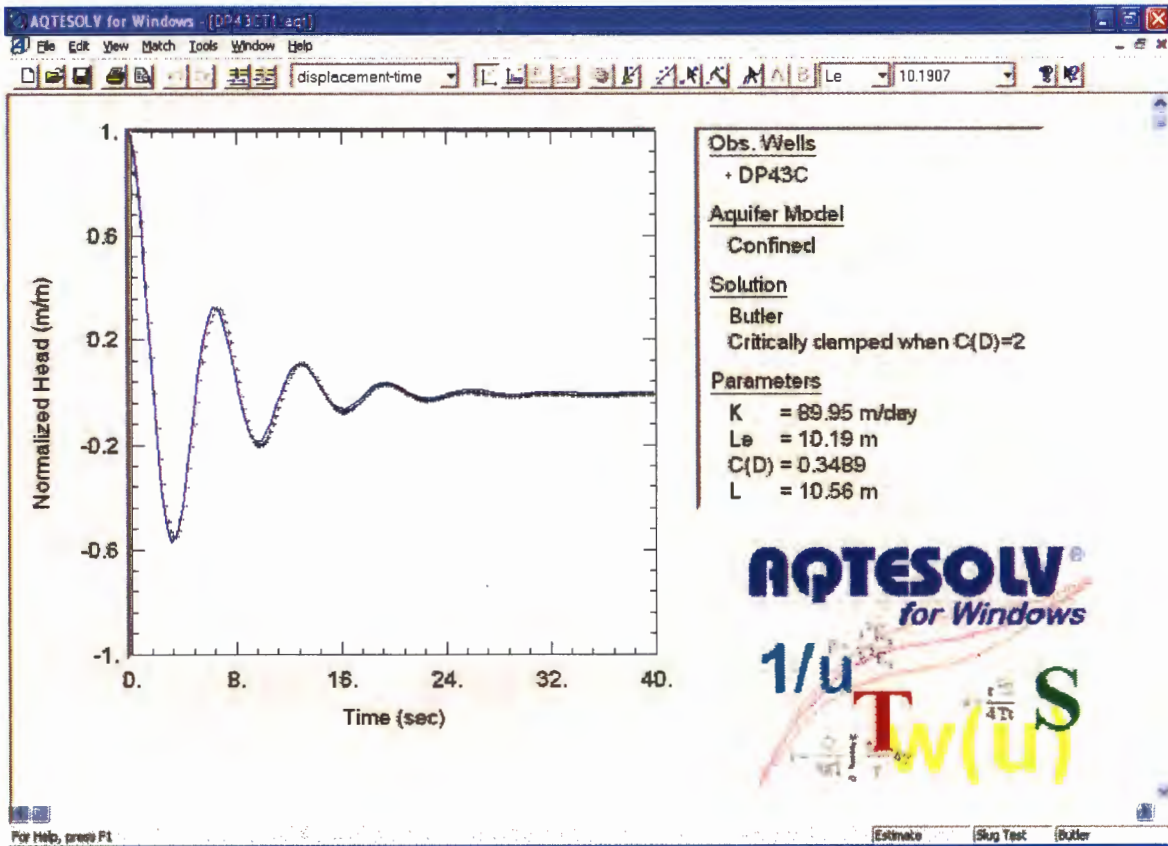# AQTESOLV™ for Windows

Version 4.5
User's Guide

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Introduction

Welcome

AQTESOLV is the world's *leading* software for the analysis of aquifer tests (pumping tests, constant-head tests and slug tests).

AQTESOLV--**AQ**uifer **TE**st **SOLV**er (listen)

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Training
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AQTESOLV for Windows HTML Help (2007.6.16)
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Duffield, G.M., 2007. *AQTESOLV for Windows Version 4.5 User's Guide*, HydroSOLVE, Inc., Reston, VA.

Related Topics

What's New in AQTESOLV

New Features in Version 4.5

1. New Solution for Water-Table Aquifers

   - AQTESOLV now includes a pumping test solution by Tartakovsky and Neuman (2007) that accounts for **three-dimensional saturated and unsaturated flow** in an unconfined aquifer.

2. New Solution for Step-Drawdown Tests

   - Analyze data from a **step-drawdown test in a confined aquifer** using the Jacob-Rorabaugh well-loss equation combined with the Dougherty-Babu (1984) solution.

   - Instead of assuming a line source like the Theis (1935) solution, the Dougherty-Babu solution accounts for **wellbore storage**.

   - Bear (1979, p. 375) discusses how the formation loss term in the well-loss

equation may be represented by any appropriate pumping test solution for a given aquifer type.

New Features in Version 4

1. Constant-Head Tests

   - Analyze **constant-head tests** in confined, leaky and fractured aquifers.

   - Solution methods include options for **wellbore skin** and **fracture skin**.

   - Analyze **recovery data** for constant-head tests using either the exact method of Ehlig-Economides (1982) or the approximate method of Uraiet and Raghavan (1980).

2. Solutions for Nonuniform Aquifers

   - Use a solution by Moench and Prickett (1972) to analyze data from pumping tests in an aquifer undergoing conversion from confined to unconfined conditions.

   - Use a solution by Butler (1988) to analyze data from pumping tests in nonuniform aquifers.

3. Generalized Radial Flow Model

   - Analyze pumping tests and constant-head tests using the **generalized radial flow (GRF) solution** of Barker (1988).

   - Solution methods available for **confined and double-porosity fractured aquifers**.

4. Solution for a Water-Table Aquitard

   - Use a solution by Cooley and Case (1973) to analyze data from pumping tests in a confined aquifer overlain by a **water-table aquitard**.

5. New Solution for Underdamped Slug Tests

   - A new solution by Butler and Zhan (2004) simulates multi-well slug tests in a confined aquifer with fully and partially penetrating wells, inertial effects in the test and observation wells, and frictional loss.

6. Dagan's Slug Test Solution for Wells Screened Across Water Table

   - Use this solution by Dagan (1978) for the evaluation of **slug tests in wells screened across the water table**.

   - Butler (1998) recommends this method for the analysis of wells screened across the water table.

7. Slug Tests in Fractured Aquifers

   - Analyze a **slug test in a double-porosity fractured aquifer** with slab-shaped blocks using a solution by Barker and Black (1985).

8. Dougherty-Babu Slug Test Solution

- Analyze a slug test in a partially well in a confined aquifer with wellbore skin and delayed observation well response using the Dougherty-Babu (1984) solution.

- Simulate **single- or multi-well tests**.

9. Horizontal Wells

- A solution by Daviau et al. (1985) allows you to analyze pumping tests with **horizontal wells** in confined aquifers.

10. Step-Drawdown Test in a Leaky Aquifer

- Analyze data from a **step-drawdown test in a leaky aquifer** using the Jacob-Rorabaugh well-loss equation combined with the Hantush-Jacob (1955) solution.

- Bear (1979, p. 375) discusses how the formation loss term in the well-loss equation may be represented by any appropriate pumping test solution for a given aquifer type.

11. New Single-Fracture Solution

- Evaluate data from pumping tests and constant-head tests using a solution by Gringarten et al. (1974) for an **infinite-conductivity vertical fracture** in a confined aquifer.

- This new solution supplements the uniform-flux vertical fracture solution by Gringarten and Witherspoon (1972) released in AQTESOLV v3.0.

12. Aquifer Boundaries With Automatic Image Well Generation

- **Automatically generate image wells** to analyze pumping tests in bounded aquifers including single boundaries, two intersecting boundaries, infinite strip aquifers (two parallel boundaries), semi-infinite strip aquifers (three boundaries) and closed rectangular reservoirs (four boundaries).

- An intuitive interface lets you easily enter **boundary geometry** and select any combination of **no-flow and constant-head boundaries**.

- Easily **toggle boundaries on and off** during analyses.

13. Distance-Drawdown Analysis

- Use distance-drawdown plots to display pumping test data

- Perform distance-drawdown **visual curve matching** with any pumping test solution.

14. Agarwal's Method for Recovery Data Analysis

- Use Agarwal plots to **analyze recovery data from pumping tests and constant-head tests**.

- Agarwal's straightforward method allows you to **match standard drawdown solutions** (e.g., Theis 1935; Cooper-Jacob 1946; Neuman 1974; etc.) to recovery data.

15. Delayed Observation Well Response

- AQTESOLV includes solutions that accounts for delayed response in an observation well during a pumping test (Black and Kipp 1977; Moench 1997).

16. Solution Expert

- The new Solution Expertinterface for selecting solution methods puts essential solution method information at your fingertips.

- Use intelligent filters to **query the software** for solutions that match your test configuration. For example, you can search for all solutions that include wellbore storage, wellbore skin effect and partial penetration.

- Click the **Help** button for any selected solution and go directly to a detailed help topic associated with the method (e.g., Theis 1935).

17. New Diagnostic Tool

- AQTESOLV v4.0 introduces a **new diagnostic tool** for interactively testing the slope of data from pumping tests and constant-head tests.

- This diagnostic tool assists in the selection of appropriate solution methods by helping to **identify key features** such as wellbore storage, linear flow, boundary effects and flow dimension.

- The new interactive tool supplements the diagnostic flow plots feature introduced in AQTESOLV v3.0.

18. Groundwater Mounding in Water-Table Aquifers

- Predict transient water-table rise beneath circular and rectangular recharge areas using solutions by Hantush (1967).

- Prepare contour maps of groundwater mounds using **Surfer**.

19. Batch Printing

- Select a group of AQTESOLV data sets and **apply consistent formatting** when printing plots and reports.

- Batch printing is a very useful feature, for example, if you've conducted a large number of tests at a site and you need to print your results for a project report.

20. New Interface Features

- A unified interface simplifies well data entry for pumping tests, constant-head tests and slug tests.

- New plots added for distance-drawdown and Agarwal analysis.

- An interactive slope checking tool helps you perform diagnostic analysis.

21. Revised Help System

- A new and improved **HTML help system** increases your productivity with new topics, an expanded index and greater cross-referencing.

- The program provides even **more context-sensitive help**.

New Features in Earlier Versions

For a summary of features introduced in previous versions, please visit the AQTESOLV web site.

Features

Unique Features in AQTESOLV*

1. Solution for Unconfined Aquifer with 3D Saturated/Unsaturated Flow

   Only AQTESOLV includes a solution by Tartakovsky and Neuman (2007) for a pumping test in an unconfined aquifer with three-dimensional flow in the saturated and unsaturated zones.

2. Constant-Head Tests

   Only AQTESOLV has solutions for constant-head tests in confined, leaky and fractured aquifers.

3. Solutions for Nonuniform Aquifers

   Only AQTESOLV includes solutions by Moench and Prickett (1972) for a pumping test in an aquifer undergoing conversion from confined to unconfined conditions and Butler (1988) for a pumping test in a heterogeneous aquifer.

4. Generalized Radial Flow Model

   AQTESOLV is the only software to feature the generalized radial flow (GRF) solution by Barker (1988) which allows you to evaluate pumping tests and constant-head tests for integer and non-integer flow dimensions.

5. Solution for a Water-Table Aquitard

   Only AQTESOLV includes a solution by Cooley and Case (1973) for a pumping test in a confined aquifer overlain by a water-table aquitard.

6. Underdamped Slug Tests with Partially Penetrating Wells

   Only AQTESOLV provides solutions for slug tests with underdamped response in partially penetrating wells.

7. Horizontal Wells

   Only AQTESOLV provides a solution for analyzing flow to a uniform-flux or infinite-conductivity horizontal well.

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8. Single-Fracture Solutions

   AQTESOLV is the only software for aquifer test analysis that includes solutions
     for vertical and horizontal fractures. Single fracture solutions are available
     for both pumping tests and constant-head tests.

9. Step-Drawdown Test in Leaky Aquifer

   AQTESOLV is the first aquifer test software to provide a solution for a step-
     drawdown test in a leaky aquifer.

10. Confined Two-Aquifer System

   Only AQTESOLV lets you use the Neuman-Witherspoon (1969) solution to
     analyze drawdown in the pumped aquifer, an aquitard and an unpumped
     source aquifer.

11. Automatic Image Well Generation

   AQTESOLV is the only software the provides automatic image well generation
     for bounded aquifers with one to four boundaries and any combination of
     no-flow and constant-head conditions.

12. Delayed Observation Well Response

   Only AQTESOLV provides solutions for pumping tests in confined and
     fractured aquifers with delayed response in observation wells.

13. Dagan's Slug Test Method for Wells Screened Across Water Table

   Only AQTESOLV includes the Dagan (1978) solution for slug tests. This
     solution is recommended by Butler (1998) for well screened across the
     water table.

14. Slug Tests in Fractured Aquifers

   Only AQTESOLV includes the solution by Barker and Black (1985) for a slug
     test in a double-porosity fractured aquifer with slab-shaped blocks.

15. Diagnostic Flow Plots

   Diagnostic flow plots (radial, linear, bilinear and spherical) are a unique
     feature of AQTESOLV. Use these plots to diagnose wellbore storage, linear
     flow, and boundary effects.

16. Active Type Curves

   AQTESOLV v3.0 introduced a unique curve matching technique called active
     type curves that radically alters the way you perform visual curve matching
     with variable-rate pumping test solutions and underdamped (oscillatory)
     slug test solutions.

17. Distance-Drawdown Analysis

   AQTESOLV is the only software that lets you perform distance-drawdown
     analysis using any of its pumping test solutions.

18. Agarwal Method for Recovery Data

   AQTESOLV is the first program to introduce the Agarwal method for analyzing recovery data from pumping tests and constant-head tests.

19. Groundwater Mounding

   Only AQTESOLV has solutions for predicting the transient rise of the water table beneath circular and rectangular recharge areas using solutions by Hantush (1967).

Unique Solution Methods in AQTESOLV*

1. Moench-Prickett (1972) solution for a pumping test in a confined aquifer undergoing conversion to water-table conditions.

2. Butler (1988) solution for a pumping test in a nonuniform aquifer.

3. Dougherty-Babu (1984) solution for a pumping test in a confined aquifer with partially penetrating wells, wellbore storage and wellbore skin.

4. Hantush (1962) solution for a pumping test in a confined wedge-shaped aquifer.

5. Murdoch (1994) solution for a pumping test in a confined aquifer with an interceptor trench.

6. Daviau et al. (1985) solution for a pumping test in a confined aquifer with a uniform-flux or infinite-conductivity horizontal well.

7. Barker (1988) generalized radial flow solution for a pumping test in a single-porosity confined aquifer with wellbore skin and nonintegral flow dimension.

8. Cooley-Case (1973) solution for a pumping test in a leaky confined aquifer overlain by a water-table aquitard.

9. Neuman-Witherspoon (1969) solution for a pumping test in a leaky confined two-aquifer system.

10. Tartakovsky-Neuman (2007) solution for a pumping test in an unconfined aquifer with 3D flow in the saturated and unsaturated zones.

11. Gringarten-Witherspoon (1972) solution for a pumping test in a fractured aquifer with a uniform-flux vertical fracture.

12. Gringarten-Ramey-Raghavan (1974) solution for a pumping test in a fractured aquifer with an infinite-conductivity vertical fracture.

13. Gringarten-Ramey (1974) solution for a pumping test in a fractured aquifer with a horizontal fracture.

14. Barker (1988) generalized radial flow solution for a pumping test in a double-porosity fractured aquifer with slab shaped or spherical blocks, fracture skin, wellbore storage, wellbore skin and nonintegral flow dimension.

15. Dougherty-Babu (1984) solution for a slug test in a confined aquifer with

partially penetrating wells and wellbore skin.

16. Butler (1998) solution for a slug test in a confined aquifer with partially penetrating well and underdamped (oscillatory) response.

17. Butler-Zhan (2004) solution for a slug test in a confined aquifer with partially penetrating wells and underdamped (oscillatory) response.

18. Springer-Gelhar (1991) solution for a slug test in an unconfined aquifer with partially penetrating well and underdamped (oscillatory) response.

19. Dagan (1978) solution for a slug test in an unconfined aquifer with a well screened across the water table.

20. Barker-Black (1985) solution for a slug test in a double-porosity fractured aquifer with slab-shaped blocks.

21. Jacob-Lohman (1952) solution for a constant-head test in a confined aquifer.

22. Hurst-Clark-Brauer (1969) solution for a constant-head test in a confined aquifer with wellbore skin.

23. Dougherty-Babu (1984) solution for a constant-head test in a confined aquifer with partially penetrating wells and wellbore skin.

24. Barker (1988) solution for a constant-head test in a single-porosity confined aquifer with wellbore skin and nonintegral flow dimension.

25. Hantush (1959) solution for a constant-head test in a leaky aquifer.

26. Moench (1985) solution for a constant-head test in a leaky aquifer with wellbore skin and storage in the aquitard(s).

27. Barker (1988) generalized radial flow solution for a constant-head test in a double-porosity fractured aquifer with slab shaped or spherical blocks, fracture skin, wellbore skin and nonintegral flow dimension.

28. Ozkan-Raghavan (1991) solution for a constant-head test in a fractured aquifer with a uniform-flux or infinite-conductivity vertical fracture.

Summary of Solution Methods

Pumping Test Solution Methods	
Solution Category	Methods Available
Constant-Rate Tests	35
Variable-Rate Tests	34
Recovery Tests	33
Step-Drawdown Tests	3
Wellbore Storage	12
Confined Aquifers	14
Leaky Aquifers	9
Unconfined Aquifers	5
Fractured Aquifers	7
Bounded Aquifers	23

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Constant-Head Test Solution Methods	
Solution Category	Methods Available
Constant-Head Tests	11
Recovery Tests	10
Wellbore Skin	6
Confined Aquifers	5
Leaky Aquifers	2
Fractured Aquifers	4

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Slug Test Methods	
Solution Category	Methods Available
Slug Tests	18
Partial Penetration	15
Underdamped	5
Confined Aquifers	11
Unconfined Aquifers	6
Fractured Aquifers	1

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*Compared to AquiferTestPro v3.5 and AquiferWin32 v3.0. Please notify HydroSOLVE, Inc. of any changes to this information.

Using Help

Using the Help System

This help system includes several types of navigation components. Click on the examples below to see how they work:

- o Expanding Hotspot

    - When you click on an expanding hotspot, details appear below it.

    - Click on the hotspot again to hide the details.

- o defined term (Click on a defined term to display its definition. Click the term again to hide the definition)

- o Related Topics

Context-Sensitive Help

AQTESOLV provides context-sensitive help and tips throughout its menus and windows.

- Use What's This help to learn about a menu option or toolbar button.

- Click **Help** or press **F1** in dialog windows to view context-sensitive help.

- Display **tooltips** by hovering the mouse over toolbar buttons and edit windows.

- Activate Quick Tips to display helpful prompts at key stages in the program.

Getting Started

You'll find step-by-step examples in the Quick Start chapter to lead you through the process of analyzing many different types of aquifer tests using AQTESOLV.

More Help On The Web

Visit the AQTESOLV web site for additional help resources including the Knowledge Base, examples and tutorials.

Quick Start

How To Use AQTESOLV

How to Analyze an Aquifer Test

Follow these steps to analyze an aquifer test (pumping test, slug test or constant-head test) with AQTESOLV:

➡ Develop a Conceptual Model

The first step in the analysis of an aquifer test is the development of a conceptual model. The conceptual model translates the elements of the real groundwater flow system into a simpler model suitable for mathematical analysis.

In developing a conceptual model for an aquifer test, one should address the following questions:

- What is the basic configuration for the aquifer under consideration (e.g., confined, leaky confined, unconfined or fractured)? What is the thickness of the aquifer? Is the aquifer isotropic?

- What are the well construction details (e.g., casing radius, screen radius, borehole radius, depth to top of screen and screen length)?

- For a pumping test, what is the rate history (i.e., constant or variable)? What was the duration of pumping?

- For a slug test, what was the initial displacement in the test well? What was the static water column height in the well? Is the filter pack, if present, more permeable than the aquifer?

- Is the aquifer infinite-acting? Are there recharge or no-flow boundaries that may influence hydraulic response during the test?

- Are there external sources or sinks that affect hydraulic response such as pumping or injection wells, precipitation or infiltration basins?

- Are there nearby bodies of water with fluctuating water levels that influence water levels in the aquifer (e.g., tidal fluctuations)?

- Do barometric pressure changes influence water levels in the aquifer?

➡ Enter Data

After developing a conceptual model, enter data from the test into AQTESOLV.

Create a new data set and select an appropriate data entry wizard for a pumping test, slug test or constant-head test.

When you have completed the steps in the data entry wizard, AQTESOLV displays an Error Log that shows any missing data or errors detected in your data set. To correct

any reported errors, choose options from the Edit menu.

You are not restricted to using one of the wizards for data entry. You also may choose options from the Edit menu to modify or add to a data set.

➡ Evaluate Diagnostic Flow Plots

After entering data into AQTESOLV, use diagnostic flow plots and derivative analysis to identify features such as wellbore storage, radial flow in an infinite-acting aquifer, linear flow to a single fracture, boundary effects and delayed gravity response.

Diagnostic flow plots apply to the analysis of pumping tests. Radial flow plots are especially useful for identifying wellbore storage, radial flow in an infinite-acting aquifer and boundary effects. Use linear flow plots to identify periods of linear flow during a pumping test such as early-time flow to a vertical fracture.

Derivative plots help to detect many hydraulic response features of pumping tests such as wellbore storage, delayed gravity response, double-porosity effects and radial flow in an infinite-acting aquifer.

➡ Estimate Aquifer Properties (Curve Matching)

To estimate aquifer properties from your test data, first choose a solution and then perform curve matching.

When choosing a solution method, use the Solution Expert to match methods to the conditions of your test (e.g., wellbore storage, linear flow, etc.).

Use visual curve matching to estimate aquifer properties in the traditional way by fitting a straight line or type curve to your test data. AQTESOLV provides special tools to enhance the visual curve matching process such as active type curves, parameter tweaking and combined drawdown and derivative plots.

AQTESOLV also provides automatic curve matching to estimate aquifer properties from your test data using nonlinear least squares fitting procedure. Prior to performing automatic estimation, use visual curve matching to obtain preliminary estimates of aquifer properties.

➡ Test Fit of Model (Diagnostic Checking)

Use residual plots to perform diagnostic checking on the model residuals after you have performed model estimation (curve matching).

The residual-time and residual-simulated plots help you to identify model bias, i.e., correlation between the model errors and time or simulated value. Ideally, the residuals should exhibit a random pattern on these plots with no clustering of positive or negative residuals.

Use the normal probability plot to find out if the model residuals are normally distributed.

Related Topics

Pumping Test Design and Prediction

To design a pumping test or forecast drawdown due to pumping using AQTESOLV, enter the following information into the Forward Solution Wizard:

1. Units of measurement,

2. Aquifer data such as thickness and anisotropy,

3. Well data including locations, construction details and discharge rate(s), and

4. Aquifer properties (transmissivity and storativity).

After completing the wizard, choose a pumping test solution and use data plots and contouring to view the model predictions.

Related Topics

Field Applications

Enter response data into AQTESOLV to monitor the progress of a field test.

1. Perform curve matching during a test to obtain preliminary estimates of aquifer properties.

2. Examine data plots in the field to determine (a) the appropriate time for terminating a pumping test or (b) the need for additional slug testing before leaving a field site.

Related Topics

Examples

Overview (Examples)

Follow the examples in this chapter for pumping tests, slug tests, constant-head tests and groundwater mounding to help you learn to use the many features in AQTESOLV.

When you see *Pro* in one of the examples, it indicates that the example (or a section of it) presents features found only in the **Pro** version of AQTESOLV.

Pumping Test Examples

1. Constant-rate test in a nonleaky confined aquifer near Gridley, OH

   Keywords: Pumping Test Wizard; Import Wizard; diagnostic flow plots; radial flow plot; derivative plot; visual curve matching; automatic curve matching; prediction; contouring; Cooper-Jacob solution; Theis solution

2. Constant-rate test with recovery in a nonleaky confined aquifer

   Keywords: Pumping Test Wizard; Import Wizard; diagnostic flow plots; radial flow plot; derivative plot; Agarwal plot; residual drawdown plot; visual curve matching; automatic curve matching; active type curves; Theis residual drawdown solution; Theis solution

3. Variable-rate test with recovery in a nonleaky confined aquifer

   Keywords: Pumping Test Wizard; Import Wizard; visual curve matching; automatic curve matching; active type curves; Agarwal plot; Theis solution

4. Constant-rate test in pumped well (single-well test) with wellbore storage in a nonleaky confined aquifer, Saudi Arabia

   Keywords: Pumping Test Wizard; Import Wizard; single-well test; wellbore storage; diagnostic flow plots; radial flow plot; derivative plot; visual curve matching; automatic curve matching; parameter tweaking; active type curves; recharge boundary; Cooper-Jacob solution; Papadopulos-Cooper solution; Moench solution

5. Constant-rate test in pumped well (single-well test) with wellbore storage and skin in a nonleaky confined aquifer, Lynden, WA

   Keywords: Pumping Test Wizard; Import Wizard; single-well test; wellbore storage; wellbore skin; diagnostic flow plots; radial flow plot; derivative plot; visual curve matching; parameter tweaking; Cooper-Jacob solution; Papadopulos-Cooper solution; Dougherty-Babu solution

6. Step-drawdown test in a confined aquifer, Saudi Arabia

   Keywords: Pumping Test Wizard; Import Wizard, step-drawdown test; automatic curve matching; wellbore skin; effective well radius; Theis step-

drawdown solution

7. Constant-rate test with multiple observation wells in a nonleaky confined aquifer near Sioux Flats

   Keywords: Pumping Test Wizard; Import Wizard; CSV file with missing values; adding wells; diagnostic flow plots; radial flow plot; derivative plot; composite plot; visual curve matching; automatic curve matching; distance drawdown; Theis solution

8. Constant-rate test in a leaky confined aquifer near Dalem, The Netherlands

   Keywords: Pumping Test Wizard; Import Wizard; diagnostic flow plots; radial flow plot; derivative plot; automatic curve matching; Hantush-Jacob solution; Hantush solution

9. Constant-rate test with multiple observation wells in a leaky confined aquifer

   Keywords: Pumping Test Wizard; Import Wizard; CSV file; adding wells; diagnostic flow plots; radial flow plot; derivative plot; composite plot; visual curve matching; automatic curve matching; distance drawdown; Cooper-Jacob solution; Hantush-Jacob solution

10. Constant-rate test in an unconfined aquifer with delayed gravity response near Saratoga, NY

    Keywords: Pumping Test Wizard; Import Wizard; delayed gravity response; partial penetration; diagnostic flow plots; radial flow plot; derivative plot; visual curve matching; automatic curve matching; Cooper-Jacob solution; Neuman solution; Moench solution

11. Constant-rate test in an unconfined aquifer with noninstantaneous drainage at the water table at Cape Cod, MA

    Keywords: Pumping Test Wizard; Import Wizard; noninstantaneous drainage; partial penetration; diagnostic flow plots; radial flow plot; derivative plot; visual curve matching; automatic curve matching; Cooper-Jacob solution; Neuman solution; Tartakovsky-Neuman solution

12. Constant-rate test in a double-porosity (fractured) aquifer at Nevada Test Site

    Keywords: Pumping Test Wizard; Import Wizard; double porosity; adding wells; diagnostic flow plots; radial flow plot; derivative plot; composite plot; automatic curve matching; Moench solution

13. Pumping test design (forward solution)

    Keywords: Forward Solution Wizard; prediction; test design; distance drawdown;
    vertical fracture; sensitivity analysis; Gringarten-Witherspoon solution

14. Constant-rate test in a horizontal well in a confined aquifer

    Keywords: Pumping Test Wizard; Import Wizard; horizontal well; diagnostic

flow plots; derivative plot; automatic curve matching; Daviau et al. solution; sensitivity analysis

Slug Test Examples

1. Single-well slug test in an unconfined aquifer

    Keywords: Slug Test Wizard; Import Wizard; transforming depth-to-water measurements to displacement; normalized head; recommended head range; visual curve matching; automatic curve matching; sensitivity analysis; screening data with Cooper et al. solution; Bouwer-Rice solution; KGS Model; Peres et al. approximate deconvolution

2. Single-well slug test in an unconfined aquifer with noninstantaneous initiation

    Keywords: Slug Test Wizard; Import Wizard; translation method; normalized head; recommended head range; visual curve matching; Bouwer-Rice solution

3. Single-well slug test in well screened across water table with drainage from filter pack (double straight-line effect)

    Keywords: Slug Test Wizard; Import Wizard; well screened across water table; normalized head; drainage from filter pack; double straight-line effect; visual curve matching; Bouwer-Rice solution

4. Single-well slug test in a high hydraulic conductivity, confined aquifer

    Keywords: Slug Test Wizard; Import Wizard; inertial effect; underdamped; correction for frictional well loss; normalized head; visual curve matching; automatic curve matching; active type curves; Butler solution

5. Multi-well slug test in a confined aquifer in Lincoln County, Kansas

    Keywords: Slug Test Wizard; Import Wizard; adding wells; normalized head; automatic curve matching; screening data with Cooper et al. solution; KGS Model

Constant-Head Test Examples

1. Constant-head test including flow and recovery near Grand Junction, CO

    Keywords: Constant-Head Test Wizard; Import Wizard; importing rates; importing recovery data; discharge plot; residual drawdown plot; Agarwal plot; visual curve matching; automatic curve matching; Jacob-Lohman solution; Hantush solution; exact recovery solution

Mounding Examples

1. Groundwater mounding beneath a rectangular recharge area

    Keywords: mounding tools; contouring; report file; Hantush solution

Pumping Tests

Pumping Test Example: Constant Rate (Gridley)

Walton (1962) presented data from a pumping test conducted on July 2, 1953 near Gridley, Illinois. The test well (Well 3) fully penetrated an 18-ft thick sand and gravel aquifer under nonleaky artesian conditions. Pumping continued for eight hours at a constant rate of 220 gallons-per-minute (gpm). Hydraulic response was monitored in an observation well (Well 1) at a distance of 824 ft from the pumped well. Time and drawdown measurements were recorded in minutes and feet, respectively.

