit decline of the water table.

Status Bar

The horizontal area in AQTESOLV below the plot or report window that provides helpful prompts and status information.

Storage Coefficient

See Storativity.

Storativity

The volume of water released from storage per unit surface area of a confined aquifer per unit decline in hydraulic head.

Test Well Name

A user-supplied character string (up to 30 characters) storing the name of the test well used in an aquifer test.

Transmissivity

Transmissivity is the rate of flow under a unit hydraulic gradient through a cross-section of aquifer having a unit width and full saturated thickness. Also expressed as the product of hydraulic conductivity times saturated thickness.

Unconfined Aquifer

An aquifer with an unrestricted (free) upper boundary and an impermeable lower boundary (aquiclude).

Water Table Aquifer

See Unconfined Aquifer.

Wellbore Radius

Radius of well boring (adjacent to well intake or screen).

Wellbore Skin

A thin, low-permeability deposit on surface of wellbore (e.g., drilling mud) that restricts flow of water.