This example will introduce you to the following tasks and features in AQTESOLV:

- Creating a new data set with the Pumping Test Wizard

- Importing data with the Observation Data Import Wizard

- Saving a data set

- Inspecting diagnostic plots (radial flow and derivative)

- Estimating aquifer properties using Cooper-Jacob (1946) and Theis (1935) solutions (visual and automatic)

- Predicting future response over time and distance (distance-drawdown and contour plots)

TIP While following the steps in this example, click **Help** or press **F1** to obtain context sensitive help in the AQTESOLV application.

Create a New Data Set with Pumping Test Wizard

The first step in analyzing data from a pumping test is to create a new AQTESOLV data set. In this example, we will use the Pumping Test Wizard to assist us with data entry.

1. Create a new data set by choosing New from the **File** menu.

2. In the **New Data Set** dialog, select **Pumping Test Wizard** from the list. Click **OK**.

3. Choose **Multiwell test** for the type of pumping test. Click **OK**.

4. The **Pumping Test Wizard** prompts you for data required to analyze a pumping test. Click **Next** to begin the wizard.

5. For units of measurement, choose **ft** for length, **min** for time, **gal/min** for pumping rate and **gal/day/sq. ft** for hydraulic conductivity. Click **Next**.

6. For project information, enter **Gridley, Illinois** for the location and **July 2, 1953** for the test date. Click **Next**.

7. For aquifer data, enter **18** for the aquifer thickness. Enter **1** for the anisotropy ratio (i.e., assume hydraulic conductivity is isotropic). Click **Next**.

8. For pumping well data, enter **Well 3** for the well name. Enter coordinates of X=0 and Y=0. Click **Next**.

9. For pumping well construction, select the option for **vertical, full penetration**. Click **Next**.

10. For pumping well radius data, assume **0.5** for casing radius and **0.5** for well radius. Click **Next**.

11. For pumping rates, enter **0** for time and **220** for rate in the first row of the spreadsheet. Click **Next**.

12. For observation well data, enter **Well 1** for the well name. Enter **824** and **0** for the X and Y coordinates, respectively. Click **Next**.

13. For observation well construction, select the option for **vertical, full penetration**. Click **Next**.

14. For observations, click **Import** to launch the Observation Data Import Wizard for importing data from a file.

    We will import a text file consisting of 22 time-drawdown readings arranged in two columns. The first column is elapsed time since the start of the test. The second column contains drawdown measurements.

    In Step 1 of the wizard, click **Browse**. Select the import file **Gridley.txt** in the AQTESOLV installation folder and click **Open**. Click **Next**.

    In Step 2 of the wizard, enter **2** for the number of columns, **1** for the starting row in the file, **1** for the column containing elapsed time and **2** for the column containing displacement. Click **Next**.

    In Step 3 of the wizard, click **Finish**. Inspect the import file summary and click **OK**.

    Click **Next** to proceed with the **Pumping Test Wizard**.
    ---

15. You have completed the **Pumping Test Wizard**. Click **Finish**.

After completing the **Pumping Test Wizard**, AQTESOLV automatically displays an Error Log to let you know if the data set contains any errors. If the **Error Log** identifies any mistakes, choose options from the Edit menu to correct them.

Save Data Set

At this point, it's a good idea to save your work.

Save the data set by choosing Save As from the **File** menu. Choose a folder and enter **Gridley Well No. 1** for the name of the file. Click **Save**. AQTESOLV saves the file with an **.aqt** extension.

Pro **Inspect Diagnostic Plots**

Before performing curve matching to estimate aquifer properties, you may use diagnostic features in AQTESOLV to evaluate aquifer and flow conditions.

Diagnostic flow plots help you select an appropriate solution method for your pumping test data.

1. Choose Radial Flow from the **View** menu to display a radial flow plot on log-linear axes.

   View Radial Flow Plot

   At late time on this graph, data plotting as a straight line indicate radial flow conditions in an infinite-acting confined aquifer.
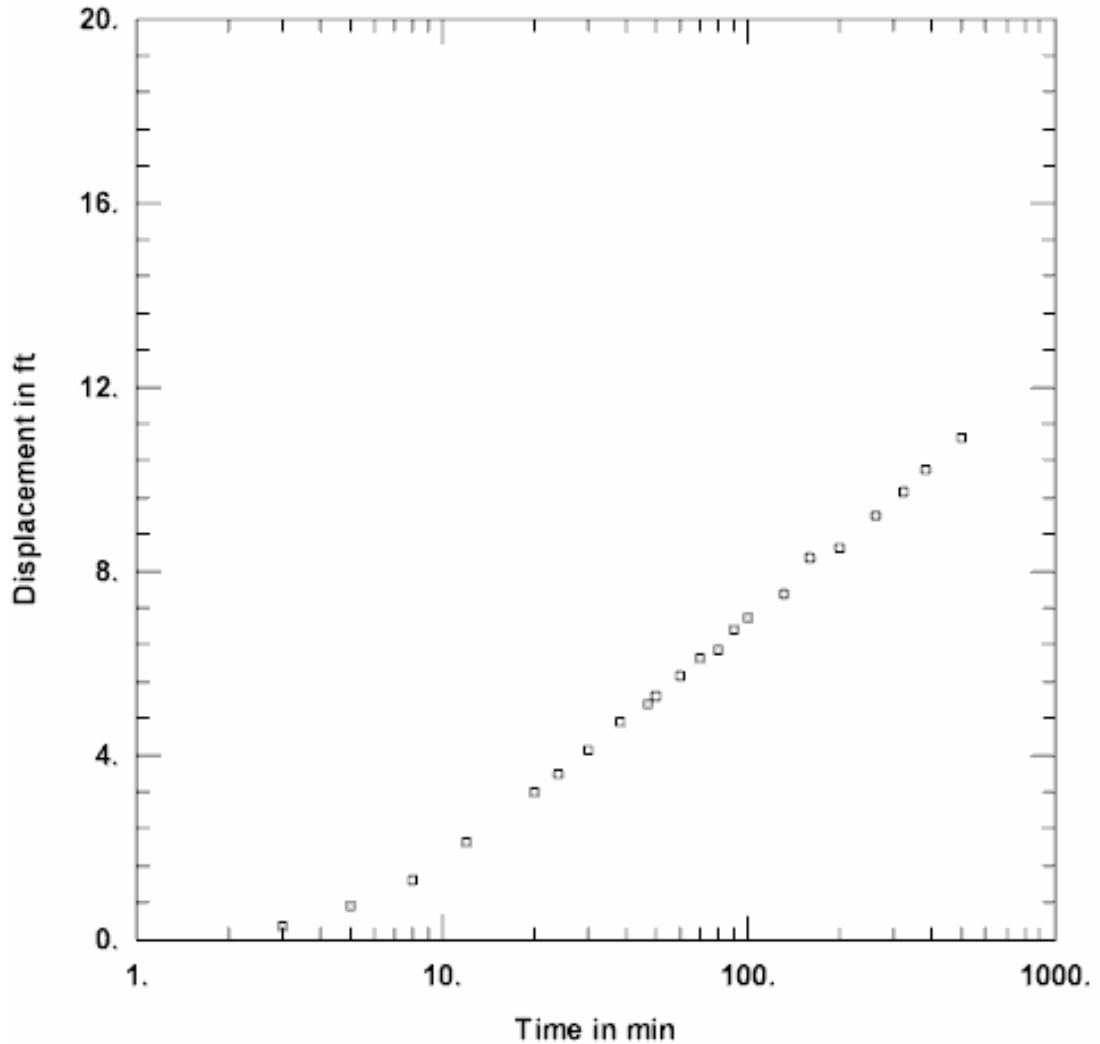
Derivative analysis is another useful diagnostic tool for evaluating aquifer conditions.

1. Choose Displacement-Time from the **View** menu to display a plot of the test data. On semi-log axes, this plot is identical to the radial flow plot above.

2. Choose Wells from the **Edit** menu. Select **Well 1** from the list and click **Modify**.

   In the **Symbols** tab, remove the check from **Use data symbols properties** and select **cross** for the derivative symbol.

   In the **Curves** tab, remove the check from **Use type curve properties**. Click **Color** for the derivative curve properties, change the color to **red**, and click **OK**.

   Click **OK** and then **Close**.

3. Select Options from the **View** menu. In the **Plots** tab, check **Derivative curves**. In the **Derivative** tab, select the option for **Bourdet** and enter a differentiation interval of **0.3**. Click **OK**.

View Derivative Plot

The form of the derivative plot is characteristic of radial flow in an infinite confined aquifer. At late time, the derivative becomes essentially constant when the data plot as a straight line.
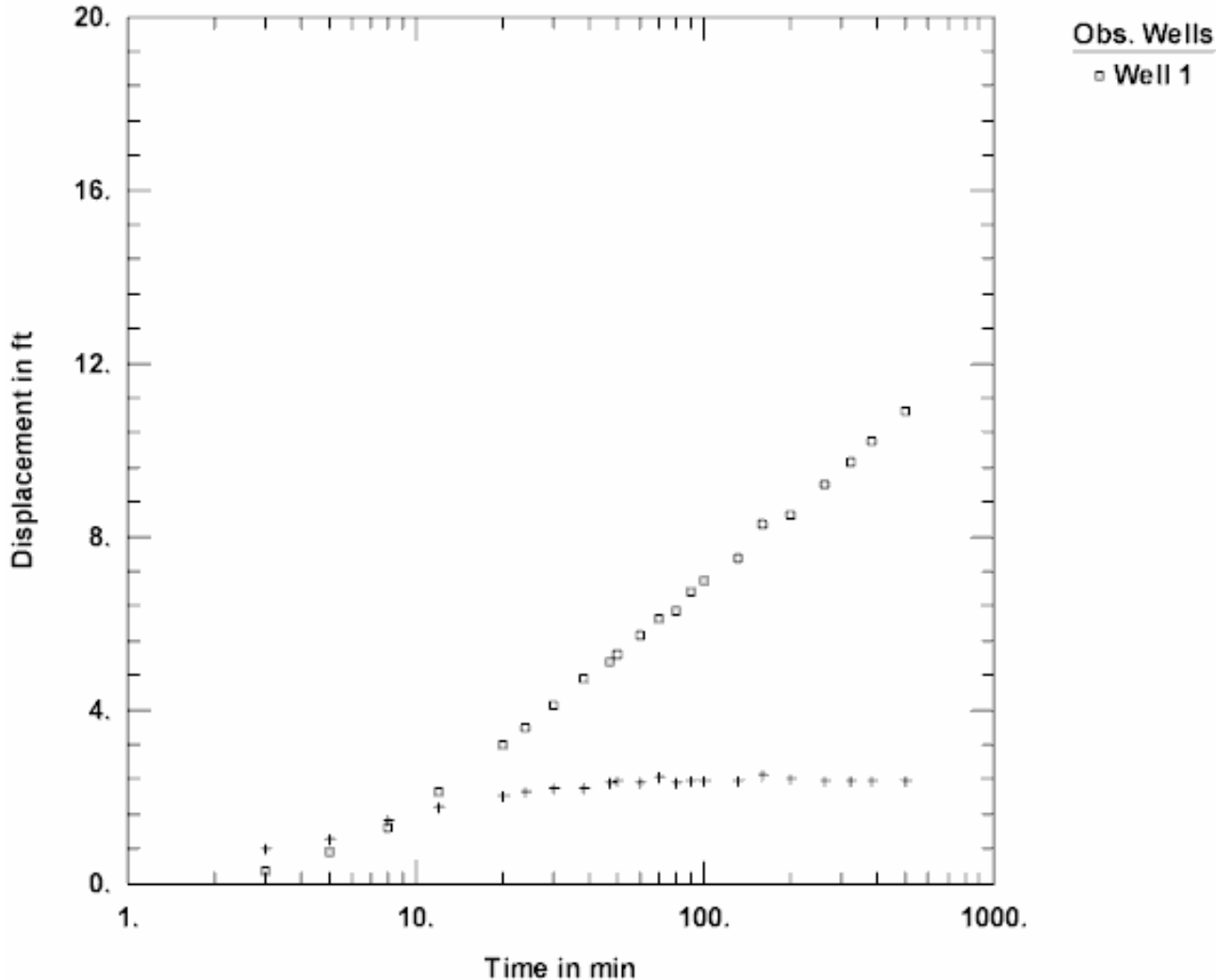
Estimate Aquifer Properties

The radial flow and derivative plots that we have examined for this test confirm the assumption of radial flow in an infinite-acting confined aquifer. To start our analysis, we can use the Cooper-Jacob (1946) solution to obtain preliminary estimates of aquifer properties.

1. Choose Solution from the **Match** menu to select a method for analyzing the data.

2. Remove the check from **Solution is inactive**. Click the **+** next to **Confined Aquifers** to expand the list of available solutions for confined aquifers. Select **Cooper-Jacob (1946)** and click **OK**.

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3. Choose Displacement-Time from the **View** menu.

4. Choose Options from the **View** menu. In the **Plots** tab, remove the check from **Derivative curve(s)** and check **Valid time for Cooper-Jacob approximation**. Click **OK**.

The dashed vertical line shown on the plot is a guide indicating the time when the Cooper-Jacob solution becomes valid. Match the solution to data plotting to the right of the vertical line.

5. Choose Visual from the **Match** menu to perform visual curve matching with the Cooper-Jacob solution.

To perform visual matching, move the mouse to a point where you wish to begin drawing a new line with the Cooper-Jacob solution.

Click and hold down the left mouse button to anchor the new line at this point.

Continue to hold the mouse button down and move the mouse to match a new straight line to your data. As you move the mouse, AQTESOLV draws a straight line between the anchor point and the position of the mouse.

Release the left mouse button when you have finished matching a new straight line. AQTESOLV automatically updates the plot legend to reflect changes in parameter values.

6. Repeat the previous step as needed to achieve a satisfactory match.

View Visual Match With Cooper-Jacob

Note that very few data points near the end of the test meet the validity criterion (u 0.01) for the Cooper-Jacob solution. You can change the validity criterion to a less stringent value if desired.
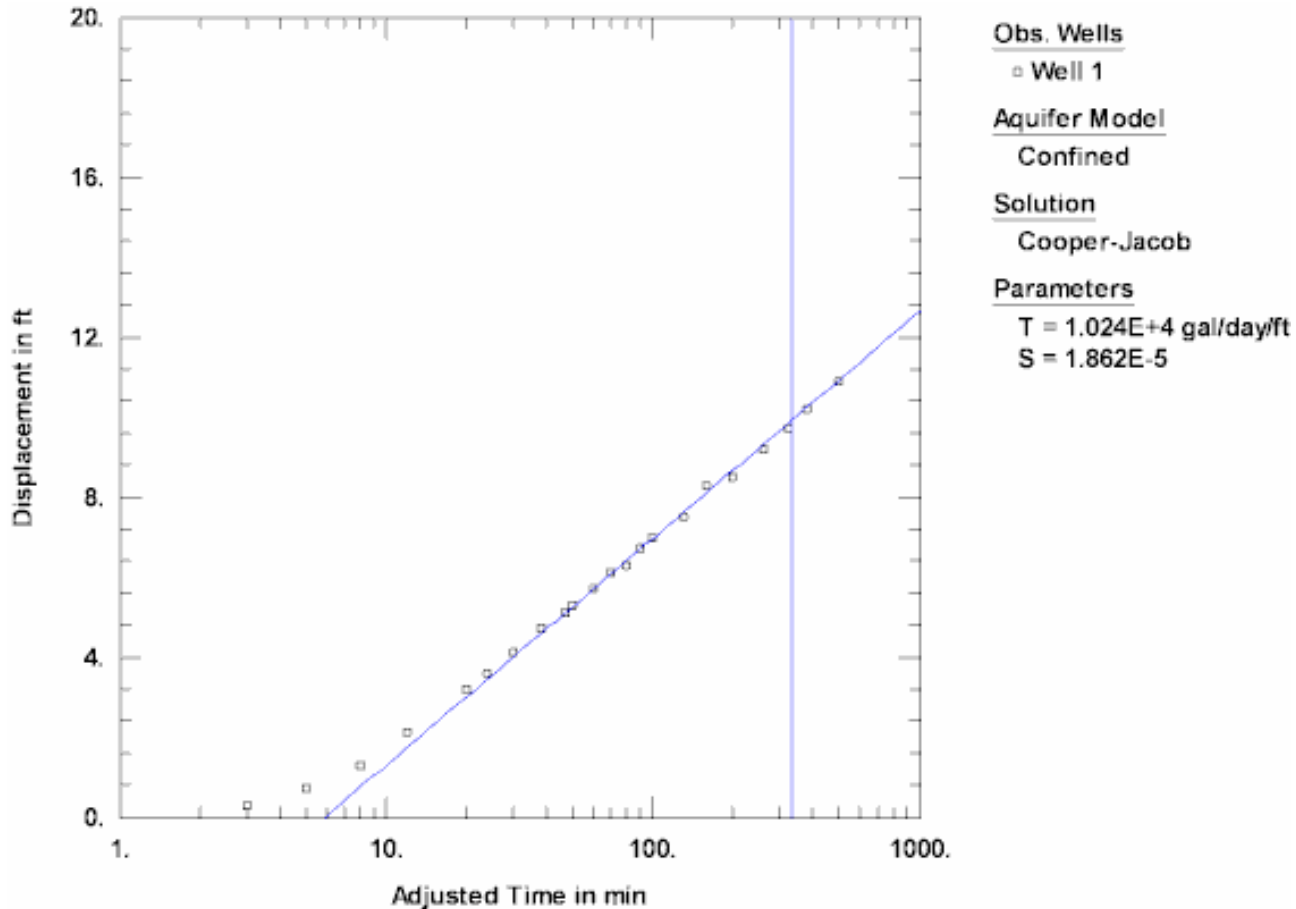
Having completed our preliminary analysis with Cooper-Jacob, let's continue by matching the data with the Theis (1935) solution for a confined aquifer.

1. Choose Solution from the **Match** menu to select a method for analyzing the data.

2. From the list of solutions for **Confined Aquifers**, select **Theis (1935)** and click **OK**.

3. Choose Log Axes from the **View** menu to change the axes to a log-log format.

4. Select Options from the **View** menu. In the **Plots** tab, check **Derivative curves**. Click **OK**.

The plot displays two curves. The blue curve is the drawdown predicted by the Theis solution (i.e., the trace of the Theis type curve projected on the data plot). The red curve is the derivative curve predicted by the Theis solution.

5. Choose Visual from the **Match** menu to perform visual curve matching with the Theis solution.

Click and hold the left mouse button down over a point within the plot area.

> Continue to hold the mouse button down and move the mouse to match the curves to the drawdown and derivative data. As you move the type curve, AQTESOLV automatically updates the plot legend to reflect changes in parameter values.
>
> Release the left mouse button when you have finished matching the curves.

6. Walton (1962) reported values of T = 10,100 gal/day/ft and S = 0.00002 for this test.

   View Visual Match With Theis
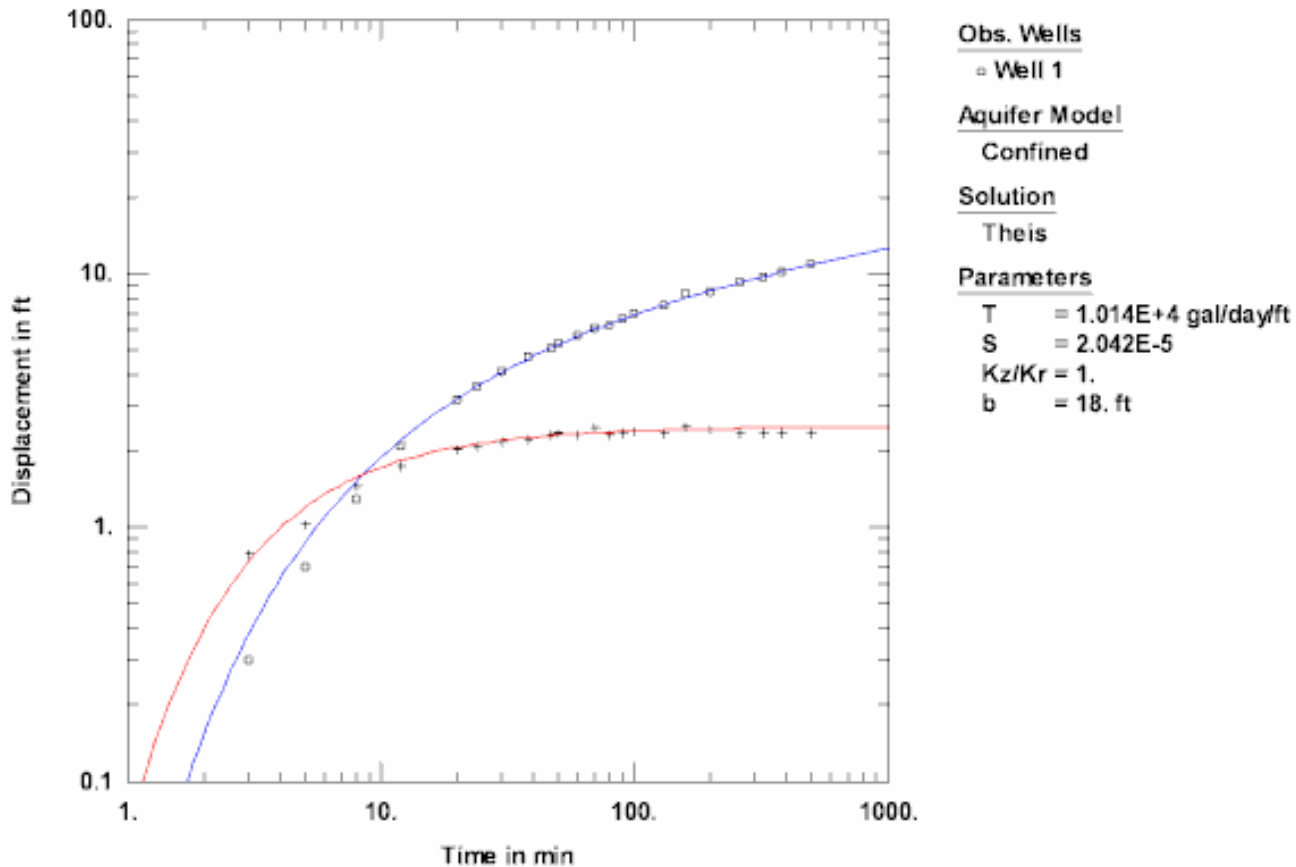
Obs. Wells
  □ Well 1

Aquifer Model
  Confined

Solution
  Theis

Parameters
  T   = 1.014E+4 gal/day/ft
  S   = 2.042E-5
  Kz/Kr = 1.
  b   = 18. ft

7. Choose Automatic from the **Match** menu and click **Estimate** to perform automatic curve matching.

   During the iterative estimation procedure, AQTESOLV displays a progress window and updates the curves displayed on the plot in the background.

8. When estimation has finished, click **OK** and then **Close**. Click **OK** to view the new position of the type curve. The new values of T and S are close to the estimates from visual curve matching.

9. Use residual-time, residual-simulated and normal probability plots to evaluate the fit of the curve by examining residuals. The diagnostics report also presents residual statistics for curve fitting.

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

Prediction

AQTESOLV provides tools for predicting response in the aquifer under future conditions. Using the aquifer properties determined from curve matching analysis, you may forecast drawdown over time or distance.

You may use the **displacement-time plot** to predict drawdown with time for the observation well(s) in your data set.

1. Choose Displacement-time from the **View** menu to display a plot of drawdown versus time.

2. Choose Log-Linear Axes from the **View** menu to display the plot on semi-log axes.

3. Choose Format from the **View** menu and click the **X Axis** tab. Remove the check from **Auto** and enter **10000** for the maximum value. Click **OK**.

Forecast drawdown over distance on a **distance-drawdown plot**.

1. Choose Distance drawdown from the **View** menu to display a plot of drawdown versus distance.

2. Choose Options from the **View** menu and click the **Distance** tab. Enter **43200** min (30 days) for the time used in distance-drawdown calculations. Click **OK**.

3. Choose Format from the **View** menu and click the **Y Axis** tab. Remove the check from **Auto** and enter **50** ft for the maximum value. Click **OK**.

4. If observation wells in your data set do not contain a measurement at the time specified for a distance-drawdown plot, AQTESOLV automatically interpolates/extrapolates a data point for you.

If you have Surfer installed on your computer, you may use the Grid Wizard to generate a **contour plot** of drawdown.

1. Choose Contour from the **View** menu.

2. In Step 1 of the **Grid Wizard**, enter the name of a **Grid file** to store data for the contour plot. Select **X-Y (Plan)** for the grid orientation. Click **Next**.

3. In Step 2 of the **Grid Wizard**, enter **-1000** and **1000** for the minimum and maximum dimensions in the X and Y directions. Enter **51** for the number of grid lines for both directions. For the depths, enter **0** and **18** (i.e., compute the average drawdown over the full thickness of the aquifer). Enter **43200** for the time. Click **Next**.

4. In Step 3 of the **Grid Wizard**, check **Display grid file with Surfer** and select **Contour**. Click **Finish** to display the contour plot with Surfer. Use options in Surfer to customize the appearance of the plot.

Pumping Test Example: Recovery

This example guides you through the analysis of drawdown and recovery data from a pumping test in a nonleaky confined aquifer (USBR 1995). The test well was pumped at a constant rate of 162.9 ft^3/min for 800 minutes. Drawdown was measured in an observation well located 100 ft from the test well. Recovery was monitored for 800 minutes after pumping stopped.

This example will introduce you to the following tasks and features in AQTESOLV:

- Creating a new data set for a recovery test with the Pumping Test Wizard

- Importing data from a text file

- Saving a data set

- Inspecting diagnostic plots (radial flow and derivative)

- Estimating aquifer properties using Theis (1935) type curve and Theis (1935) residual drawdown solutions (visual and automatic)

- Matching recovery data using Agarwal's method

While following the steps in this example, click **Help** or press **F1** to context sensitive help in the AQTESOLV application.

Create a New Data Set with Pumping Test Wizard

The first step in analyzing data from a pumping test is to create a new AQTESOLV data set. In this example, you will use the Pumping Test Wizard to assist with data entry.

1. Create a new data set by choosing New from the **File** menu.

2. In the **New Data Set** dialog, select **Pumping Test Wizard** from the list. Click **OK**.

3. Choose **Multiwell test** for the type of pumping test. Click **OK**.

4. The **Pumping Test Wizard** prompts you for data required to analyze a pumping test. Click **Next** to begin the wizard.

5. For units of measurement, choose **ft** for length, **min** for time, **consistent** for pumping rate and **consistent** for hydraulic conductivity.

Click **Next**.

Consistent units for pumping rate and hydraulic conductivity are based on the units of length and time selected for the data set. In this example, consistent units are ft^3/min for Q and ft/min for K.

6. For project information, enter **Las Vegas** for the location. Click **Next**.

7. For aquifer data, assume **100** for the aquifer thickness. Enter **1** for the anisotropy ratio (i.e., assume hydraulic conductivity is isotropic). Click **Next**.

8. For pumping well data, enter **Test Well** for the well name. Enter coordinates of X=0 and Y=0. Click **Next**.

9. For pumping well construction, select the option for **vertical, full penetration**. Click **Next**.

10. For pumping well radius data, assume **0.5** for casing radius and **0.5** for well radius. Click **Next**.

11. For pumping rates, click **Insert Row**. In the first row of the spreadsheet, enter **0** for time and **162.9** for rate. In the second row, enter **800** for time and **0** for rate. Click **Next**.

The first period is the constant-rate pumping phase of the test; the second period is the recovery phase. Whenever you analyze recovery data, you need to enter the pumping history prior to recovery as well as the time when recovery begins.

12. For observation well data, enter **Obs. Well** for the well name. Enter **100** and **0** for the X and Y coordinates, respectively. Click **Next**.

13. For observation well construction, select the option for **vertical, full penetration**. Click **Next**.

14. For observations, click **Import** to launch the Observation Data Import Wizard for importing data from a file.

    You will import a text file consisting of time-drawdown readings arranged in two columns. The first column is elapsed time since the start of the test. The second column contains drawdown measurements.

> In Step 1 of the wizard, click **Browse**. Select the import file **USBR Recovery.txt** in the AQTESOLV installation folder and click **Open**. Click **Next**.
>
> In Step 2 of the wizard, use the defaults determined by the Import Wizard. Click **Next**.
>
> In Step 3 of the wizard, accept the defaults and click **Finish**. Inspect the import file summary and click **OK**.
>
> Click **Next** to proceed with the **Pumping Test Wizard**.

15. You have completed the **Pumping Test Wizard**. Click **Finish**.

After completing the **Pumping Test Wizard**, AQTESOLV automatically displays an Error Log to let you know if the data set contains any errors. If the **Error Log** identifies any mistakes, choose options from the Edit menu to correct them.

Save Data Set

At this point, it's a good idea to save your work.

Save the data set by choosing Save As from the **File** menu. Choose a folder and enter **USBR Recovery** for the name of the file. Click **Save**. The default extension for an AQTESOLV data set is **.aqt**.

Pro **Inspect Diagnostic Plots**

Before performing curve matching to estimate aquifer properties, you may use diagnostic features in AQTESOLV to evaluate aquifer and flow conditions.

Diagnostic flow plots help you select an appropriate solution method for your pumping test data.

1. Choose Radial Flow from the **View** menu to display a radial flow plot on log-linear axes.

   View Radial Flow Plot

   During the first 800 minutes of the test (prior to the peak), the data approach a straight line with time indicating radial flow conditions in an

infinite-acting confined aquifer. Data from the recovery phase of this test display a declining trend on the plot after 800 minutes.
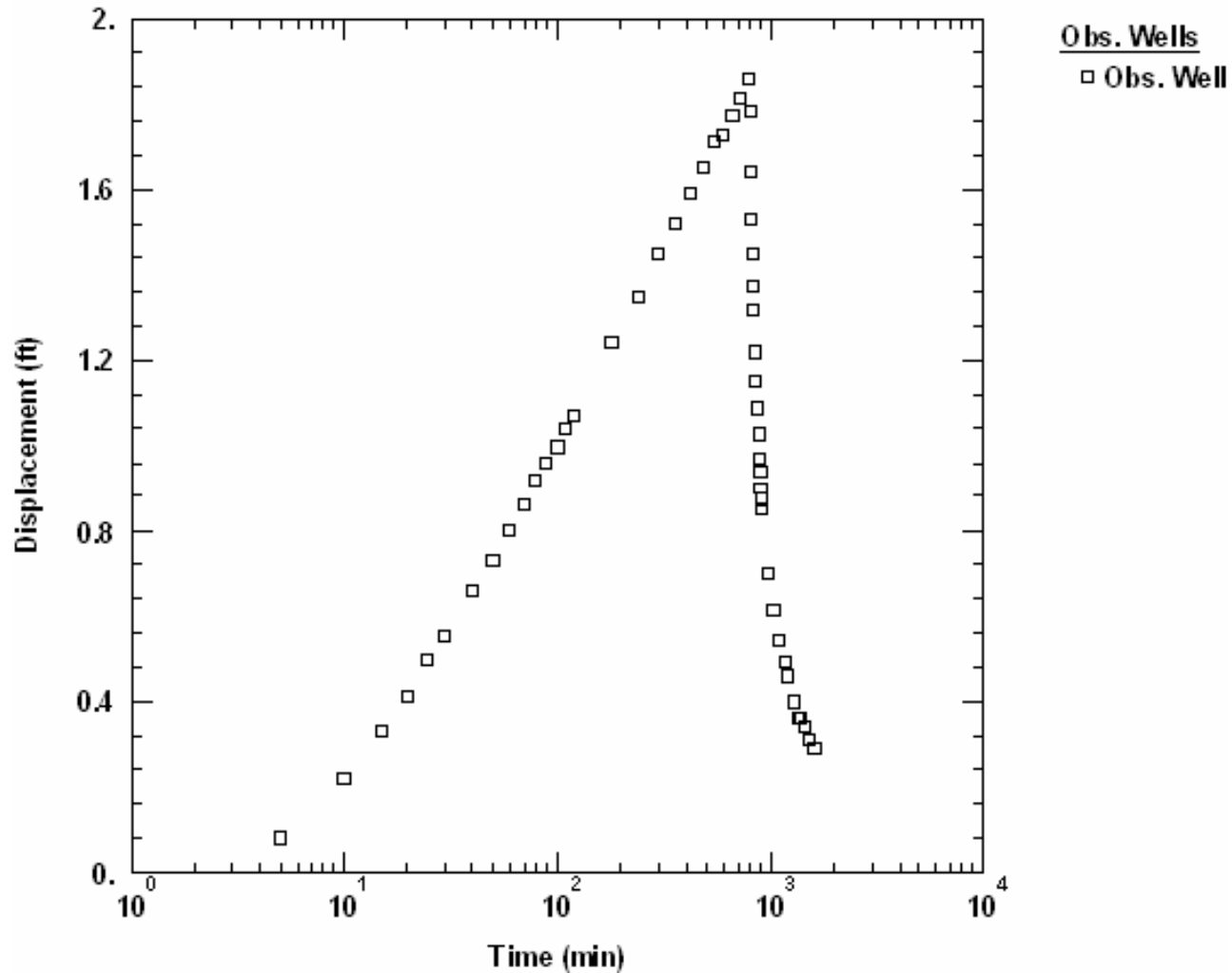
Derivative analysis is another useful diagnostic tool for evaluating aquifer conditions.

1. Choose Displacement-Time from the **View** menu to display a plot of the test data. On semi-log axes, this plot is identical to the radial flow plot above.

2. Choose Log Axes from the **View** menu to plot the data on log-log axes.

3. Choose Wells from the **Edit** menu. Select **Obs. Well** from the list and click **Modify**.

    In the **Symbols** tab, remove the check from **Use data symbols properties** and select **cross** for the derivative symbol.

    In the **Curves** tab, remove the check from **Use type curve properties**. Click **Color** for the derivative curve properties, change the color to **red**, and click **OK**.

    Click **OK** and then **Close**.

4. Select Options from the **View** menu. In the **Plots** tab, check **Derivative curves**. In the **Derivative** tab, select the option for **Spane** and enter **0.3** for the differentiation interval. Click **OK**.

View Derivative Plot

During the first 800 minutes of the test (prior to the peak in the drawdown data), the derivative approaches a constant value with time which is characteristic of radial flow in an infinite confined aquifer.
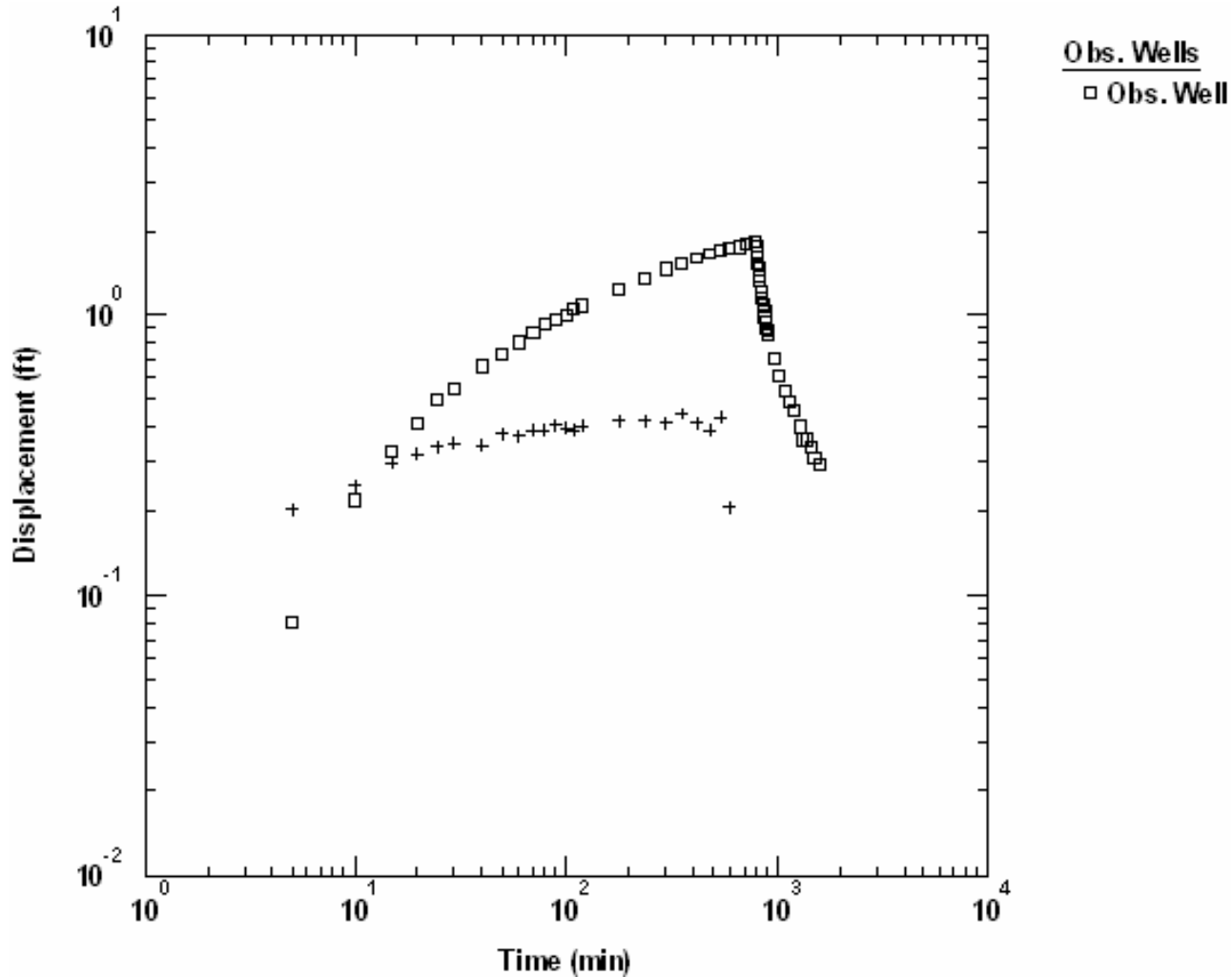
Match Solution to Recovery Data

The radial flow and derivative plots that we have examined for this test confirm the assumption of radial flow in an infinite-acting confined aquifer. You could begin the analysis of this test by analyzing either the drawdown or the recovery data, but in this example, you will start with the recovery phase of the test.

Begin your analysis using the familiar Theis (1935) residual drawdown method which matches a straight line to the recovery data on a residual drawdown plot.

1. Choose Solution from the **Match** menu to select a method for analyzing the

data.

2. Remove the check from **Solution is inactive**. Click the **+** next to **Confined Aquifers** to expand the list of available solutions for confined aquifers. Select **Theis (1935) residual drawdown/recovery** and click **OK**.

3. Choose Residual Drawdown from the **View** menu.

The graph on log-linear axes shows residual drawdown, s', plotted as a function of t/t' where t is time since pumping began and t' is time since pumping stopped. Early recovery data (large t/t') plot to the right; as recovery continues (decreasing s'), t/t' approaches unity.

4. Choose Visual from the **Match** menu to perform visual curve matching with the Theis residual drawdown solution.

Match the straight line to late-time recovery data (t/t' approaching unity) to achieve a valid match with the Theis residual drawdown solution.

To perform visual matching, move the mouse to a point where you wish to begin drawing a new line.

Click and hold down the left mouse button to anchor the new line at this point.

Continue to hold the mouse button down and move the mouse to match a new straight line to your data. As you move the mouse, AQTESOLV draws a straight line between the anchor point and the position of the mouse.

Release the left mouse button when you have finished matching a new straight line. AQTESOLV automatically updates the plot legend to reflect changes in parameter values.

5. Repeat the previous step as needed to achieve a satisfactory match.

View Visual Match With Theis Residual Drawdown

Obs. Wells
□ Obs. Well

Aquifer Model
Confined

Solution
Theis (Recovery)

Parameters
T   = 31.32 ft^2/min
S/S' = 0.9871

(Chart y-axis: Residual Drawdown (ft), x-axis: Time, t/t')
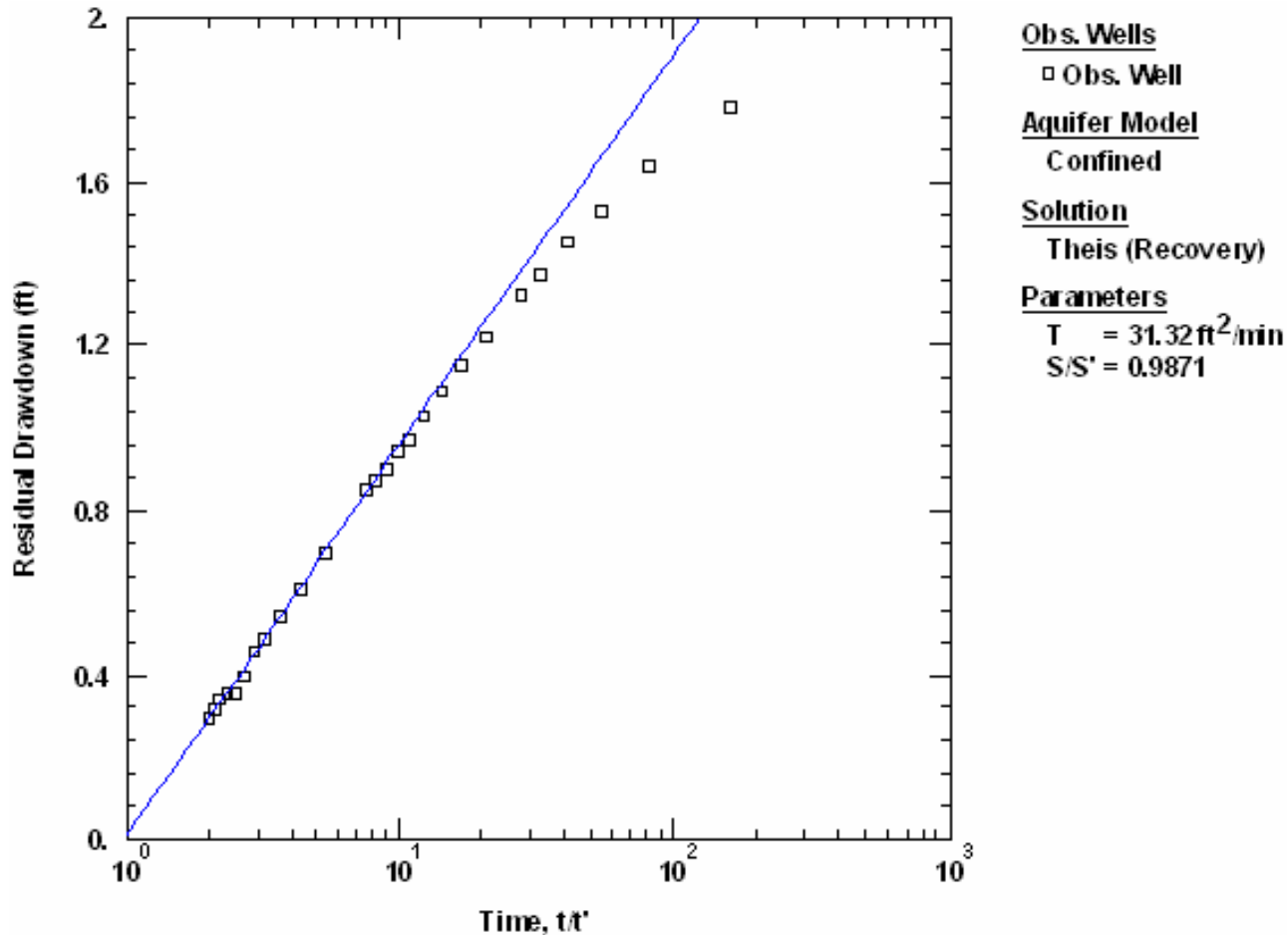
6. Curve matching with straight-line methods relies on your judgment to position the line over the appropriate range of data; therefore, visual curve matching is generally more efficient than automatic curve matching.

Now you will use Agarwal's method to analyze the same recovery data with the Theis (1935) solution. Agarwal's procedure is used routinely in the petroleum industry for recovery test analysis.

1. Choose Solution from the **Match** menu to select a method for analyzing the data.

2. From the list of solutions for **Confined Aquifers**, select **Theis (1935)** and click **OK**.

3. Choose Agarwal from the **View** menu.

   The Agarwal method plots recovery as a function of Agarwal equivalent time. Through a simple transformation of the time scale, Agarwal's method enables you to analyze recovery data with type curves developed for drawdown analysis.

4. Choose Log Axes from the **View** menu.

   The plot displays two curves. The blue curve is the recovery predicted by the

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5. Choose Visual from the **Match** menu to perform visual curve matching with the Theis solution using Agarwal's method for recovery data.

Click and hold the left mouse button down over a point within the plot area.

Continue to hold the mouse button down and move the mouse to match the curves to the recovery and derivative data. As you move the type curve, AQTESOLV automatically updates the plot legend to reflect changes in parameter values.

Release the left mouse button when you have finished matching the curves.

---

6. Repeat the previous step as need to match the recovery data.

View Agarwal Match

Match Solution to Drawdown and Recovery Data

You are not limited to analyzing recovery data separately from drawdown data as we did in the previous section. Now you will use the Theis (1935) solution to analyze drawdown and recovery together.

> You may use any pumping test solution in AQTESOLV (with the exception of straight-line methods) to combine the analysis of drawdown and recovery data.

1. Choose Displacement-Time from the **View** menu to display a plot of drawdown/residual drawdown versus time.

2. Choose Log Axes from the **View** menu to display the plot on log-log axes.

3. Choose Automatic from the **Match** menu and click **Estimate** to perform automatic curve matching.

   During the iterative estimation procedure, AQTESOLV displays a progress window and updates the curves displayed on the plot in the background.

4. When estimation has finished, click **OK** and then **Close**. Click **OK** to view the new position of the type curve.

   The estimated values of T and S are close to the values determined from visual curve matching.

   View Automatic Match for Drawdown and Recovery Data

The plot legend shows:

Obs. Wells
☐ Obs. Well

Aquifer Model
Confined

Solution
Theis

Parameters
$T = 31.43 \text{ ft}^2/\text{min}$
$S = 0.06633$
$Kz/Kr = 1.$
$b = 100. \text{ ft}$

5. Use residual-time, residual-simulated and normal probability plots to evaluate the fit of the curve by examining residuals. The diagnostics report also presents residual statistics for curve fitting.

6. Choose Active Curves from the **Match** menu to perform visual curve matching with **Active Type Curves**.

Use **Active Type Curves** when matching pumping test data with variable rates (including recovery). Visual curve matching with the active curves option in AQTESOLV is a major improvement over static (traditional) curves that assume a constant pumping rate. Active type curves are enabled when you see a check next to the Active Curves option in the **Match** menu.

Click and hold the left mouse button down over a point within the plot area.

Continue to hold the mouse button down and move the mouse to match the curves to the drawdown and derivative data. As you move the type curve, AQTESOLV automatically updates the plot legend to reflect changes in parameter values.

Release the left mouse button when you have finished matching the curves.

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

Pumping Test Example: Variable Rate

This example guides you through the analysis of drawdown and recovery data from a hypothetical variable-rate pumping test in a nonleaky confined aquifer (modified from Kruseman and De Ridder 1990). The rate in the fully penetrating test well changed in a stepwise fashion over a period of 150 minutes.

Step	Elapsed Time (min)	Duration (min)	Rate (m³/day)
1	0	30	500
2	30	50	700
3	80	50	600
4	150	-	0

Drawdown was measured in an observation well located 5 m from the test well. Recovery was monitored after pumping stopped at 150 minutes.

This example will introduce you to the following tasks and features in AQTESOLV:

- Creating a new data set for a recovery test with the Pumping Test Wizard

- Importing data from a text file

- Saving a data set

- Estimating aquifer properties using Theis (1935) solution (visual and automatic)

- Matching data with active type curves

While following the steps in this example, click **Help** or press **F1** to context sensitive help in the AQTESOLV application.

Create a New Data Set with Pumping Test Wizard

The first step in analyzing data from a pumping test is to create a new AQTESOLV data set. In this example, you will use the Pumping Test Wizard to assist with data entry.

1. Create a new data set by choosing New from the **File** menu.

2. In the **New Data Set** dialog, select **Pumping Test Wizard** from the list. Click **OK**.

3. Choose **Multiwell test** for the type of pumping test. Click **OK**.

4. The **Pumping Test Wizard** prompts you for data required to analyze a pumping test. Click **Next** to begin the wizard.

5. For units of measurement, choose **m** for length, **min** for time, **m³/day** for pumping rate and **m/day** for hydraulic conductivity. Click **Next**.

6. For project information, enter **Variable-Rate Test** for the title. Click **Next**.

7. For aquifer data, assume **50** for the aquifer thickness. Enter **1** for the anisotropy ratio (i.e., assume hydraulic conductivity is isotropic). Click **Next**.

8. For pumping well data, enter **PW** for the well name. Enter coordinates of **X=0** and **Y=0**. Click **Next**.

9. For pumping well construction, select the option for **vertical, full penetration**. Click **Next**.

10. For pumping well radius data, assume **0.25** for casing radius and **0.25** for well radius. Click **Next**.

11. For pumping rates, click **Add Rows**. Enter **3** for the number of rows to add and click **OK**. Enter the rates for the test as shown below. Click **Next**.

Enter the time for pumping periods as time since the start of the test. To enter recovery, enter the time when pumping stopped and a rate of zero.

12. For observation well data, enter **OW** for the well name. Enter **5** and **0** for the

X and Y coordinates, respectively. Click **Next**.

13. For observation well construction, select the option for **vertical, full penetration**. Click **Next**.

14. For observations, click **Import** to launch the Observation Data Import Wizard for importing data from a file.

    You will import a text file consisting of time-drawdown readings arranged in two columns. The first column is elapsed time since the start of the test. The second column contains drawdown and recovery measurements.

> In Step 1 of the wizard, click **Browse**. Select the import file **Variable Rate.txt** in the AQTESOLV installation folder and click **Open**. Click **Next**.
>
> In Step 2 of the wizard, use the defaults determined by the Import Wizard. Click **Next**.
>
> In Step 3 of the wizard, accept the defaults and click **Finish**. Inspect the import file summary and click **OK**.
>
> Click **Next** to proceed with the **Pumping Test Wizard**.

15. You have completed the **Pumping Test Wizard**. Click **Finish**.

After completing the **Pumping Test Wizard**, AQTESOLV automatically displays an Error Log to let you know if the data set contains any errors. If the **Error Log** identifies any mistakes, choose options from the Edit menu to correct them.

Save Data Set

At this point, it's a good idea to save your work.

Save the data set by choosing Save As from the **File** menu. Choose a folder and enter **Variable Rate** for the name of the file. Click **Save**. The default extension for an AQTESOLV data set is **.aqt**.

Match Solution to Drawdown and Recovery Data

Use the Theis (1935) solution to analyze drawdown and recovery together.

> You may use any pumping test solution in AQTESOLV (with the exception of straight-line methods) to combine the analysis of drawdown and recovery data.

1. Choose Solution from the **Match** menu to select a method for analyzing the data.

2. Remove the check from **Solution is inactive**. Click the **+** next to **Confined Aquifers** to expand the list of available solutions for confined aquifers. Select **Theis (1935)** and click **OK**.

3. Choose Displacement-Time from the **View** menu to display a plot of drawdown/residual drawdown versus time.

4. Choose Log Axes from the **View** menu to display the plot on log-log axes.

5. Choose Automatic from the **Match** menu and click **Estimate** to perform automatic curve matching.
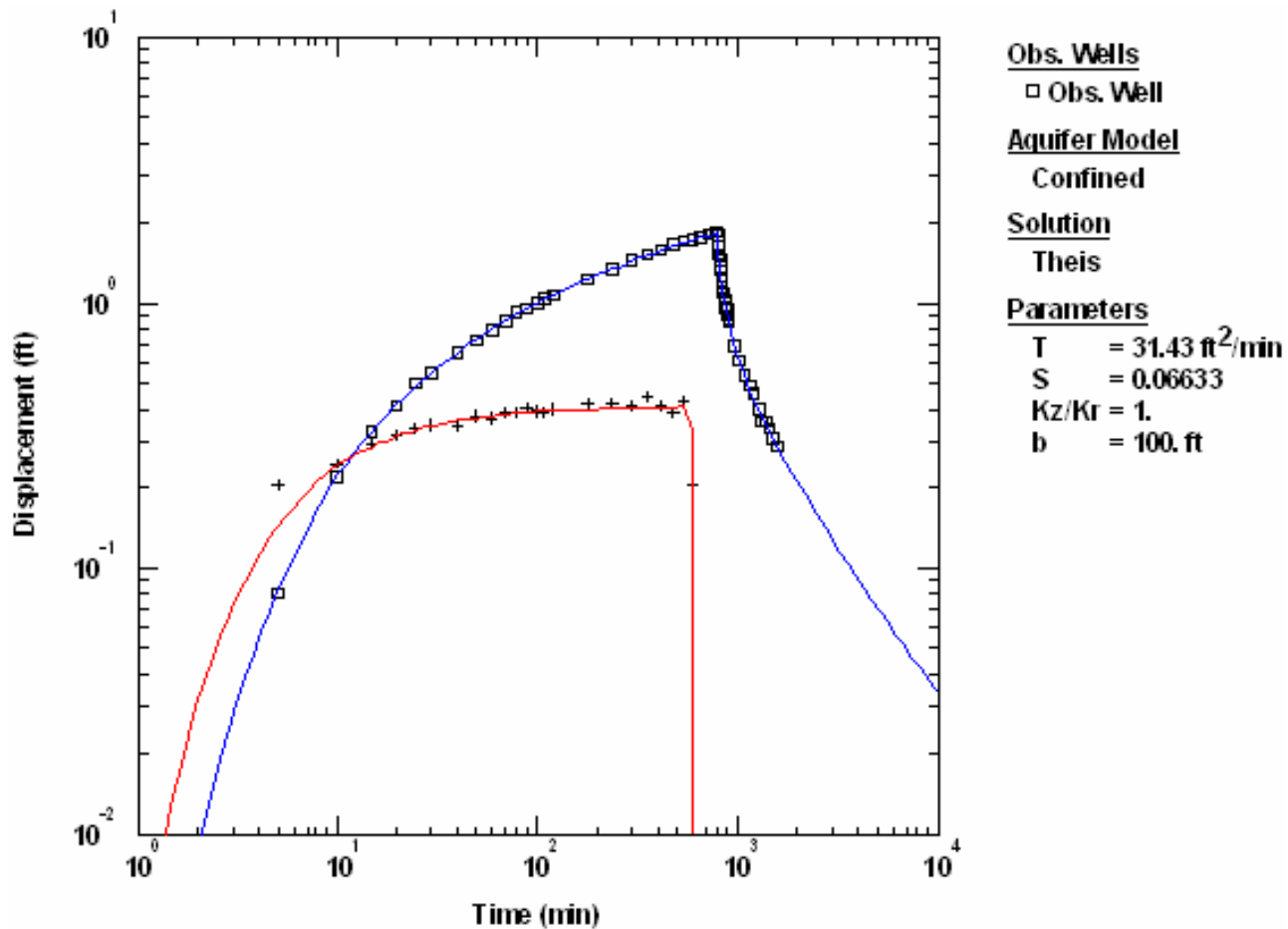
   During the iterative estimation procedure, AQTESOLV displays a progress window and updates the curves displayed on the plot in the background.

6. When estimation has finished, click **OK** and then **Close**. Click **OK** to view the new position of the type curve.

   View Automatic Match for Drawdown and Recovery Data

7. Use residual-time, residual-simulated and normal probability plots to evaluate the fit of the curve by examining residuals. The diagnostics report also presents residual statistics for curve fitting.

8. Choose Active Curves from the **Match** menu to perform visual curve matching with **Active Type Curves**.

   Use **Active Type Curves** when matching pumping test data with variable rates (including recovery). Visual curve matching with the active curves option in AQTESOLV is a major improvement over static (traditional) curves

Click and hold the left mouse button down over a point within the plot area.

Continue to hold the mouse button down and move the mouse to match the curve to the drawdown data. As you adjust the curve, AQTESOLV automatically updates the plot legend to reflect changes in parameter values.

Release the left mouse button when you have finished matching the curves.

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

Match Solution to Recovery Data

Now you will use Agarwal's method to analyze the recovery data with the Theis (1935) solution. Agarwal's procedure is used routinely in the petroleum industry for recovery test analysis.

1. Choose Agarwal from the **View** menu.

    The Agarwal method plots recovery as a function of Agarwal equivalent time. Through a simple transformation of the time scale, Agarwal's method enables you to analyze recovery data from a variable-rate test with type curves developed for constant-rate drawdown analysis.

2. Choose Log Axes from the **View** menu.

3. Choose Visual from the **Match** menu to perform visual curve matching with the Theis solution using Agarwal's method for recovery data.

Click and hold the left mouse button down over a point within the plot area.

Continue to hold the mouse button down and move the mouse to match the curve to the recovery data. As you move the type curve, AQTESOLV automatically updates the plot legend to reflect changes in parameter values.

Release the left mouse button when you have finished matching the curves.

4. Repeat the previous step as need to match the recovery data.

    View Match with Agarwal Method

Variable-Rate Test
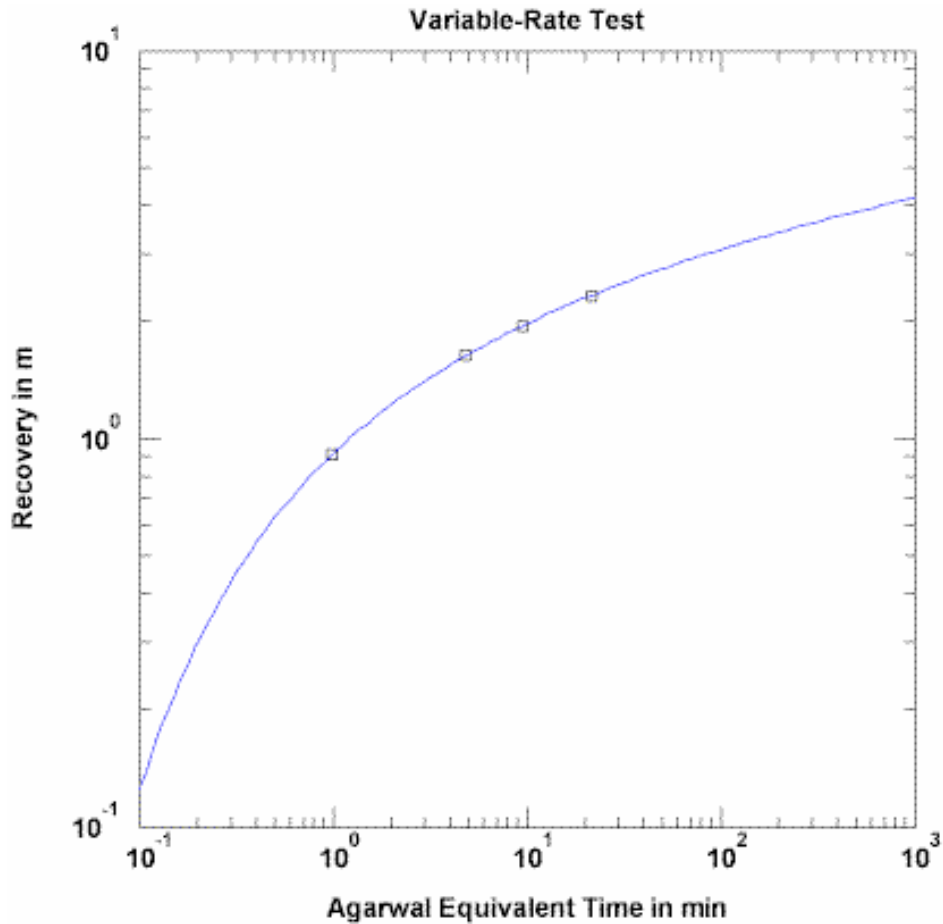
Obs. Wells
□ OW

Aquifer Model
Confined

Solution
Theis

Parameters
T   = 100.1 m²/day
S   = 0.001002
Kz/Kr = 1.
b   = 50. m

Recovery in m (y-axis)

Agarwal Equivalent Time in min (x-axis)

Pumping Test Example: Wellbore Storage (Saudi Arabia)

In this example, you will analyze data from a single-well pumping test described by Sen (1995). The 3-m diameter test well fully penetrates an aquifer consisting of fine- and coarse-grained Quaternary deposits in wadi Uoranah in the eastern provinces of Saudi Arabia. The aquifer is reportedly overlain by a thin layer of silt. Pumping continued for more than 200 minutes at a constant rate of 0.478 m³/min. Time and drawdown measurements were recorded in minutes and meters, respectively.

This example will introduce you to the following tasks and features in AQTESOLV:

- Creating a new data set with the Pumping Test Wizard

- Importing data with the Observation Data Import Wizard

- Saving a data set

- Inspecting diagnostic plots (radial flow and derivative)

- Estimating aquifer properties using the Cooper-Jacob (1946) and Papadopulos-Cooper (1967) solutions (visual and automatic)

> While following the steps in this example, click **Help** or press **F1** to obtain context sensitive help in the AQTESOLV application.

Create a New Data Set with Pumping Test Wizard

The first step in analyzing data from a single-well pumping test is to create a new AQTESOLV data set. In this example, we will use the Pumping Test Wizard to assist us with data entry.

1. Create a new data set by choosing New from the **File** menu.

2. In the **New Data Set** dialog, select **Pumping Test Wizard** from the list. Click **OK**.

3. Choose **Single-well test** for the type of pumping test. Click **OK**.

4. The **Pumping Test Wizard** prompts you for data required to analyze a single-well pumping test. Click **Next** to begin the wizard.

5. For units of measurement, choose **m** for length, **min** for time, **consistent** for pumping rate and **m/day** for hydraulic conductivity. Click **Next**.

   Consistent units for pumping rate are based on the units of length and time selected for the data set. In this example, consistent units are m^3/min for Q.

6. For project information, enter **Saudi Arabia** for the location. Click **Next**.

7. For aquifer data, assume **100** for the aquifer thickness. Enter **1** for the anisotropy ratio (i.e., assume hydraulic conductivity is isotropic). Click **Next**.

8. For pumping well data, enter **PW** for the well name. Enter coordinates of X=0 and Y=0. Click **Next**.

9. For pumping well construction, select the option for **vertical, full penetration**. Click **Next**.

10. For pumping well radius data, enter **1.5** for casing radius and **1.5** for well radius. Click **Next**.

11. For pumping rates, enter **0** for time and **0.478** for rate in the first row of the spreadsheet. Click **Next**.

12. For observations, click **Import** to launch the Observation Data Import Wizard for importing data from a file.

We will import a text file consisting of 39 time-drawdown readings arranged in two columns. The first column is elapsed time since the start of the test. The second column contains drawdown measurements.

In Step 1 of the wizard, click **Browse**. Select the import file **Uoranah.txt** in the AQTESOLV installation folder and click **Open**. Click **Next**.

In Step 2 of the wizard, accept the default entries and click **Next**.

In Step 3 of the wizard, click **Finish**. Inspect the import file summary and click **OK**.

Click **Next** to proceed with the **Pumping Test Wizard**.

13. You have completed the **Pumping Test Wizard**. Click **Finish**.

After completing the **Pumping Test Wizard**, AQTESOLV automatically displays an Error Log to let you know if the data set contains any errors. If the **Error Log** identifies any mistakes, choose options from the Edit menu to correct them.

Save Data Set

At this point, it's a good idea to save your work.

Save the data set by choosing Save As from the **File** menu. Choose a folder, enter **Uoranah** for the name of the file and click **Save**. AQTESOLV saves the file with an **.aqt** extension.

Inspect Diagnostic Plots

Before performing curve matching to estimate aquifer properties, you may use diagnostic features in AQTESOLV to evaluate aquifer and flow conditions.

Diagnostic flow plots help you select an appropriate solution method for your pumping test data.

1. Choose Radial Flow from the **View** menu to display a radial flow plot on log-linear axes.

View Semi-Log Radial Flow Plot

At late time, the data begin to flatten suggesting the influence of a recharge boundary or leakage. Prior to the recharge effect, data plotting as a straight line indicates radial flow conditions in an infinite-acting aquifer.
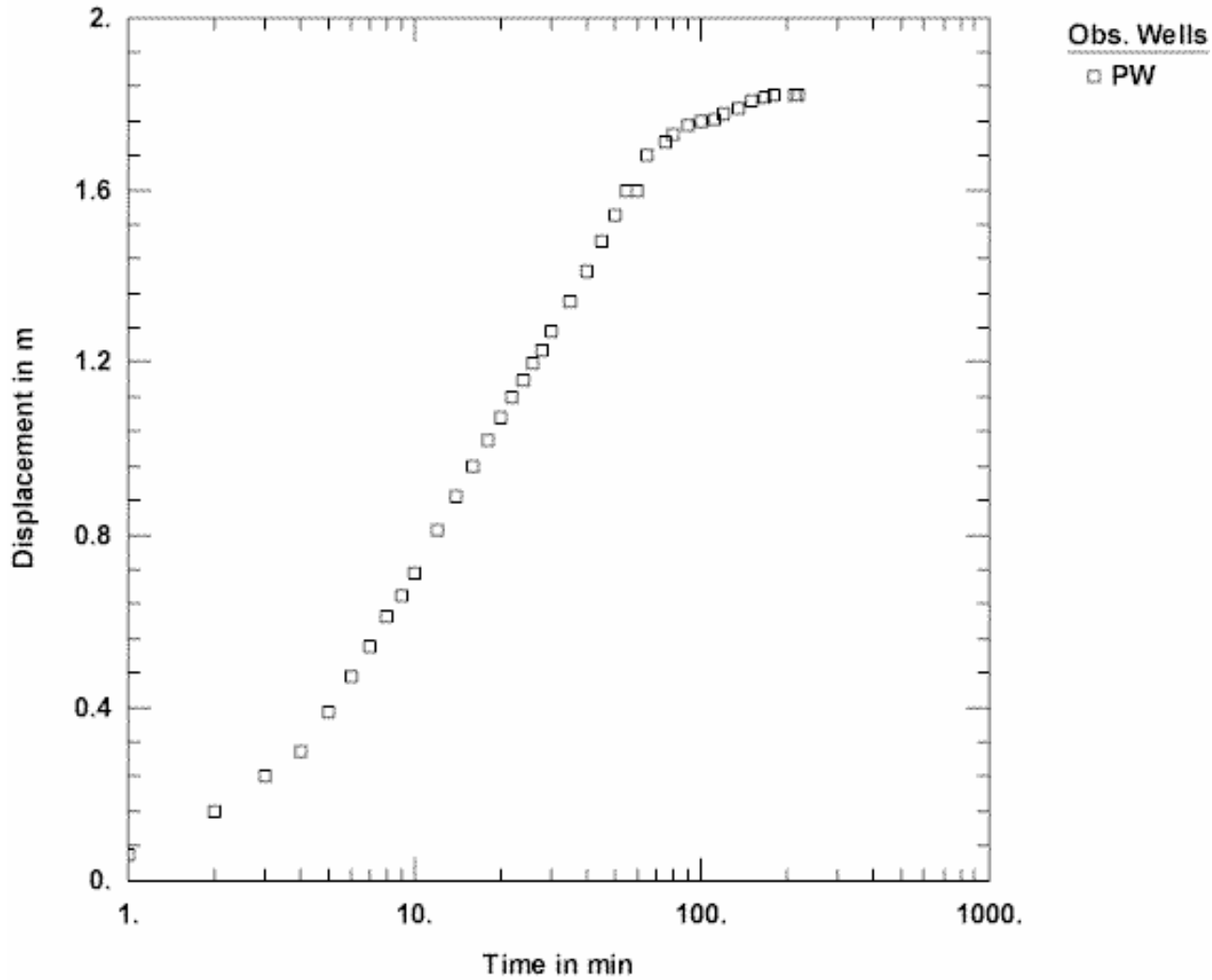
Obs. Wells
□ PW

2. Choose Log Axes from the **View** menu to display the radial flow plot on log-log axes.

3. Choose Visual from the **Match** menu. Click the mouse over the second data point on the plot to display a line with unit slope over the early-time data.

View Log-Log Radial Flow Plot

Early-time data with unit slope on a radial flow plot with log-log axes is characteristic of wellbore storage.

Derivative analysis is another useful diagnostic tool for evaluating aquifer conditions.

1. Choose Displacement-Time from the **View** menu to display a plot of the test data. On semi-log axes, this plot is identical to the radial flow plot above.

2. Choose Wells from the **Edit** menu. Select **PW** from the list and click **Modify**.

    In the **Symbols** tab, remove the check from **Use data symbols properties** and select **cross** for the derivative symbol.

    In the **Curves** tab, remove the check from **Use type curve properties**. Click **Color** for the derivative curve properties, change the color to **red**, and click **OK**.

    Click **OK** and then **Close**.

3. Select Options from the **View** menu. In the **Plots** tab, check **Derivative curves**. In the **Derivative** tab, select the option for **Smoothing** and enter a factor of **2**. Click **OK**.

    View Derivative Plot

Estimate Aquifer Properties

The radial flow and derivative plots that we have examined for this test suggest a confined or semi-confined aquifer. Although the data exhibit wellbore storage, we can use the Cooper-Jacob (1946) solution, which neglects storage in the wellbore, to obtain preliminary estimates of aquifer properties.

1. Choose Solution from the **Match** menu to select a method for analyzing the data.

2. Remove the check from **Solution is inactive**. Click the **+** next to **Confined Aquifers** to expand the list of available solutions for confined aquifers. Select **Cooper-Jacob (1946)** and click **OK**.

3. Choose Displacement-Time from the **View** menu.

4. Choose Visual from the **Match** menu to perform visual curve matching with the Cooper-Jacob solution. Match the line to late-time data after the wellbore storage effect has dissipated but before the onset of the recharge effect.

> To perform visual matching, move the mouse to a point where you wish to begin drawing a new line with the Cooper-Jacob solution.
>
> Click and hold down the left mouse button to anchor the new line at this point.
>
> Continue to hold the mouse button down and move the mouse to match a new straight line to your data. As you move the mouse, AQTESOLV draws a straight line between the anchor point and the position of the mouse.
>
> Release the left mouse button when you have finished matching a new straight line. AQTESOLV automatically updates the plot legend to reflect changes in parameter values.

5. Repeat the previous step as needed to achieve a satisfactory match to the late-time data. Your estimate of T should be on the order of 500 m^2/day. Because Cooper-Jacob assumes a line source for the pumped well, the estimate of S is less reliable.

 View Visual Match with Cooper-Jacob
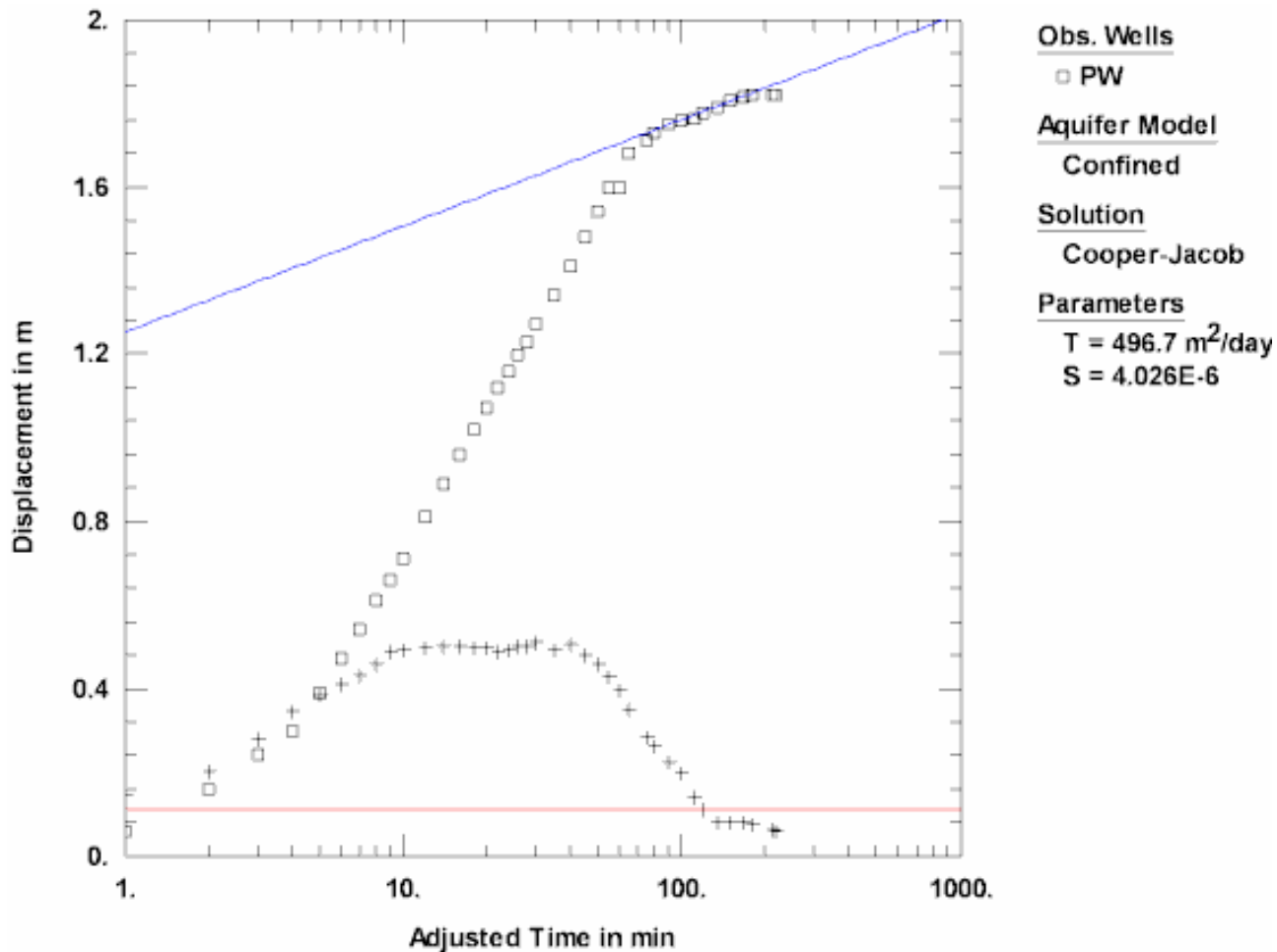
Having completed our preliminary analysis with Cooper-Jacob, let's account for wellbore storage by matching the Papadopulos-Cooper (1967) solution to the data.

1. Choose Solution from the **Match** menu to select a method for analyzing the data.

2. From the list of solutions for **Confined Aquifers**, select **Papadopulos-Cooper (1967)** and click **OK**.

3. Choose Log Axes from the **View** menu to view the data on log-log axes.

4. Choose Toolbox from the **Match** menu. In the **Tweak** tab, select **r(c)** from the list of parameters. Use the scroll bar to adjust the value of casing radius to match the early-time data. You can limit the range of casing radius values by editing the minimum and maximum values for r(c) in the **Parameters** tab. After you have aligned the curve with the early-time data, click **OK**.

View Tweaked Casing Radius

Adjust the casing radius value to match early-time data affected by wellbore storage. In many cases, the effective casing radius turns out to be less than the nominal value because of equipment in the well such as discharge tubing

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and transducer cable.
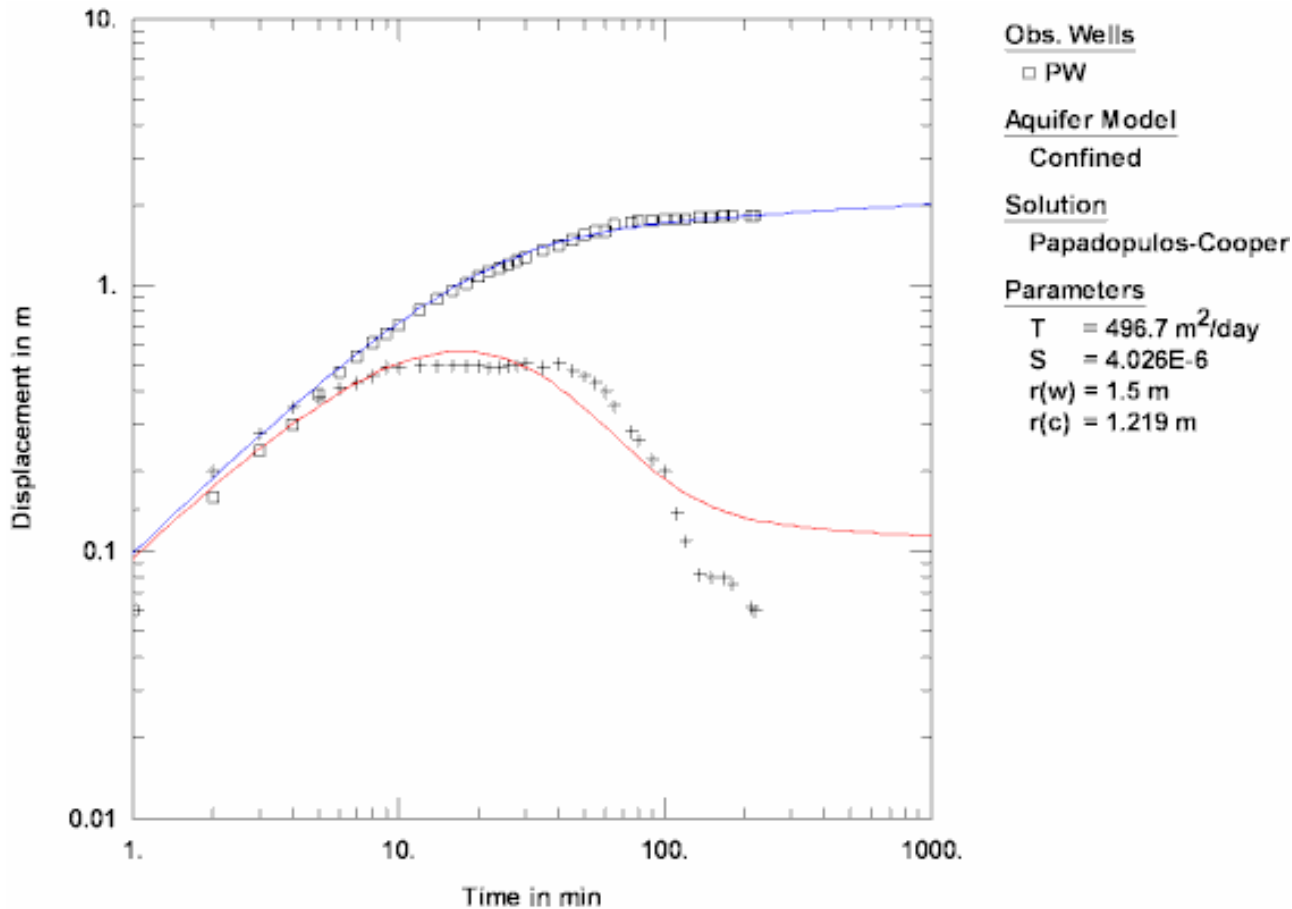
5. Choose Active Curves from the **Match** menu to initiate visual curve matching with **Active Type Curves**.

> Click and hold the left mouse button down over a point within the plot area.
>
> Continue to hold the mouse button down and move the mouse to match the curves to the drawdown and derivative data. As you move the type curve, AQTESOLV automatically updates parameter values in the plot legend.
>
> Release the left mouse button when you have finished matching the curves.

6. Repeat the previous step as necessary to match the data.

7. Choose Wells from the **Edit** menu. Select **PW** from the list and click **Modify**. In the **Observations** tab, scroll to the bottom of the spreadsheet. Change the weight for the last three observations to **0**. By changing the weights to zero, these observations, which reflect the influence of recharge or leakage, will be ignored during automatic curve matching. Click **OK** and **Close**.

You may use observation weights to control which measurements are

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8. Choose Automatic from the **Match** menu. In the Parameters tab, select **Active** for the estimation status of r(c) and **Inactive** for r(w). In the equations for the Papadopulos-Cooper solution, the values of S and r(w) are correlated (i.e., appear together); hence we are unable to estimate both parameters simultaneously in a single-well test. Click **Estimate** to perform automatic curve matching.

9. When estimation has finished, click **OK** and then **Close**. Click **OK** to view the new position of the type curve.

View Automatic Match with Papadopulos-Cooper
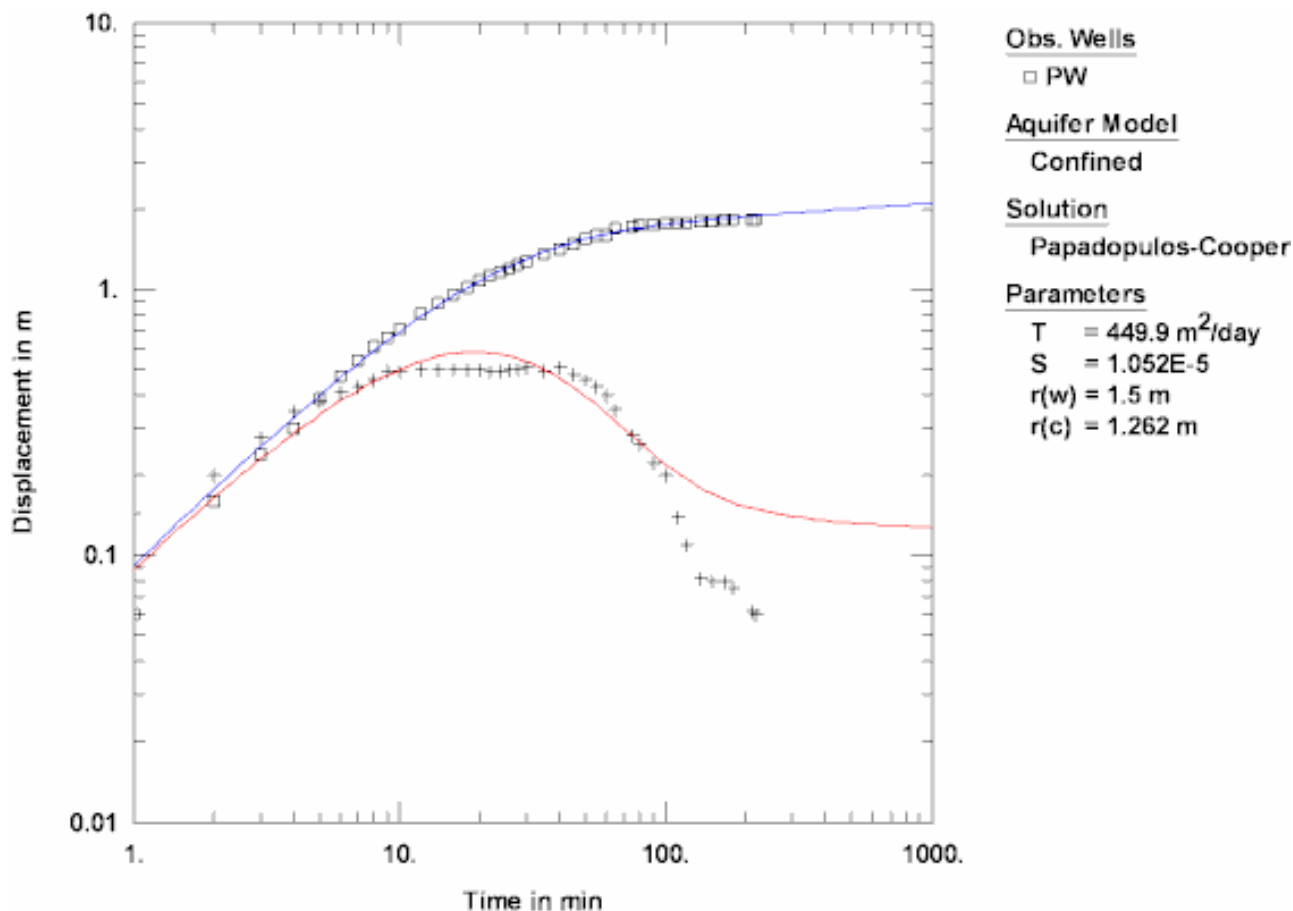
10. Use residual-time, residual-simulated and normal probability plots to evaluate the fit of the curve by examining residuals. The diagnostics report also presents residual statistics for curve fitting.

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

Evaluate Sources of Recharge

No specific information is available to define potential sources of recharge at the site such as aquifer boundaries. Nevertheless, we can use AQTESOLV to simulate a stream boundary.

1. Choose Aquifer Data from the **Edit** menu. In the **Boundaries** tab, check **Enable Boundaries**. Assume a single linear boundary and select **Constant-Head** for condition along boundary B-C. For the remaining boundaries, A-B, C-D and D-A, choose **None** for the boundary condition.

   Next, enter two points along the boundary B-C. To place the boundary 1800 m from the pumped well, enter **1800** and **100** for the coordinates of point B and **1800** and **-100** for point C.

   Click **Apply** to view the effect of the constant-head boundary on the simulated drawdown curve. You can change the distance to the boundary to evaluate different boundary locations.

   Remove the check from **Enable Boundaries** and click **OK**.

   View Effect of Constant-Head Boundary at 1800 m
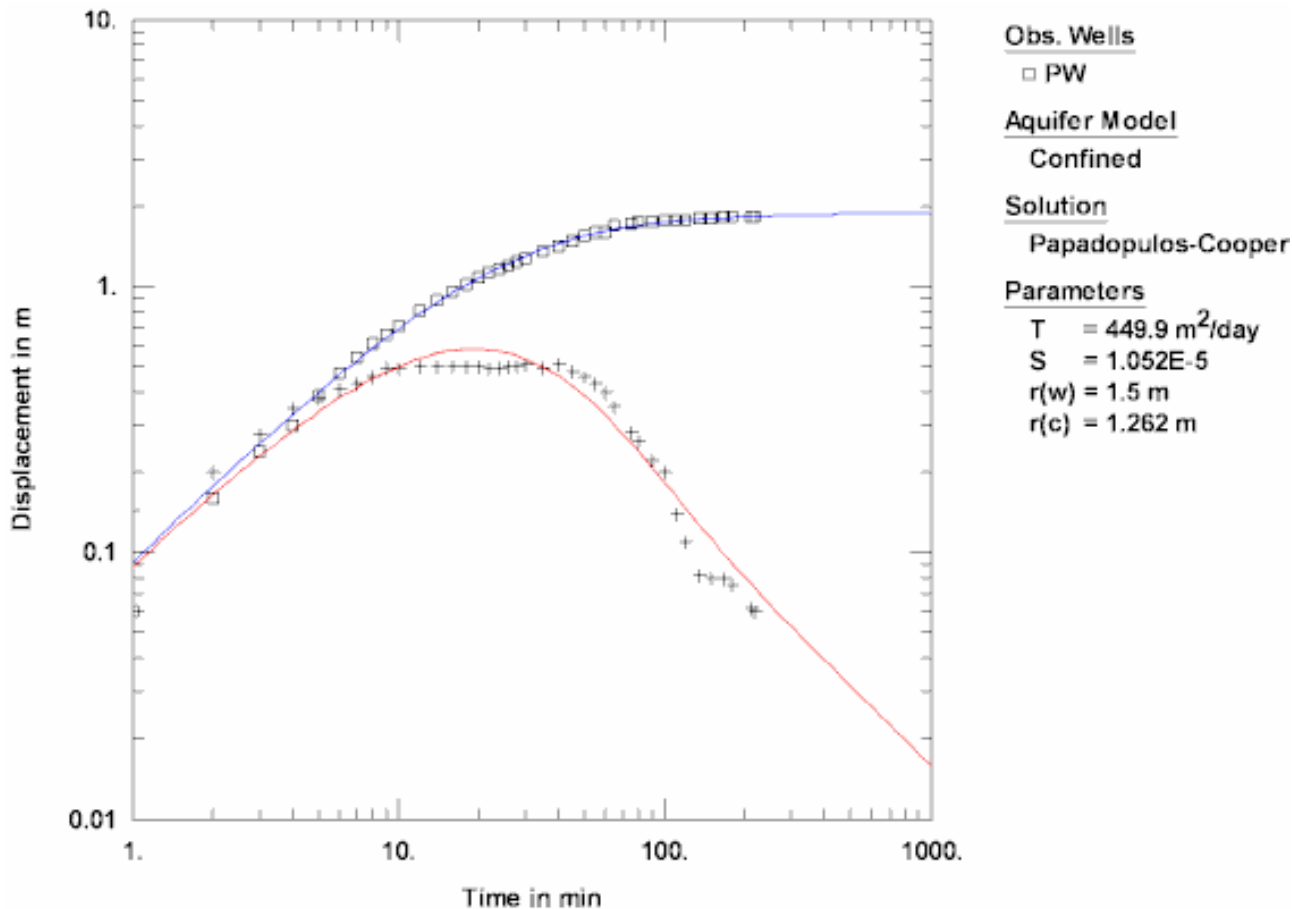
Pumping Test Example: Wellbore Storage and Skin (Lynden)

In this example, you will analyze data from a single-well pumping test conducted in a 500-ft deep confined aquifer near Lynden, Washington. The six-inch diameter test well was constructed in an eight-inch borehole. The well is screened over the lower 10 feet of the sand and gravel comprising the 40-ft thick aquifer. Pumping continued for more than two weeks at a constant rate of 50 gallons-per-minute (gpm). Time and drawdown measurements were recorded in minutes and feet, respectively. Data for this example provided courtesy of Associated Earth Sciences, Inc.

This example will introduce you to the following tasks and features in AQTESOLV:

- Creating a new data set with the Pumping Test Wizard

- Importing data with the Observation Data Import Wizard

- Saving a data set

- Inspecting diagnostic plots (radial flow and derivative)

- Visual estimation of aquifer properties using the Cooper-Jacob (1946) and Dougherty-Babu (1984) solutions (parameter tweaking)

> **TIP** While following the steps in this example, click **Help** or press **F1** to obtain context sensitive help in the AQTESOLV application.

Create a New Data Set with Pumping Test Wizard

The first step in analyzing data from a single-well pumping test is to create a new AQTESOLV data set. In this example, we will use the Pumping Test Wizard to assist us with data entry.

1. Create a new data set by choosing New from the **File** menu.

2. In the **New Data Set** dialog, select **Pumping Test Wizard** from the list. Click **OK**.

3. Choose **Single-well test** for the type of pumping test. Click **OK**.

4. The **Pumping Test Wizard** prompts you for data required to analyze a single-well pumping test. Click **Next** to begin the wizard.

5. For units of measurement, choose **ft** for length, **min** for time, **gal/min** for pumping rate and **ft/day** for hydraulic conductivity. Click **Next**.

6. For project information, enter **Lynden, WA** for the location. Click **Next**.

7. For aquifer data, assume **40** for the aquifer thickness. Enter **1** for the anisotropy ratio (i.e., assume hydraulic conductivity is isotropic). Click **Next**.

8. For pumping well data, enter **PW-3** for the well name. Enter coordinates of X=0 and Y=0. Click **Next**.

9. For pumping well construction, select the option for **vertical, partial penetration**. Enter **30** for depth to top of screen and **10** for screen length. Click **Next**.

10. For pumping well radius data, enter **0.333** for casing radius and **0.25** for well radius. Click **Next**.

11. For pumping rates, enter **0** for time and **50** for rate in the first row of the spreadsheet. Click **Next**.

12. For observations, click **Import** to launch the Observation Data Import Wizard for importing data from a file.

    We will import a text file consisting of 92 time-drawdown readings arranged in two columns. The first column is elapsed time since the start of the test. The second column contains drawdown measurements.

In Step 1 of the wizard, click **Browse**. Select the import file **PW-3.txt** in the AQTESOLV installation folder and click **Open**. Click **Next**.   In Step 2 of the wizard, accept the default entries and click **Next**.   In Step 3 of the wizard, click **Finish**. Inspect the import file summary and click **OK**.   Click **Next** to proceed with the **Pumping Test Wizard**.

13. You have completed the **Pumping Test Wizard**. Click **Finish**.

After completing the **Pumping Test Wizard**, AQTESOLV automatically displays an Error Log to let you know if the data set contains any errors. If the **Error Log** identifies any mistakes, choose options from the Edit menu to correct them.

Save Data Set

At this point, it's a good idea to save your work.

Save the data set by choosing Save As from the **File** menu. Choose a folder, enter **PW-3** for the name of the file and click **Save**. AQTESOLV saves the file with an **.aqt** extension.

Pro **Inspect Diagnostic Plots**

Before performing curve matching to estimate aquifer properties, you may use diagnostic features in AQTESOLV to evaluate aquifer and flow conditions.

Diagnostic flow plots help you select an appropriate solution method for your

pumping test data.

1. Choose Radial Flow from the **View** menu to display a radial flow plot on log-linear axes.

View Semi-Log Radial Flow Plot

Late-time data plotting as a straight line indicate radial flow conditions in an infinite-acting aquifer.

2. Choose Log Axes from the **View** menu to display the radial flow plot on log-log axes.

3. Choose Visual from the **Match** menu. Click the mouse over the second data point on the plot to display a line with unit slope over the early-time data.

View Log-Log Radial Flow Plot

Early-time data with unit slope on a radial flow plot with log-log axes is characteristic of wellbore storage.

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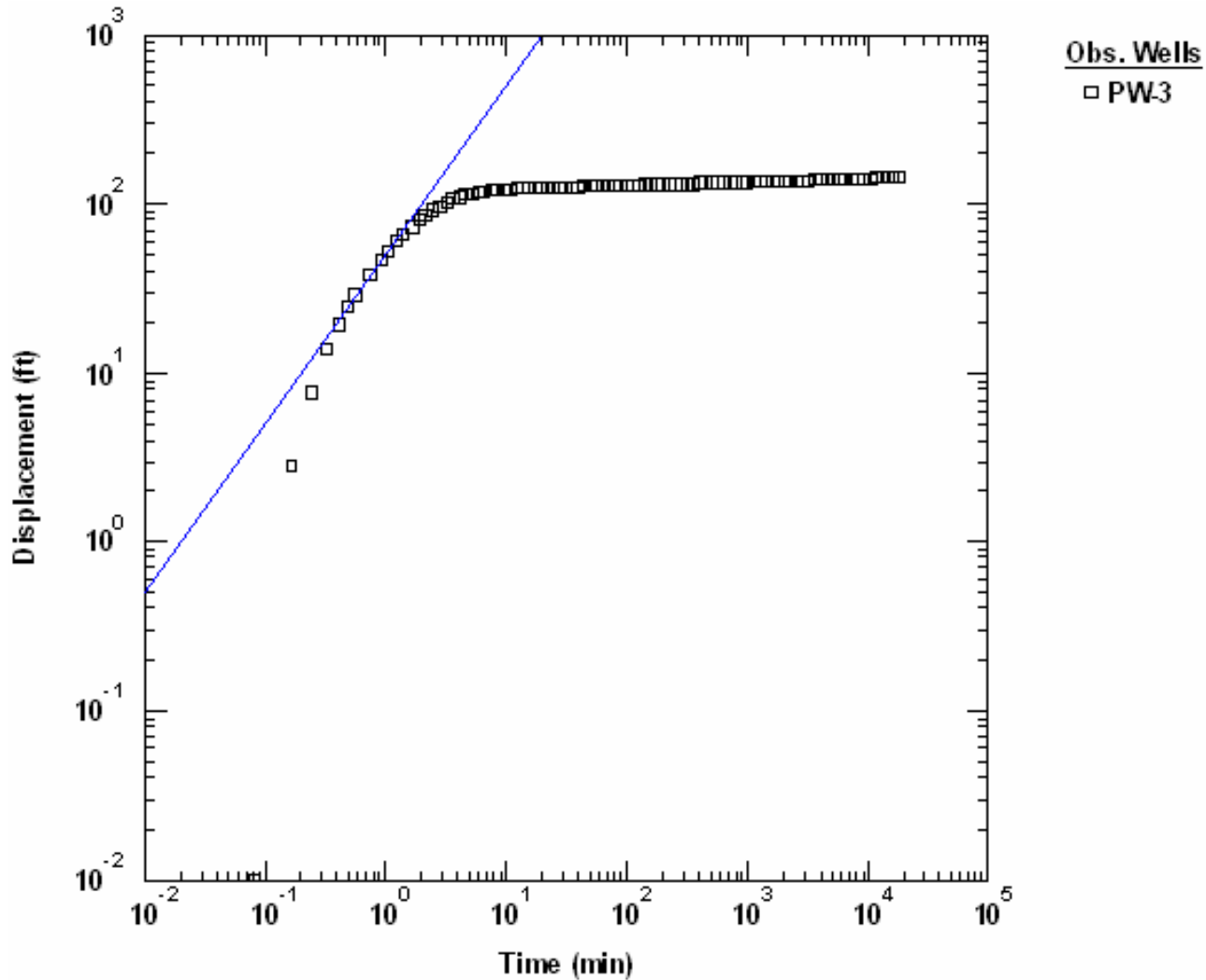
Derivative analysis is another useful diagnostic tool for evaluating aquifer conditions.

1. Choose Displacement-Time from the **View** menu to display a plot of the test data.

2. Choose Log Axes from the **View** menu to display the data on log-log axes.

3. Choose Wells from the **Edit** menu. Select **PW-3** from the list and click **Modify**.

    In the **Symbols** tab, remove the check from **Use data symbols properties** and select **cross** for the derivative symbol.

    In the **Curves** tab, remove the check from **Use type curve properties**. Click **Color** for the derivative curve properties, change the color to **red**, and click **OK**.

    Click **OK** and then **Close**.

4. Select Options from the **View** menu. In the **Plots** tab, check **Derivative**

curves. In the **Derivative** tab, select the option for **Bourdet** and enter a differentiation interval of **0.4**. Click **OK**.

View Derivative Plot

The peak on the derivative plot is characteristic of wellbore storage. At intermediate to late time, the derivative approaches a constant value when the aquifer is infinite acting.
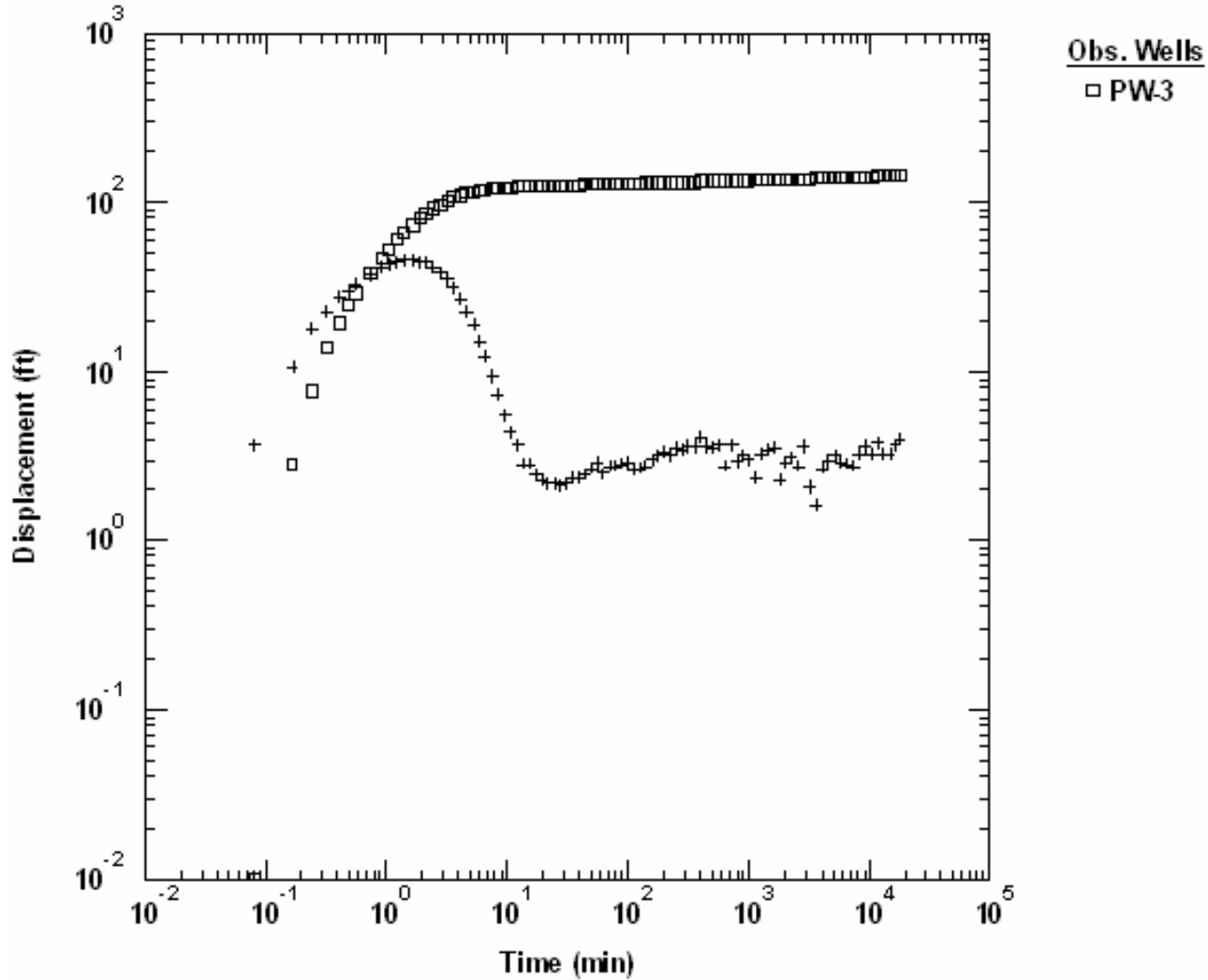
Estimate Aquifer Properties

The radial flow and derivative plots that we have examined for this test suggest a confined aquifer. Although the data exhibit wellbore storage, we can use the Cooper-Jacob (1946) solution, which neglects both wellbore storage and partial penetration, to obtain preliminary estimates of transmissivity.

1. Choose Solution from the **Match** menu to select a method for analyzing the data.

2. Remove the check from **Solution is inactive**. Click the **+** next to **Confined**

Aquifers to expand the list of available solutions for confined aquifers. Select **Cooper-Jacob (1946)** and click **OK**.

3. Choose Displacement-Time from the **View** menu.

4. Choose Visual from the **Match** menu to perform visual curve matching with the Cooper-Jacob solution. Match the line to late-time data after the wellbore storage effect has dissipated.

> To perform visual matching, move the mouse to a point where you wish to begin drawing a new line with the Cooper-Jacob solution.
>
> Click and hold down the left mouse button to anchor the new line at this point.
>
> Continue to hold the mouse button down and move the mouse to match a new straight line to your data. As you move the mouse, AQTESOLV draws a straight line between the anchor point and the position of the mouse.
>
> Release the left mouse button when you have finished matching a new straight line. AQTESOLV automatically updates the plot legend to reflect changes in parameter values.

5. Repeat the previous step as needed to achieve a satisfactory match to the late-time data. Your estimate of T should be on the order of 250 ft^2/day.

View Visual Match with Cooper-Jacob

The low value of S that you obtain with the Cooper-Jacob solution is an indication of partial penetration effect and possibly wellbore skin effect at the pumped well.

Obs. Wells
□ PW-3

Aquifer Model
Confined

Solution
Cooper-Jacob

Parameters
T = 250. ft²/day
S = 2.806E-16
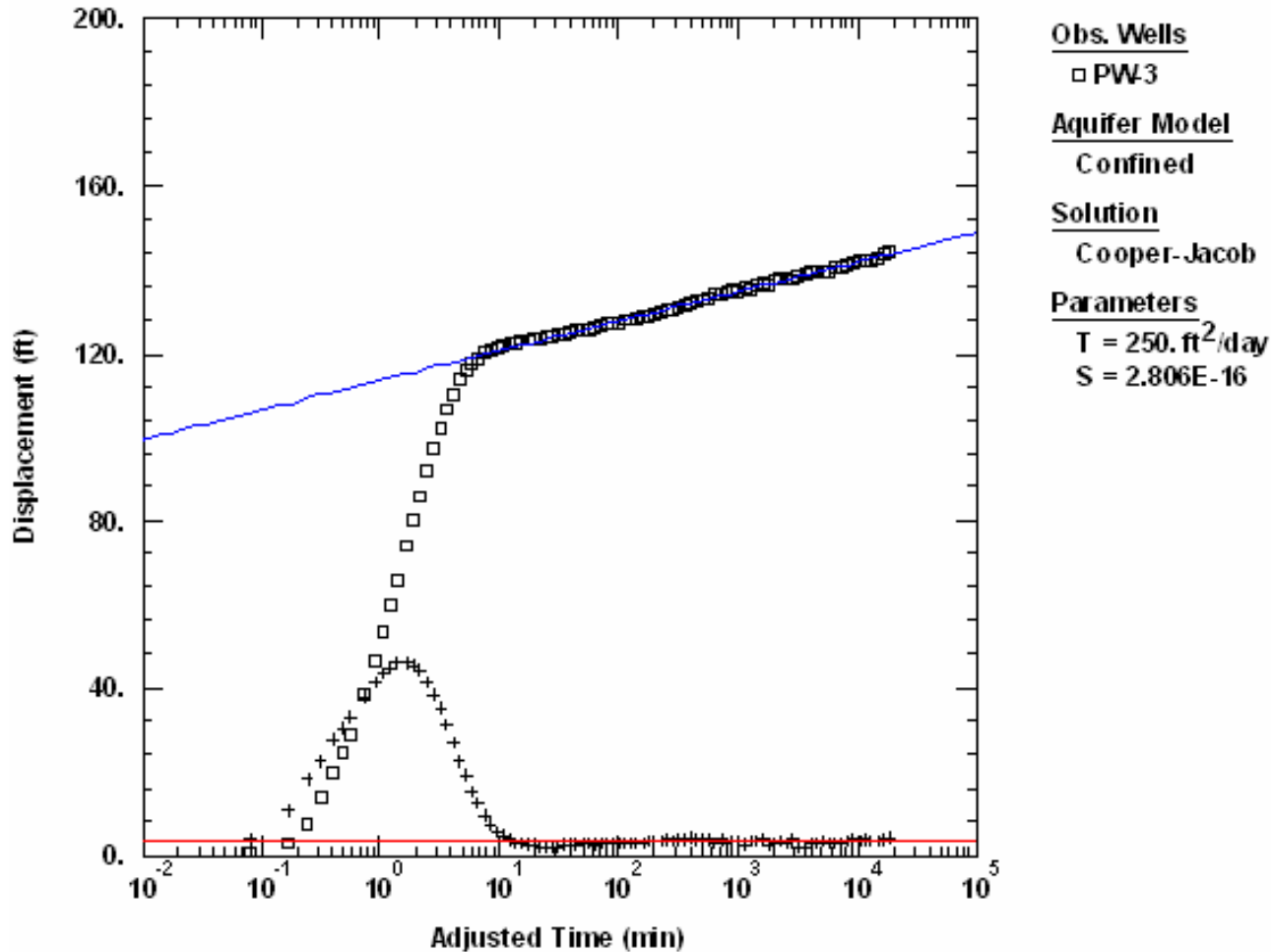
Pro Having completed our preliminary analysis with Cooper-Jacob, let's account for wellbore storage, wellbore skin and partial penetration by matching the Dougherty-Babu (1984) solution to the data.

1. Choose Solution from the **Match** menu to select a method for analyzing the data.

2. From the list of solutions for **Confined Aquifers**, select **Dougherty-Babu (1984)** and click **OK**.

3. Choose Log-Linear Axes from the **View** menu to view the data on log-linear axes.

4. Choose Toolbox from the **Match** menu. In the **Tweak** tab, select **S** from the list of parameters. Use the scroll bar to adjust the value of storativity to match the late-time data. You can set the range of storativity values by editing the minimum and maximum values for S in the **Parameters** tab.

View Match with Tweaked S

The Dougherty-Babu solution accounts for partial penetration; however, the implausibly low value of S determined from this analysis indicates wellbore skin effect.

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Obs. Wells
□ PW-3

Aquifer Model
Confined

Solution
Dougherty-Babu

Parameters
T   = 250. ft^2/day
S   = 6.814E-8
Kz/Kr = 1.
Sw   = 0.
r(w) = 0.333 ft
r(c) = 0.25 ft
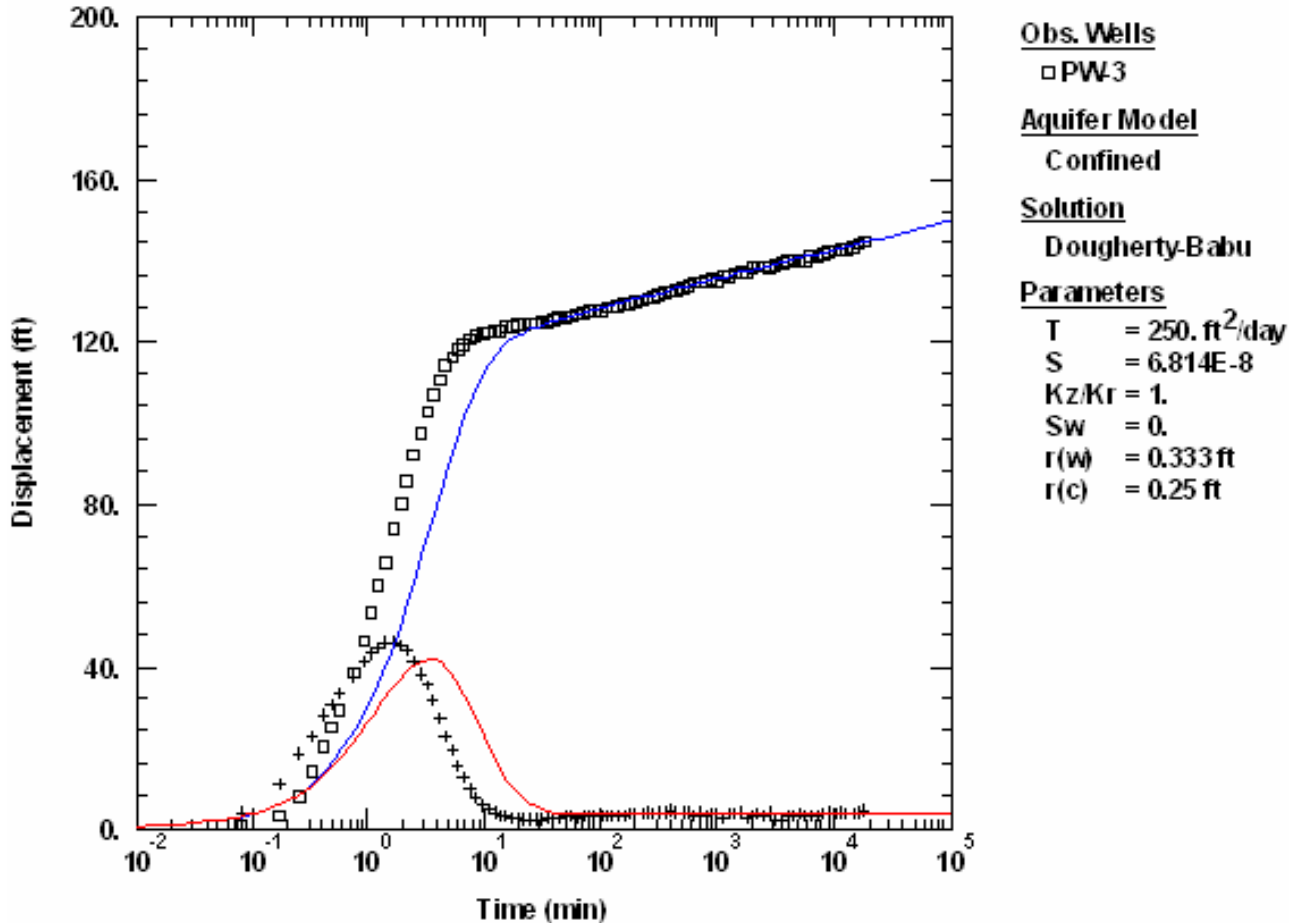
5. In the **Parameters** tab, enter 0.0002 for S as a plausible estimate of storativity in a confined aquifer. In the **Tweak** tab, select **Sw** from the list of parameters. Use the scroll bar to adjust the value of wellbore skin factor to match the late-time data. You can set the range of wellbore skin factor values by editing the minimum and maximum values for Sw in the **Parameters** tab.

 View Match with Tweaked Sw

 It is not possible to estimate S and Sw simultaneously from a single-well test. If an estimate of S is available independently from an observation well, we may use it as a known value in the analysis of pumping well data; otherwise, we may assume a value of S based on local hydrogeologic conditions.

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Obs. Wells
□ PW-3

Aquifer Model
Confined

Solution
Dougherty-Babu

Parameters
T   = 250. ft^2/day
S   = 0.0002
Kz/Kr = 1.
Sw   = 1.
r(w) = 0.333 ft
r(c) = 0.25 ft
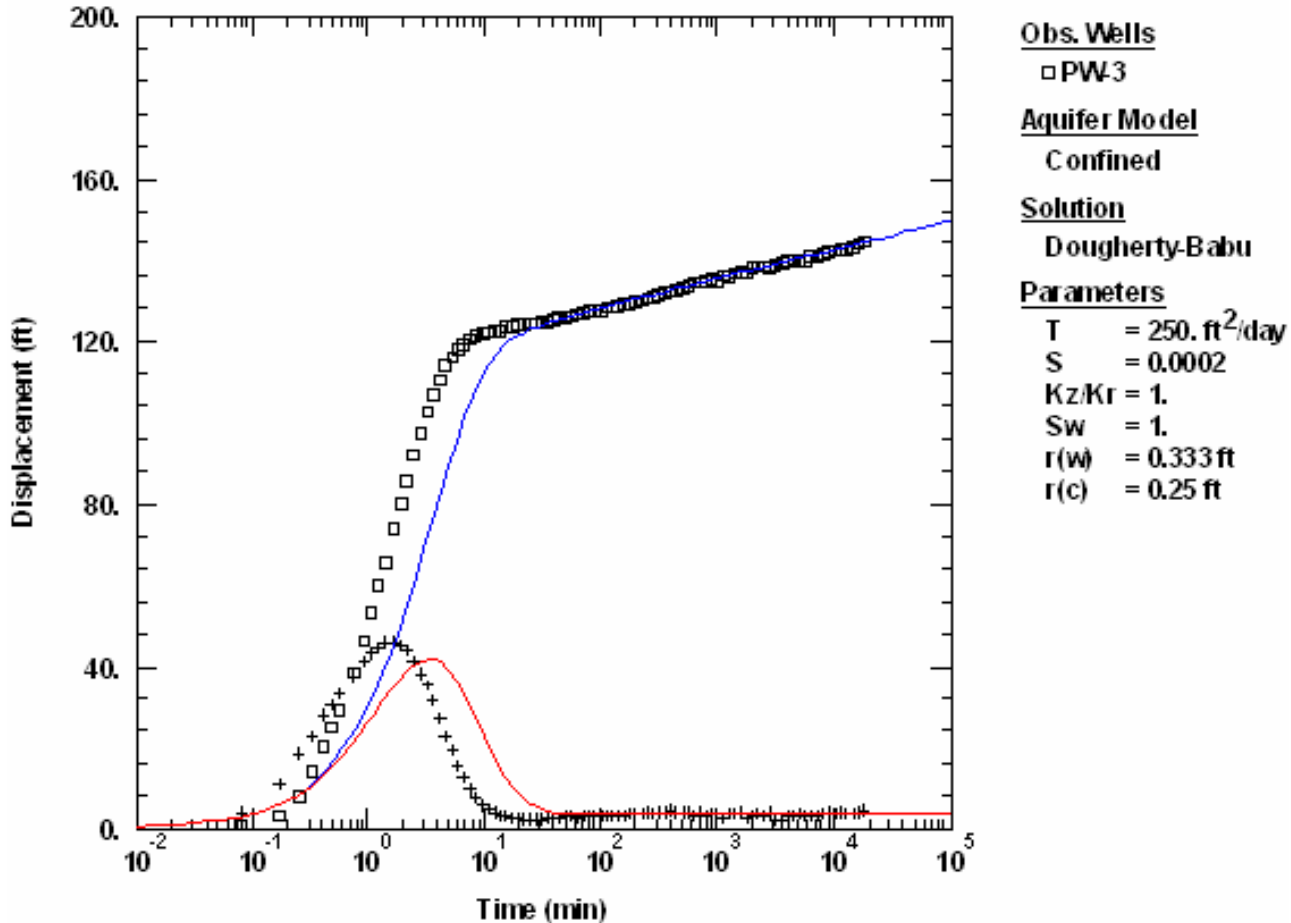
6. In the **Tweak** tab, select **r(c)** from the list of parameters. Use the scroll bar to adjust the value of casing radius to match the early-time data. You can limit the range of casing radius values by editing the minimum and maximum values for r(c) in the **Parameters** tab. After you have aligned the curve with the early-time data, click **OK**.

View Final Match with Dougherty-Babu

Adjust the casing radius value to match early-time data affected by wellbore storage. In many cases, the effective casing radius turns out to be less than the nominal value because of equipment in the well such as discharge tubing and transducer cable.

Obs. Wells
  □ PW-3

Aquifer Model
  Confined

Solution
  Dougherty-Babu

Parameters
  T   = 250. ft²/day
  S   = 0.0002
  Kz/Kr = 1.
  Sw   = 1.
  r(w) = 0.333 ft
  r(c) = 0.165 ft
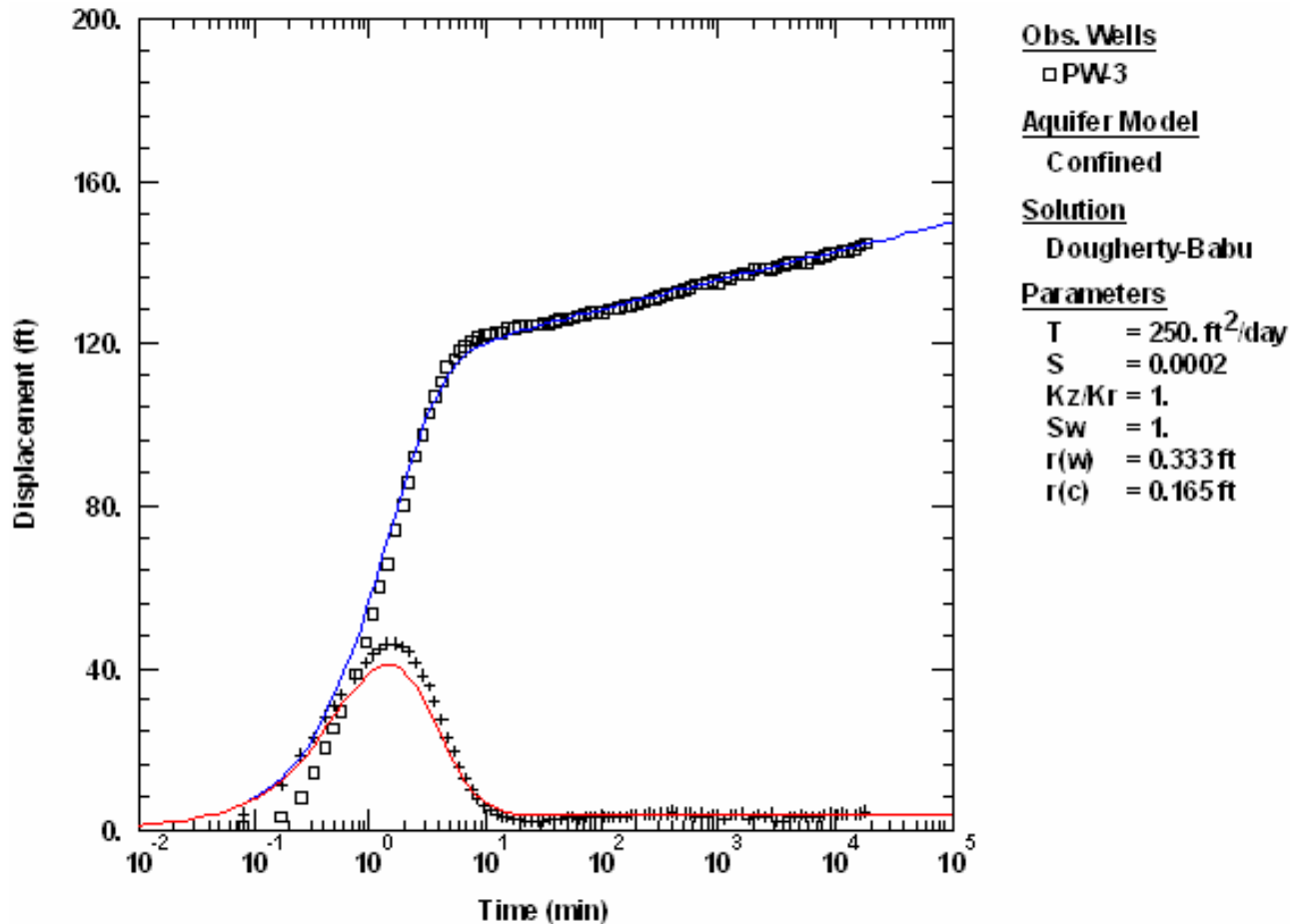
7. Choose Save from the **File** menu to save your work.

Uncertainty Analysis

Let's examine the relationship between wellbore skin factor and partial penetration.

1. Choose Aquifer Data from the **Edit** menu and enter **50** for the aquifer thickness.

2. Choose Wells from the **Edit** menu, select **PW-3** from the list and click **Modify**. In the Construction tab, enter **40** for the depth to the top of screen. Click **OK**. Click **Close**.

3. Choose Toolbox from the **Match** menu. In the **Tweak** tab, select **Sw** from the list of parameters. Use the scroll bar to adjust the value of wellbore skin factor to match the late-time data. You can set the range of wellbore skin factor values by editing the minimum and maximum values for Sw in the **Parameters** tab.

   View Match with Tweaked Sw

   Partial penetration and wellbore skin can produce virtually identical effects in a pumping well's drawdown response. In this case, decreasing the penetration ratio, L/b, was equivalent to increasing the wellbore skin factor. In the

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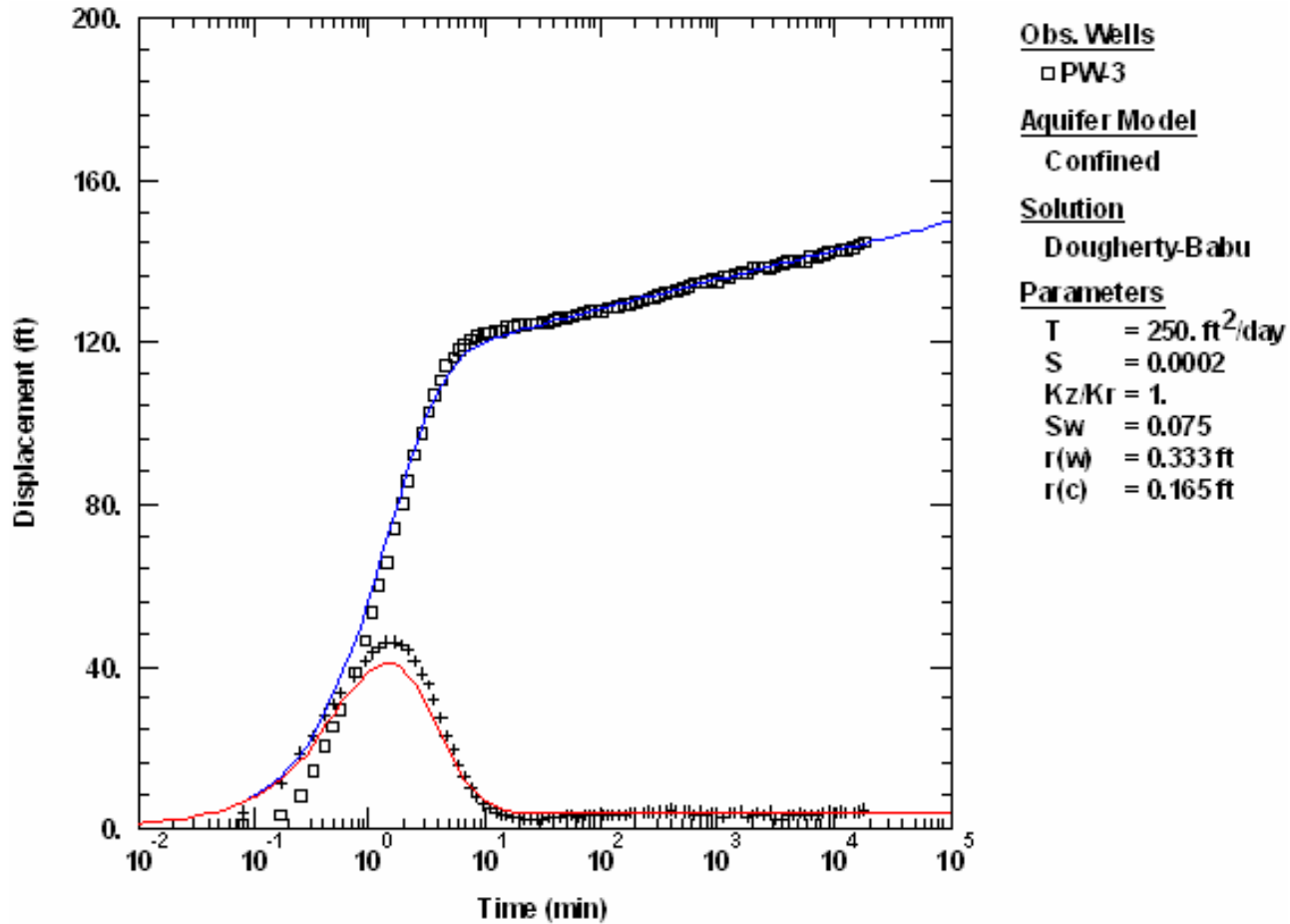
Pumping Test Example: Step-Drawdown (Saudi Arabia)

Clark (1977) presented data from a step-drawdown test in a well completed in a confined sandstone aquifer in Saudi Arabia. The test consisted of six steps, each lasting 180 minutes. Pumping stopped after 1080 minutes and recovery was monitored for an additional 1570 minutes. Time and drawdown measurements were recorded in minutes and meters, respectively.

This example will introduce you to the following tasks and features in AQTESOLV:

- Creating a new data set with the Pumping Test Wizard

- Importing data with the Observation Data Import Wizard

- Saving a data set

- Estimating aquifer properties using the Theis (1935) step-drawdown solution (visual and automatic)

Create a New Data Set with Pumping Test Wizard

The first step in analyzing data from a single-well pumping test is to create a new AQTESOLV data set. In this example, we will use the Pumping Test Wizard to assist us with data entry.

1. Create a new data set by choosing New from the **File** menu.

2. In the **New Data Set** dialog, select **Pumping Test Wizard** from the list. Click **OK**.

3. Choose **Single-well test** for the type of pumping test. Click **OK**.

4. The **Pumping Test Wizard** prompts you for data required to analyze a single-well pumping test. Click **Next** to begin the wizard.

5. For units of measurement, choose **m** for length, **min** for time, **m³/day** for pumping rate and **m/day** for hydraulic conductivity. Click **Next**.

6. For project information, enter **Saudi Arabia** for the location. Click **Next**.

7. For aquifer data, assume **100** for the aquifer thickness. Enter **1** for the anisotropy ratio (i.e., assume hydraulic conductivity is isotropic). Click **Next**.

8. For pumping well data, enter **Test Well 1** for the well name. Enter coordinates of X=0 and Y=0. Click **Next**.

9. For pumping well construction, select the option for **vertical, full penetration**. Click **Next**.

10. For pumping well radius data, assume **0.25** for casing radius and **0.25** for well radius. Click **Next**.

11. For pumping rates, click **Add Rows**, enter **6** for the number of rows and click **OK**. Enter the seven time and rate readings shown below for the test. The last step, with a rate of zero, represents the recovery period. Click **Next**.

Pumping Period	Elapsed Time Since Start of Test (min)	Rate (m³/day)
1	0	1306
2	180	1693
3	360	2423
4	540	3261
5	720	4094

6	900	5019
7	1080	0

12. For observations, click **Import** to launch the Observation Data Import Wizard for importing data from a file.

    We will import a text file consisting of 201 time-drawdown readings arranged in two columns. The first column is elapsed time since the start of the test. The second column contains drawdown measurements.

> In Step 1 of the wizard, click **Browse**. Select the import file **Clark.txt** in the AQTESOLV installation folder and click **Open**. Click **Next**.
>
> In Step 2 of the wizard, accept the default entries and click **Next**.
>
> In Step 3 of the wizard, click **Finish**. Inspect the import file summary and click **OK**.
>
> Click **Next** to proceed with the **Pumping Test Wizard**.

13. You have completed the **Pumping Test Wizard**. Click **Finish**.

After completing the **Pumping Test Wizard**, AQTESOLV automatically displays an Error Log to let you know if the data set contains any errors. If the **Error Log** identifies any mistakes, choose options from the Edit menu to correct them.

Save Data Set

At this point, it's a good idea to save your work.

Save the data set by choosing Save As from the **File** menu. Choose a folder, enter **Clark** for the name of the file and click **Save**. AQTESOLV saves the file with an **.aqt** extension.

Estimate Aquifer Properties

To evaluate the data from this test, we will use the Theis (1935) step-drawdown test solution.

1. Choose Solution from the **Match** menu to select a method for analyzing the data.

2. Remove the check from **Solution is inactive**. Click the **+** next to **Confined Aquifers** to expand the list of available solutions for confined aquifers. Select **Theis (1935) step-drawdown test** and click **OK**.

3. Choose Displacement-Time from the **View** menu to display the test data.

4. Choose Log Axes from the **View** menu to view the data on log-log axes.

5. Choose Wells from the **Edit** menu. Select **Test Well 1** from the list and click **Modify**. In the **Observations** tab, change the weight for the first two observations to **0**. By changing the weights to zero, these observations, which reflect the influence of recharge or leakage, will be ignored during automatic curve matching. Click **OK** and **Close**.

6. Choose Automatic from the **Match** menu.

In the Estimation tab, enter **50** for the maximum number of iterations.

In the Parameters tab, select **Inactive** for the estimation status of Sw and P. In the equations for the Theis step-drawdown test solution, the values of S and Sw are correlated (i.e., appear together); hence we are unable to estimate both parameters simultaneously in a single-well test. In this case, we'll assume that nonlinear well loss is quadratic (i.e., P=2). Enter **1.e-5** and **0.1** for the minimum and maximum values of S.

Click **Estimate** to perform automatic curve matching.

7. When estimation has finished, click **OK** and then **Close**. Click **OK** to view the new position of the type curve.

View Automatic Match with Theis

Obs. Wells
☐ Test Well 1

Aquifer Model
Confined

Solution
Theis (Step Test)

Parameters
T = 387.1 m^2/day
S = 0.0002619
Sw = 0.
C = 0.3726 min^2/m^5
P = 2.
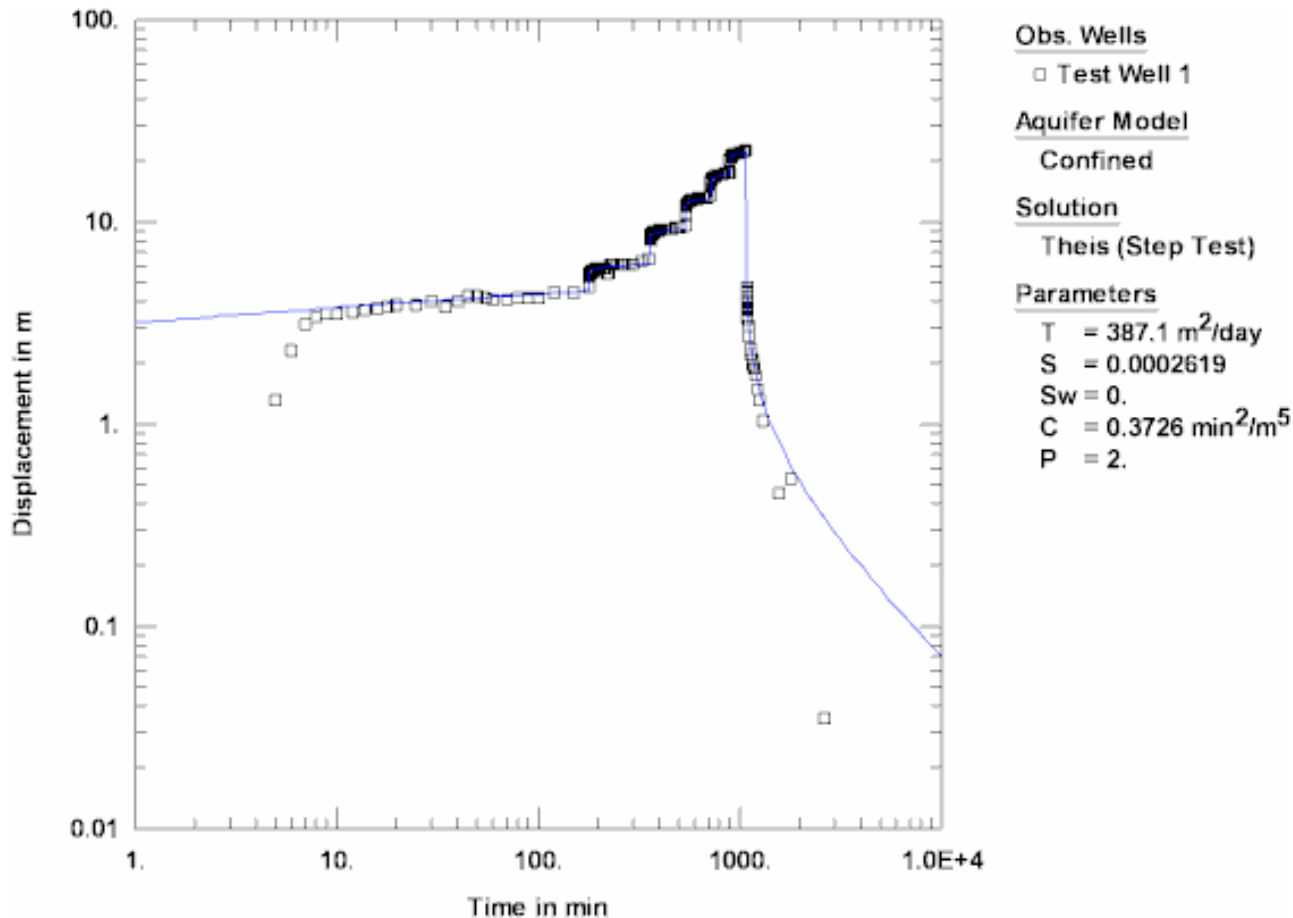
8. Use residual-time, residual-simulated and normal probability plots to evaluate the fit of the curve by examining residuals. The diagnostics report also presents residual statistics for curve fitting.

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

Estimate Wellbore Skin

It is not feasible to estimate both S and Sw from a single-well test due to parameter correlation. If data from a step-drawdown test included an observation well, however, we could estimate S because the wellbore skin parameter only affects drawdown in the pumped well.

Clark (1977) also conducted a constant-rate test in Test Well 1 and estimated S from drawdown data measured in a nearby observation well. Using his estimate of for S, we can determine Sw from the step-drawdown test.

1. Choose Automatic from the **Match** menu.

In the Parameters tab, select **Active** for the estimation status of Sw and **Inactive** for the estimation status of S and P. Enter for the value of S.

Click **Estimate** to perform automatic curve matching.

During the iterative estimation procedure, AQTESOLV displays a progress

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2. When estimation has finished, click **OK** and then **Close**. Click **OK** to view the new position of the type curve.

    View Automatic Match with Theis Including Skin
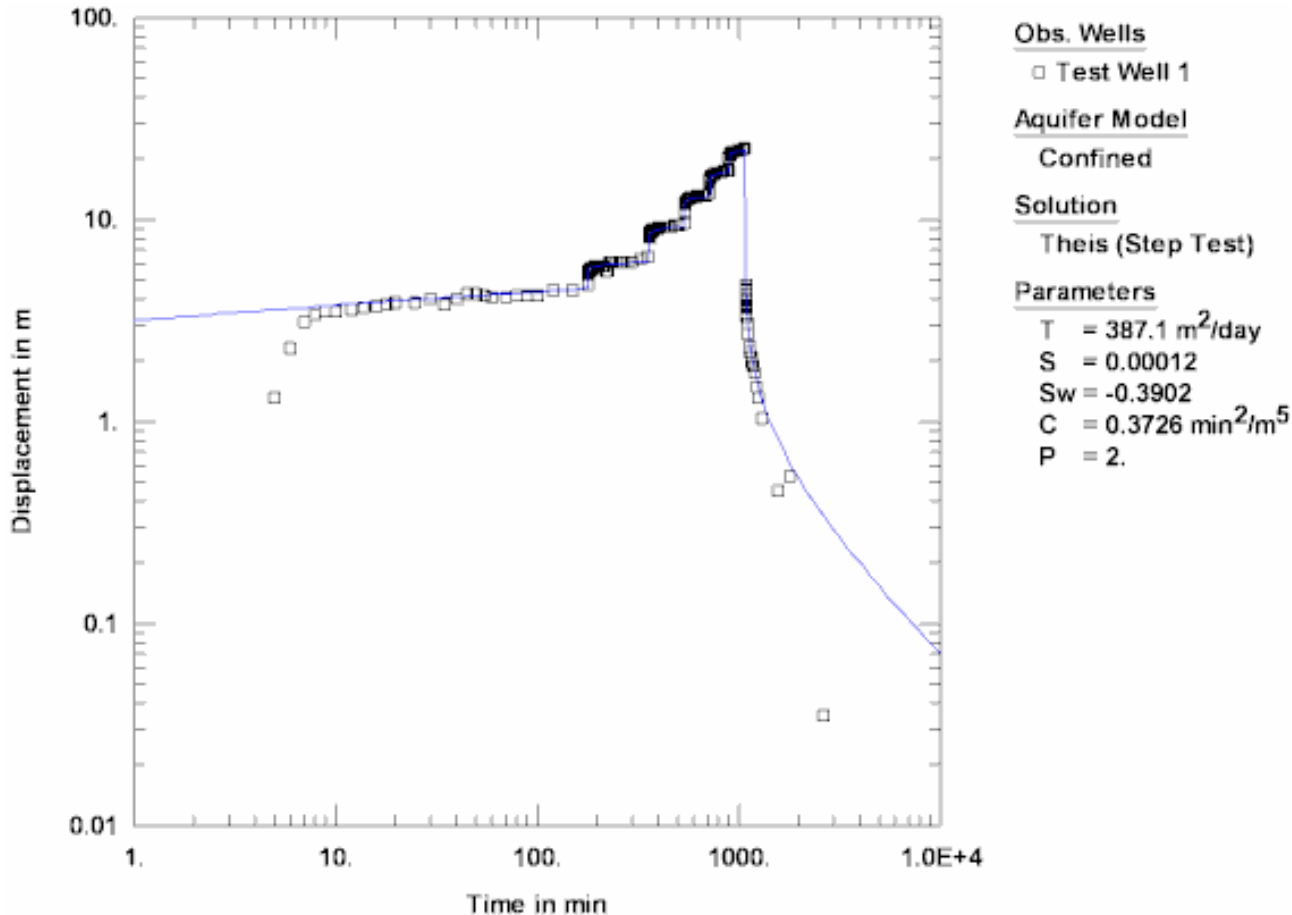
3. The estimated values of T and C remain the same when we assume the value of S = because the new estimate of Sw changes the effective radius of the well. We can use Sw (= -0.3902) to compute the effective well radius as follows:

    effective well radius = r(w)*exp(-Sw) = (0.25 m)*exp(0.3902) = 0.37 m

Pumping Test Example: Multiple Observation Wells (Sioux Flats)

This example guides you through the analysis of drawdown from a pumping test in a nonleaky confined aquifer near Sioux Flats, South Dakota (USBR 1995). The test well was pumped at a constant rate of 2.7 ft^3/sec for 2045 minutes. Drawdown was measured in three observation wells located 100, 200 and 400 ft from the test well.

This example will introduce you to the following tasks and features in AQTESOLV:

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- Creating a new data set for a pumping test with the Pumping Test Wizard

- Importing data from a CSV file using the Import Wizard

- Adding observation wells to the data set

- Saving a data set

- Inspecting diagnostic plots (radial flow and derivative)

- Estimating aquifer properties using Cooper-Jacob (1946) and Theis (1935) solutions (visual and automatic)

- Performing distance-drawdown analysis

While following the steps in this example, click **Help** or press **F1** to context sensitive help in the AQTESOLV application.

Create a New Data Set with Pumping Test Wizard

The first step in analyzing data from a pumping test is to create a new AQTESOLV data set. In this example, you will use the Pumping Test Wizard to assist with data entry.

1. Create a new data set by choosing New from the **File** menu.

2. In the **New Data Set** dialog, select **Pumping Test Wizard** from the list. Click **OK**.

3. Choose **Multiwell test** for the type of pumping test. Click **OK**.

4. The **Pumping Test Wizard** prompts you for data required to analyze a pumping test. Click **Next** to begin the wizard.

5. For units of measurement, choose **ft** for length, **min** for time, **ft³/sec** for pumping rate and **consistent** for hydraulic conductivity. Click **Next**.

6. For project information, enter **Sioux Flats** for the location. Click **Next**.

7. For aquifer data, assume **50** for the aquifer thickness. Enter **1** for the anisotropy ratio (i.e., assume hydraulic conductivity is isotropic). Click **Next**.

8. For pumping well data, enter **Test Well** for the well name. Enter coordinates

of X=0 and Y=0. Click **Next**.

9. For pumping well construction, select the option for **vertical, full penetration**. Click **Next**.

10. For pumping well radius data, assume **0.5** for casing radius and **0.5** for well radius. Click **Next**.

11. For pumping rates, enter **0** for time and **2.7** for rate. Click **Next**.

12. For observation well data, enter **OW 1** for the well name. Enter **100** and **0** for the X and Y coordinates, respectively. Click **Next**.

13. For observation well construction, select the option for **vertical, full penetration**. Click **Next**.

14. For observations, click **Import** to launch the Observation Data Import Wizard for importing data from a file.

    You will import 28 observations from a text file consisting of time-drawdown readings arranged in four columns. The first column is elapsed time since the start of the test. The remaining columns contain drawdown measurements for the three observation wells. This file contains missing values; thus, there are fewer observations for each well than rows of data in the file.

    > In Step 1 of the wizard, click **Browse**. Select the import file **Sioux Flats.csv** in the AQTESOLV installation folder and click **Open**. Click **Next**.
    >
    > In Step 2 of the wizard, use the defaults determined by the Import Wizard. Click **Next**.
    >
    > In Step 3 of the wizard, accept the defaults and click **Finish**. Inspect the import file summary and click **OK**.
    >
    > Click **Next** to proceed with the **Pumping Test Wizard**.

15. You have completed the **Pumping Test Wizard**. Click **Finish**.

After completing the **Pumping Test Wizard**, AQTESOLV automatically displays an Error Log to let you know if the data set contains any errors. If the **Error Log** identifies any mistakes, choose options from the Edit menu to correct them.

Add Observation Wells

The **Pumping Test Wizard** helped you enter data for the pumping well and the first observation well. Now you will add the two remaining observation wells to the data set.

1. Choose Wells from the **Edit** menu and click **New** to add a new well. Select the new well in the list and click **Modify** to edit the well.

2. In the **General** tab, enter **OW 2** for the well name. Enter **200** and **0** for the X and Y coordinates.

3. In the **Observations** tab, click **Import** to launch the Observation Data

Import Wizard for importing data from a file.

 You will import 27 observations from the same text file used in the **Pumping Test Wizard**. The first column is elapsed time since the start of the test. The third column contains drawdown measurements for the second observation well.

> In Step 1 of the wizard, click **Browse**. Select the import file **Sioux Flats.csv** in the AQTESOLV installation folder and click **Open**. Click **Next**.
>
> In Step 2 of the wizard, enter **3** for the displacement column and keep the other values determined by the Import Wizard. Click **Next**.
>
> In Step 3 of the wizard, accept the defaults and click **Finish**. Inspect the import file summary and click **OK**.

4. Click **OK** to finish editing OW 2.

5. Click **New** to add another well. Select the new well in the list and click **Modify** to edit the well.

6. In the **General** tab, enter **OW 3** for the well name. Enter **400** and **0** for the X and Y coordinates.

7. In the **Observations** tab, click **Import** to launch the Observation Data Import Wizard for importing data from a file.

 You will import 24 observations from the same text file used for the first two observation wells. The first column is elapsed time since the start of the test. The fourth column contains drawdown measurements for the third observation well.

> In Step 1 of the wizard, click **Browse**. Select the import file **Sioux Flats.csv** in the AQTESOLV installation folder and click **Open**. Click **Next**.
>
> In Step 2 of the wizard, enter **4** for the displacement column and keep the other values determined by the Import Wizard. Click **Next**.
>
> In Step 3 of the wizard, accept the defaults and click **Finish**. Inspect the import file summary and click **OK**.

8. Click **OK** to finish editing OW 3.

9. Click **Close** to leave the **Wells** window.

Save Data Set

At this point, it's a good idea to save your work.

Save the data set by choosing Save As from the **File** menu. Choose a folder and enter **Sioux Flats** for the name of the file. Click **Save**. The default extension for an AQTESOLV data set is **.aqt**.

Inspect Diagnostic Plots

Before performing curve matching to estimate aquifer properties, you may use diagnostic features in AQTESOLV to evaluate aquifer and flow conditions.

Diagnostic flow plots help you select an appropriate solution method for your pumping test data.

1. Choose Radial Flow from the **View** menu to display a radial flow plot on log-linear axes.

View Radial Flow Plot

By the end of the test, the data for each well approach a straight line with time indicating radial flow conditions in an infinite-acting confined aquifer.
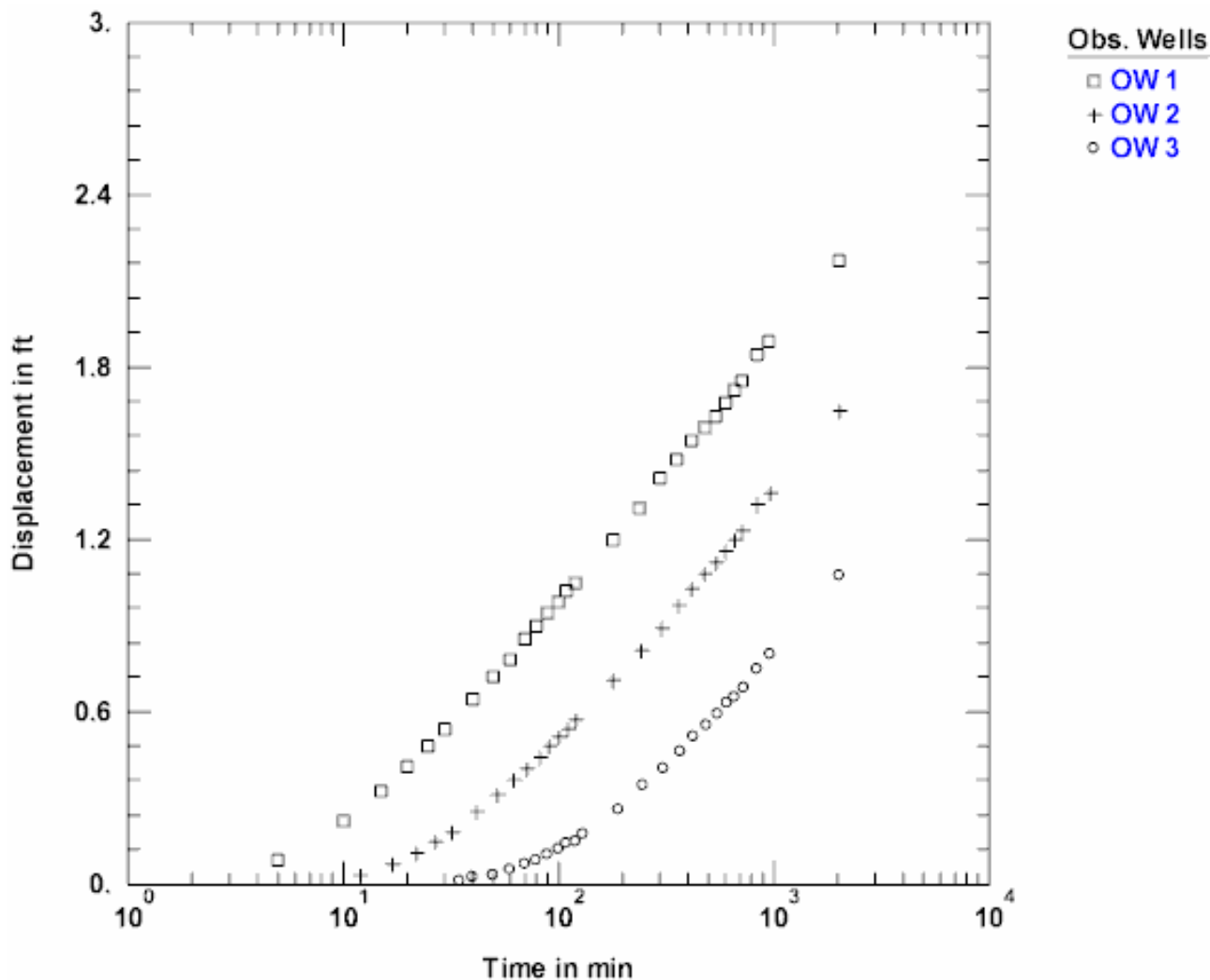
Derivative analysis is another useful diagnostic tool for evaluating aquifer conditions.

1. Choose Composite from the **View** menu to display a plot of the test data on log-linear axes.

A composite plot normalizes time by the radius squared (t/r^2). For fully penetrating wells in a homogeneous and isotropic nonleaky confined aquifer (i.e., the assumptions for the Theis solution), the composite plot facilitates visual curve matching because data from more than one observation well plot along a single curve (Theis) or straight line (Cooper-Jacob).

2. Select Options from the **View** menu. In the **Plots** tab, check **Derivative curves**. In the **Derivative** tab, select the option for **Smoothing** and enter **2** for the smoothing factor. Click **OK**.

View Derivative Plot

As the test progresses, the derivative data approach a constant value, i.e, the slope of the time drawdown data becomes constant, which is characteristic of radial flow in an infinite confined aquifer.
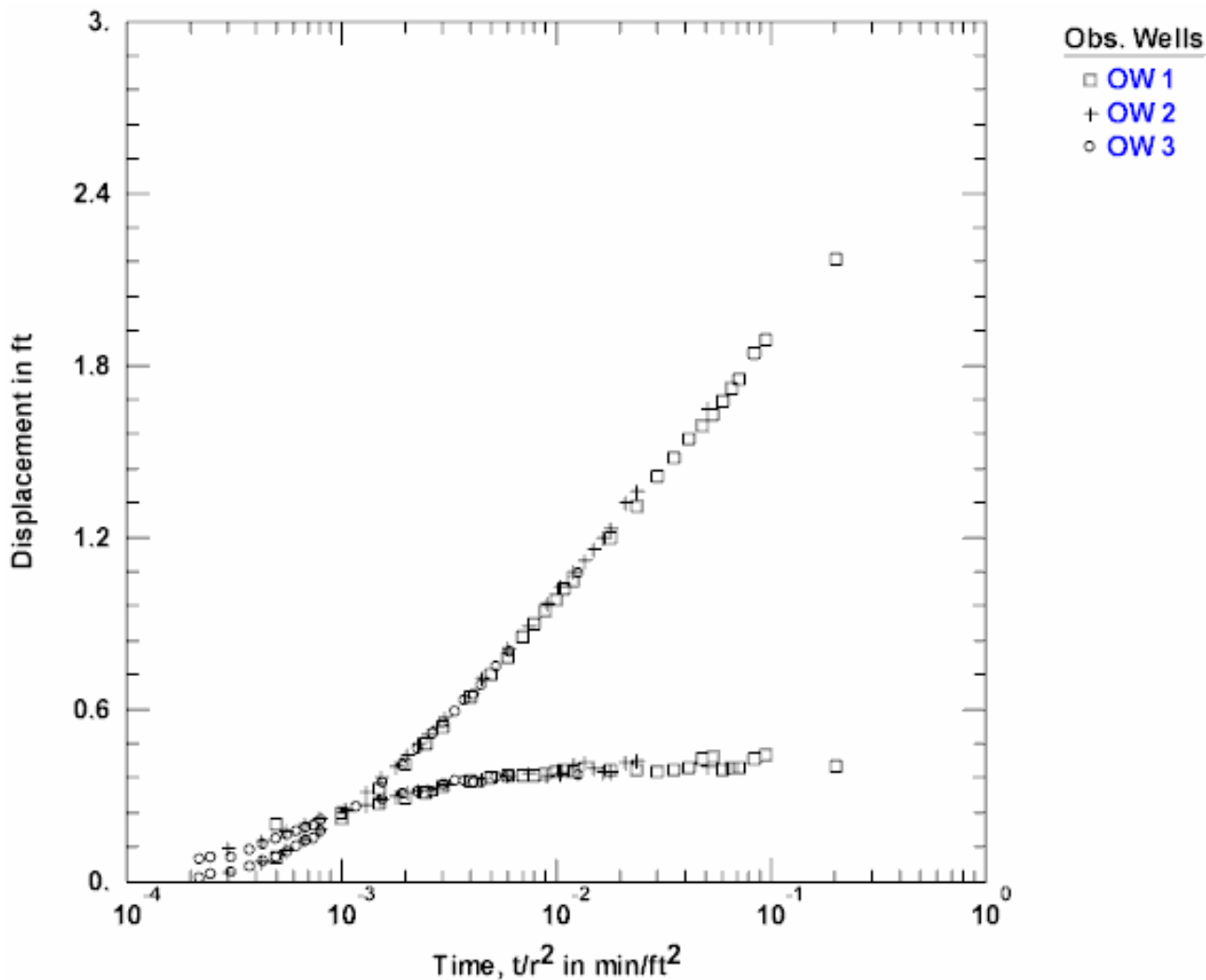
Estimate Aquifer Properties

To start our analysis, we can use the Cooper-Jacob (1946) solution to obtain preliminary estimates of aquifer properties.

1. Choose Solution from the **Match** menu to select a method for analyzing the data.

2. Remove the check from **Solution is inactive**. Click the **+** next to **Confined Aquifers** to expand the list of available solutions for confined aquifers. Select **Cooper-Jacob (1946)** and click **OK**.

3. Choose Composite from the **View** menu to display a composite plot of the data.

4. Choose Log-Linear from the **View** menu to display the plot on log-linear axes.

5. Choose Options from the **View** menu. In the **Plots** tab, remove the check from **Derivative curve(s)** and check **Valid time for Cooper-Jacob approximation**. Click **OK**.

The dashed vertical line shown on the plot is a guide indicating the time when the Cooper-Jacob solution becomes valid. Match the solution to data plotting to the right of the vertical line.

6. Choose Visual from the **Match** menu to perform visual curve matching with the Cooper-Jacob solution.

> To perform visual matching, move the mouse to a point where you wish to begin drawing a new line with the Cooper-Jacob solution.
>
> Click and hold down the left mouse button to anchor the new line at this point.
>
> Continue to hold the mouse button down and move the mouse to match a new straight line to your data. As you move the mouse, AQTESOLV draws a straight line between the anchor point and the position of the mouse.
>
> Release the left mouse button when you have finished matching a new straight line. AQTESOLV automatically updates the plot legend to reflect changes in parameter values.

7. Repeat the previous step as needed to achieve a satisfactory match.

View Visual Match With Cooper-Jacob

Note that very few data points near the end of the test meet the validity criterion (u 0.01) for the Cooper-Jacob solution.

Obs. Wells
□ OW 1
+ OW 2
○ OW 3

Aquifer Model
Confined

Solution
Cooper-Jacob

Parameters
T = 32.67 ft²/min
S = 0.0602
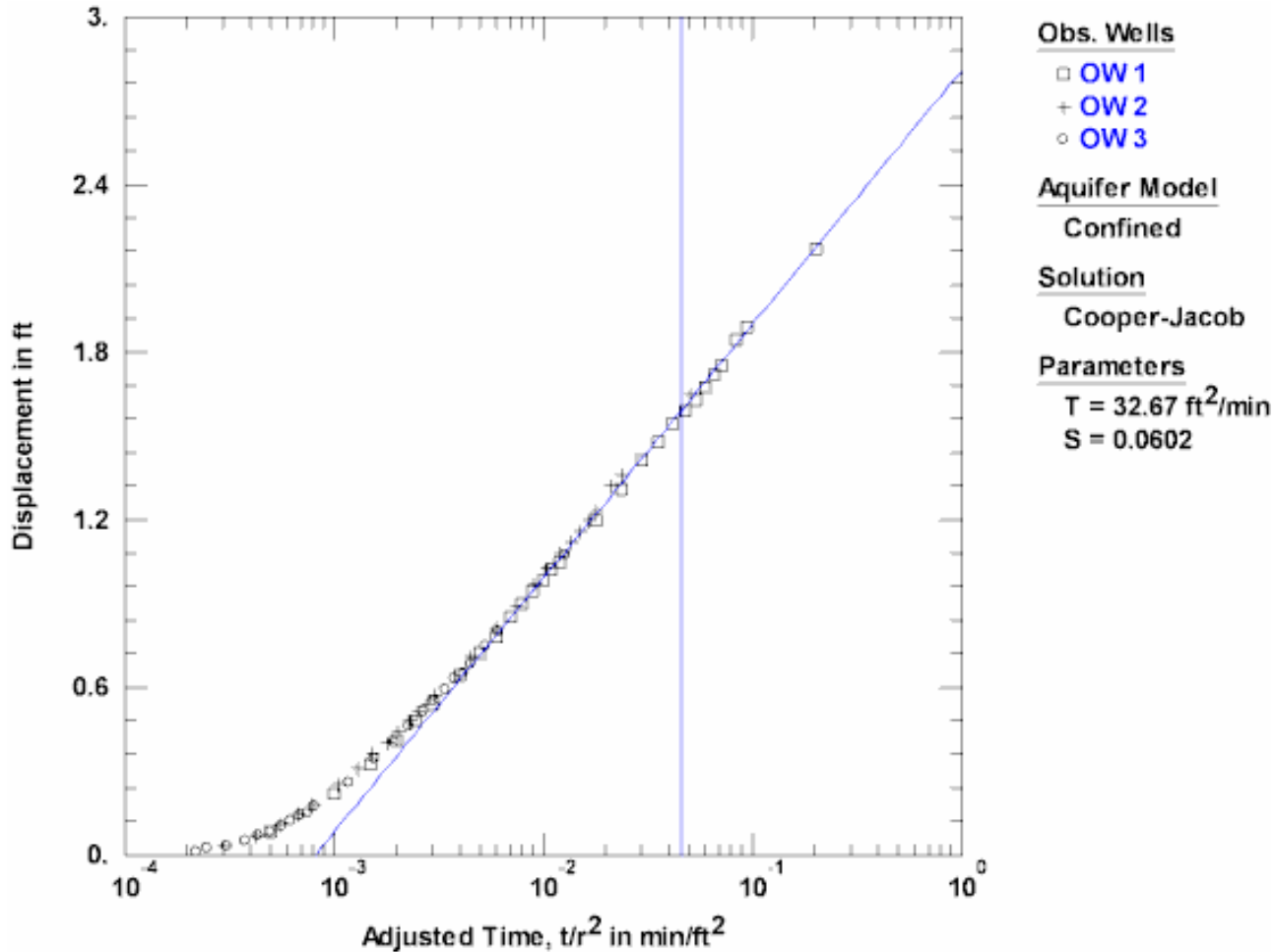
Now you will use the Theis (1935) solution to analyze the drawdown data in all three observation wells simultaneously.

1. Choose Solution from the **Match** menu to select a method for analyzing the data.

2. Select **Theis (1935)** and click **OK**.

3. Choose Log Axes from the **View** menu to display the plot on log-log axes.

4. Choose Options from the **View** menu. In the **Plots** tab, check **Derivative curve(s)**. Click **OK**.

5. Choose Visual from the **Match** menu to perform visual curve matching.

> Click and hold the left mouse button down over a point within the plot area.
>
> Continue to hold the mouse button down and move the mouse to match the curves to the drawdown and derivative data. As you move the curves, AQTESOLV automatically updates the plot legend to reflect changes in parameter values.

Release the left mouse button when you have finished matching the curves.

6. Repeat the previous step until you have achieved a satisfactory match. Try to match both the drawdown and derivative data.

View Visual Match With Theis

7. Choose Automatic from the **Match** menu and click **Estimate** to perform automatic curve matching.

During the iterative estimation procedure, AQTESOLV displays a progress window and updates the curves displayed on the plot in the background.

8. When estimation has finished, click **OK** and then **Close**. Click **OK** to view the new position of the type curve.

9. Use residual-time, residual-simulated and normal probability plots to evaluate the fit of the curve by examining residuals. The diagnostics report also presents residual statistics for curve fitting.

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

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Perform Distance-Drawdown Analysis

In addition to time-drawdown analyses, you can use AQTESOLV to evaluate distance-drawdown data.

1. Choose Distance Drawdown from the **View** menu to plot drawdown versus distance at a specified time.

2. Choose Options from the **View** menu. In the **Distance** tab, enter **2045** for the time used in distance-drawdown calculations. Click **OK**.

3. The plot shows drawdown for the three observation wells at the end of the test (2045 minutes). You may use automatic estimation to match the curve to just the distance-drawdown data points.

Pumping Test Example: Constant-Rate Test in a Leaky Confined Aquifer (Dalem)

Kruseman and De Ridder (1990) present data from a pumping test conducted in a leaky confined aquifer near Dalem, The Netherlands. The aquifer is overlain by a peat aquitard and underlain by a unit regarded as an aquiclude. The test well (M77) was pumped for eight hours at a constant rate of 761 m^3/day. Drawdown was monitored in an observation well located 90 m from the pumped well. You will analyze data that were corrected for tidal fluctuations and partial penetration. Time and drawdown measurements were recorded in days and meters, respectively.

This example will introduce you to the following tasks and features in AQTESOLV:

- Creating a new data set with the Pumping Test Wizard

- Importing data with the Observation Data Import Wizard

- Saving a data set

- Inspecting diagnostic plots (radial flow and derivative)

- Estimating aquifer properties using Hantush-Jacob (1955) and Hantush (1960) solutions (visual and automatic)

While following the steps in this example, click **Help** or press **F1** to obtain context sensitive help in the AQTESOLV application.

Create a New Data Set with Pumping Test Wizard

The first step in analyzing data from a pumping test is to create a new AQTESOLV

data set. In this example, we will use the Pumping Test Wizard to assist us with data entry.

1. Create a new data set by choosing New from the **File** menu.

2. In the **New Data Set** dialog, select **Pumping Test Wizard** from the list. Click **OK**.

3. Choose **Multiwell test** for the type of pumping test. Click **OK**.

4. The **Pumping Test Wizard** prompts you for data required to analyze a pumping test. Click **Next** to begin the wizard.

5. For units of measurement, choose **m** for length, **day** for time, **consistent** for pumping rate and **consistent** for hydraulic conductivity. Click **Next**.

   Consistent units for pumping rate and hydraulic conductivity are based on the units of length and time selected for the data set. In this example, consistent units are m^3/day for Q and m/day for K.

6. For project information, enter **Dalem, The Netherlands** for the location. Click **Next**.

7. For aquifer data, assume **40** for the aquifer thickness. Enter **1** for the anisotropy ratio (i.e., assume hydraulic conductivity is isotropic). Click **Next**.

8. For pumping well data, enter **M77** for the well name. Enter coordinates of X=0 and Y=0. Click **Next**.

9. For pumping well construction, select the option for **vertical, full penetration**. Click **Next**.

10. For pumping well radius data, assume **0.1** for casing radius and **0.1** for well radius. Click **Next**.

11. For pumping rates, enter **0** for time and **761** for rate in the first row of the spreadsheet. Click **Next**.

12. For observation well data, enter **r=90** for the well name. Enter **90** and **0** for the X and Y coordinates, respectively. Click **Next**.

13. For observation well construction, select the option for **vertical, full penetration**. Click **Next**.

14. For observations, click **Import** to launch the Observation Data Import Wizard for importing data from a file.

   We will import a text file consisting of 12 time-drawdown readings arranged in two columns. The first column is elapsed time since the start of the test. The second column contains drawdown measurements.

   In Step 1 of the wizard, click **Browse**. Select the import file **Dalem r=90 m.txt** in the AQTESOLV installation folder and click **Open**. Click **Next**.

In Step 2 of the wizard, enter **2** for the number of columns, **9** for the starting row in the file, **1** for the column containing elapsed time and **2** for the column containing displacement. Click **Next**.

In Step 3 of the wizard, click **Finish**. Inspect the import file summary and click **OK**.

Click **Next** to proceed with the **Pumping Test Wizard**.

15. You have completed the **Pumping Test Wizard**. Click **Finish**.

After completing the **Pumping Test Wizard**, AQTESOLV automatically displays an Error Log to let you know if the data set contains any errors. If the **Error Log** identifies any mistakes, choose options from the Edit menu to correct them.

Save Data Set

At this point, it's a good idea to save your work.

Save the data set by choosing Save As from the **File** menu. Choose a folder and enter **Dalem r=90 m** for the name of the file. Click **Save**. AQTESOLV saves the file with an **.aqt** extension.

Inspect Diagnostic Plots

Before performing curve matching to estimate aquifer properties, you may use diagnostic features in AQTESOLV to evaluate aquifer and flow conditions.

Diagnostic flow plots help you select an appropriate solution method for your pumping test data.

1. Choose Radial Flow from the **View** menu to display a radial flow plot on log-linear axes.

View Radial Flow Plot

At late time on this graph, the data begin to flatten suggesting the possibility of leakage or the presence of a recharge boundary.
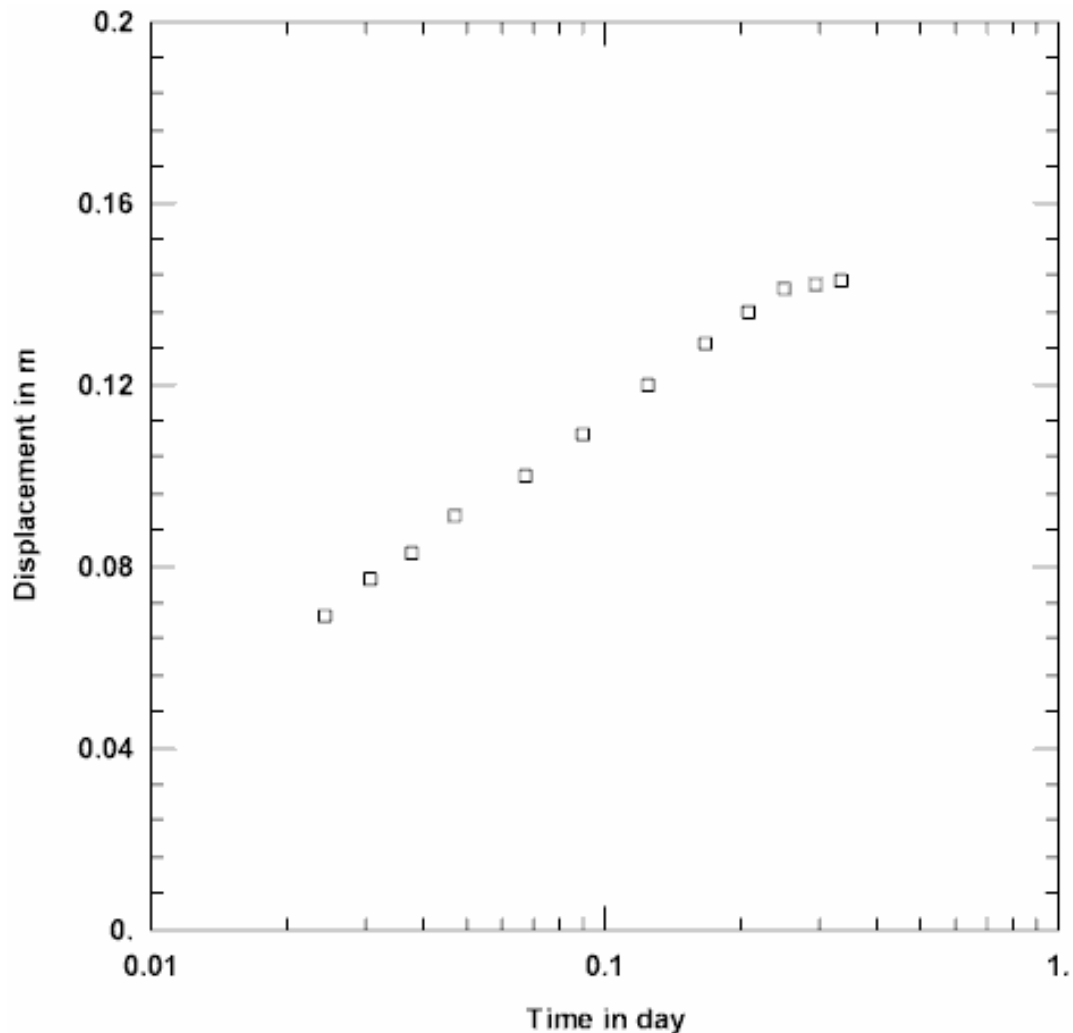
Derivative analysis is another useful diagnostic tool for evaluating aquifer conditions.

1. Choose Displacement-Time from the **View** menu to display a plot of the test data. On semi-log axes, this plot is identical to the radial flow plot above.

2. Choose Wells from the **Edit** menu. Select **r=90** from the list and click **Modify**.

   In the **Symbols** tab, remove the check from **Use data symbols properties** and select **cross** for the derivative symbol.

   In the **Curves** tab, remove the check from **Use type curve properties**. Click **Color** for the derivative curve properties, change the color to **red**, and click **OK**.

   Click **OK** and then **Close**.

3. Select Options from the **View** menu. In the **Plots** tab, check **Derivative curves**. In the **Derivative** tab, select the option for **Bourdet** and enter a differentiation interval of **0.2**. Click **OK**.

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View Derivative Plot

The derivative plot at intermediate time is fairly constant suggesting radial flow conditions. At late time, the derivative begins to approach zero which is indicative of a source of recharge (leakage or boundary).
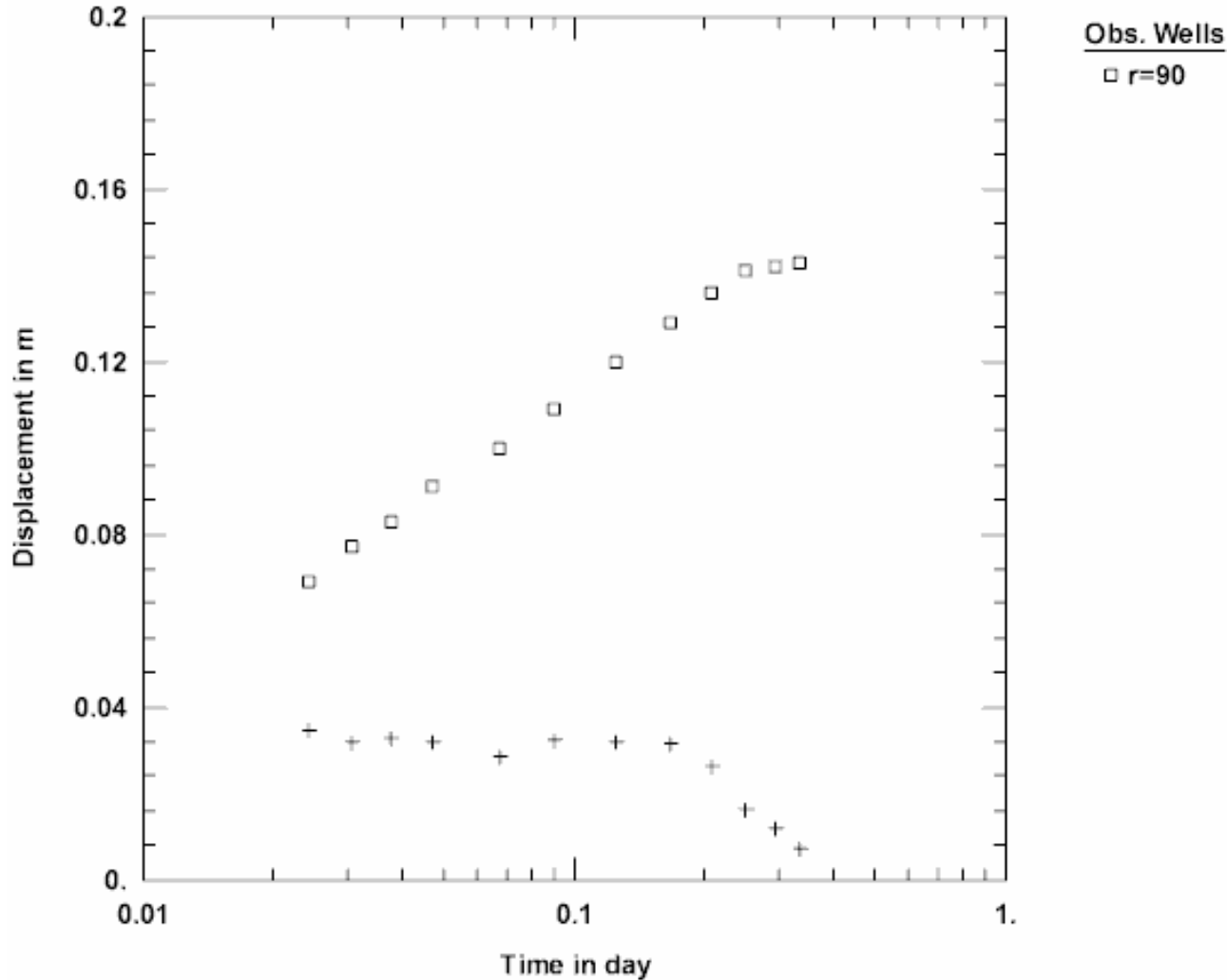
Estimate Aquifer Properties

The diagnostic plots that you have examined for this test tend to confirm a leaky confined aquifer model. To start the analysis, you will use the Hantush-Jacob (1955) solution to obtain estimates of aquifer properties. The Hantush-Jacob solution assumes no storage in the aquitard(s).

1. Choose Solution from the **Match** menu to select a method for analyzing the data.

2. Remove the check from **Solution is inactive**. Click the **+** next to **Leaky Aquifers** to expand the list of available solutions for leaky confined aquifers. Select **Hantush-Jacob (1955) w/o aquitard storage** and click **OK**.

3. Choose Displacement-Time from the **View** menu.

4. Choose Log Axes from the **View** menu to display the solution on log-log axes.

5. Choose Automatic from the **Match** menu and click **Estimate** to perform automatic curve matching.

   During the iterative estimation procedure, AQTESOLV displays a progress window and updates the curves displayed on the plot in the background.

6. When estimation has finished, click **OK** and then **Close**. Click **OK** to view the new position of the type curve.

   View Automatic Match with Hantush-Jacob

7. Use residual-time, residual-simulated and normal probability plots to evaluate the fit of the curve by examining residuals. The diagnostics report also presents residual statistics for curve fitting. For this solution, the residual sum of squares is and the residual standard deviation is 0.001458.

Now you will use the Hantush (1960) early-time solution to evaluate the data from this test assuming storage in the aquitard.

1. Choose Solution from the **Match** menu to select a method for analyzing the data.

2. From the list of available solutions for leaky confined aquifers, select

Hantush (1960) early-time solution and click **OK**.

3. Choose Automatic from the **Match** menu and click **Estimate** to perform automatic curve matching.

  During the iterative estimation procedure, AQTESOLV displays a progress window and updates the curves displayed on the plot in the background.

4. When estimation has finished, click **OK** and then **Close**. Click **OK** to view the new position of the type curve.

View Automatic Match with Hantush
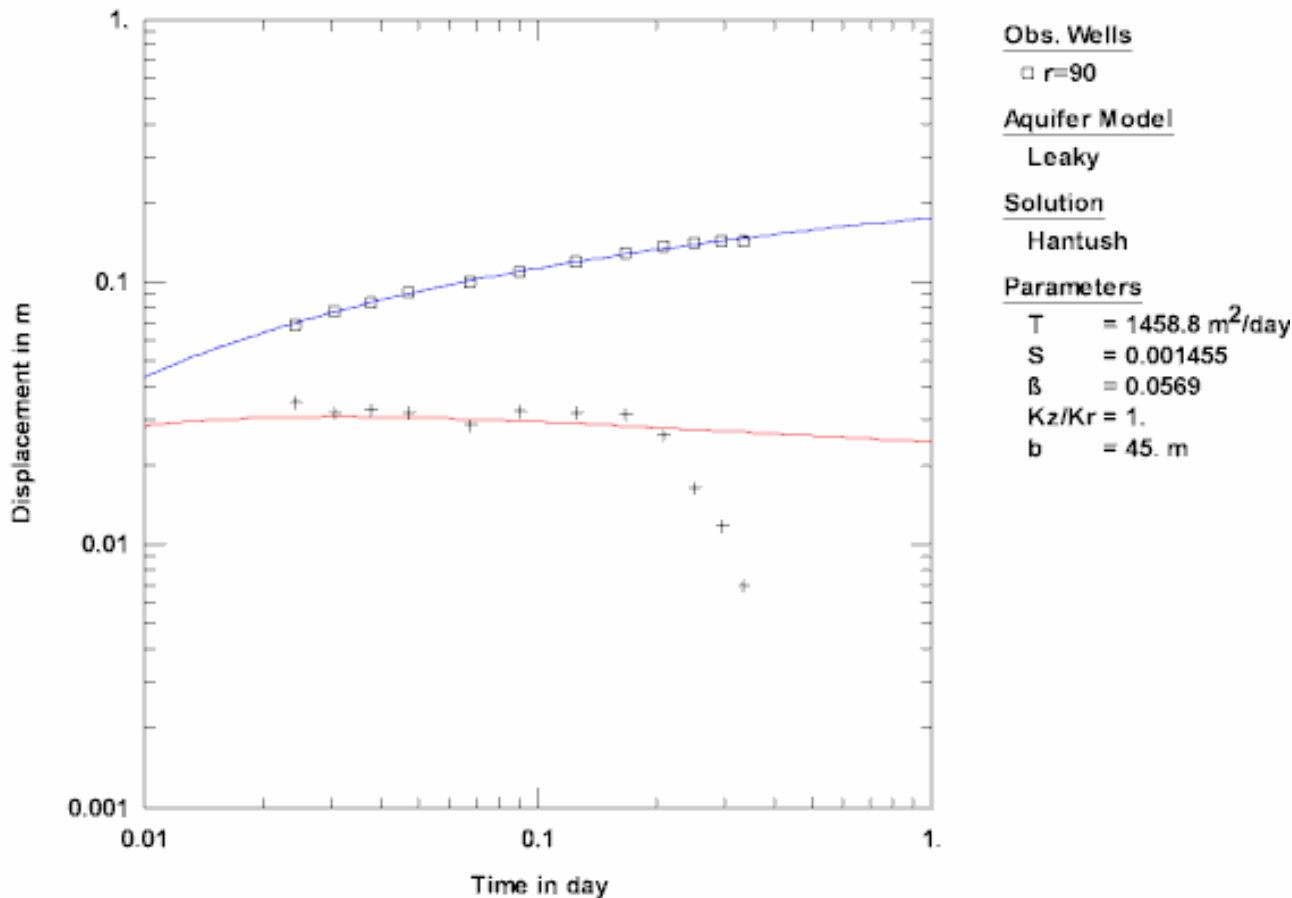
5. Choose Diagnostics from the **View** menu. For this solution, the residual sum of squares is and the residual standard deviation is 0.001818.

  Divide the value of each estimated parameter by its standard error to determine its precision. A standard error smaller than the estimated parameter indicates greater precision and less model uncertainty. In this instance, the small precision of the estimates suggests greater uncertainty in the fit of the Hantush model. This finding is consistent with the remark by Kruseman and De Ridder (1990) that curve fitting with the Hantush method is imprecise when β is less than 0.5.

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

Pro Experiment with the Hantush (1960) solution and automatic curve matching to see if you can improve the fit of the theoretical curve to the derivative data. How does the model affect the estimated value of T?

Pumping Test Example: Leaky (Texas Hill)

This example guides you through the analysis of drawdown data from a multi-observation well pumping test in a leaky confined aquifer at a site designated as Texas Hill (USBR 1995). The test well was pumped at a constant rate of 4488 gallons-per-minute (gpm) for 420 minutes. Drawdown was measured by hand in three observation wells located 40, 80 and 160 ft north of the test well.

This example will introduce you to the following tasks and features in AQTESOLV:

- Creating a new data set for a pumping test with the Pumping Test Wizard

- Importing data from a CSV file using the Import Wizard

- Adding observation wells to the data set

- Saving a data set

- Inspecting diagnostic plots (radial flow and derivative)

- Estimating aquifer properties using Cooper-Jacob (1946) and Hantush-Jacob (1955) solutions (visual and automatic)

- Performing distance-drawdown analysis

TIP While following the steps in this example, click **Help** or press **F1** to context sensitive help in the AQTESOLV application.

Create a New Data Set with Pumping Test Wizard

The first step in analyzing data from a pumping test is to create a new AQTESOLV data set. In this example, you will use the Pumping Test Wizard to assist with data entry.

1. Create a new data set by choosing New from the **File** menu.

2. In the **New Data Set** dialog, select **Pumping Test Wizard** from the list. Click **OK**.

3. Choose **Multiwell test** for the type of pumping test. Click **OK**.

4. The **Pumping Test Wizard** prompts you for data required to analyze a pumping test. Click **Next** to begin the wizard.

5. For units of measurement, choose **ft** for length, **min** for time, **gal/min** for pumping rate and **consistent** for hydraulic conductivity. Click **Next**.

6. For project information, enter **Texas Hill** for the location. Click **Next**.

7. For aquifer data, assume **50** for the aquifer thickness. Enter **1** for the anisotropy ratio (i.e., assume hydraulic conductivity is isotropic). Click **Advanced** and enter **20** for the aquitard thickness, b'. Click **Next**.

8. For pumping well data, enter **Test Well** for the well name. Enter coordinates of X=0 and Y=0. Click **Next**.

9. For pumping well construction, select the option for **vertical, full penetration**. Click **Next**.

10. For pumping well radius data, assume **0.5** for casing radius and **0.5** for well radius. Click **Next**.

11. For pumping rates, enter **0** for time and **4488** for rate. Click **Next**.

12. For observation well data, enter **OW 1** for the well name. Enter **0** and **40** for the X and Y coordinates, respectively. Click **Next**.

13. For observation well construction, select the option for **vertical, full penetration**. Click **Next**.

14. For observations, click **Import** to launch the Observation Data Import Wizard for importing data from a file.

    You will import 26 observations from a text file consisting of time-drawdown readings arranged in four columns. The first column is elapsed time since the start of the test. The remaining columns contain drawdown measurements for the three observation wells. This file contains missing values; thus, there are fewer observations for each well than rows of data in the file.

    > In Step 1 of the wizard, click **Browse**. Select the import file **Texas Hill.csv** in the AQTESOLV installation folder and click **Open**. Click **Next**.
    >
    > In Step 2 of the wizard, use the defaults determined by the Import Wizard. Click **Next**.
    >
    > In Step 3 of the wizard, accept the defaults and click **Finish**. Inspect the import file summary and click **OK**.
    >
    > Click **Next** to proceed with the **Pumping Test Wizard**.

15. You have completed the **Pumping Test Wizard**. Click **Finish**.

After completing the **Pumping Test Wizard**, AQTESOLV automatically displays an Error Log to let you know if the data set contains any errors. If the **Error Log**

identifies any mistakes, choose options from the Edit menu to correct them.

Add Observation Wells

The **Pumping Test Wizard** helped you enter data for the pumping well and the first observation well. Now you will add the two remaining observation wells to the data set.

1. Choose Wells from the **Edit** menu and click **New** to add a new well. Select the new well in the list and click **Modify** to edit the well.

2. In the **General** tab, enter **OW 2** for the well name. Enter **0** and **80** for the X and Y coordinates.

3. In the **Symbols** tab, select **cross** for the data symbol.

4. In the **Observations** tab, click **Import** to launch the Observation Data Import Wizard for importing data from a file.

   You will import 26 observations from the same text file used in the **Pumping Test Wizard**. The first column is elapsed time since the start of the test. The third column contains drawdown measurements for the second observation well.

   > In Step 1 of the wizard, click **Browse**. Select the import file **Texas Hill.csv** in the AQTESOLV installation folder and click **Open**. Click **Next**.
   >
   > In Step 2 of the wizard, enter **3** for the displacement column and keep the other values determined by the Import Wizard. Click **Next**.
   >
   > In Step 3 of the wizard, accept the defaults and click **Finish**. Inspect the import file summary and click **OK**.

5. Click **OK** to finish editing OW 2.

6. Click **New** to add another well. Select the new well in the list and click **Modify** to edit the well.

7. In the **General** tab, enter **OW 3** for the well name. Enter **0** and **160** for the X and Y coordinates.

8. In the **Symbols** tab, select **diamond** for the data symbol.

9. In the **Observations** tab, click **Import** to launch the Observation Data Import Wizard for importing data from a file.

   You will import 26 observations from the same text file used for the first two observation wells. The first column is elapsed time since the start of the test. The fourth column contains drawdown measurements for the third observation well.

   > In Step 1 of the wizard, click **Browse**. Select the import file **Texas Hill.csv** in the AQTESOLV installation folder and click **Open**. Click **Next**.

In Step 2 of the wizard, enter **4** for the displacement column and keep the other values determined by the Import Wizard. Click **Next**.

In Step 3 of the wizard, accept the defaults and click **Finish**. Inspect the import file summary and click **OK**.

10. Click **OK** to finish editing OW 3.

11. Click **Close** to leave the **Wells** window.

Save Data Set

At this point, it's a good idea to save your work.

Save the data set by choosing Save As from the **File** menu. Choose a folder and enter **Texas Hill** for the name of the file. Click **Save**. The default extension for an AQTESOLV data set is **.aqt**.

Pro **Inspect Diagnostic Plots**

Before performing curve matching to estimate aquifer properties, you may use diagnostic features in AQTESOLV to evaluate aquifer and flow conditions.

Diagnostic flow plots help you select an appropriate solution method for your pumping test data.

1. Choose Radial Flow from the **View** menu to display a radial flow plot on log-linear axes.

View Radial Flow Plot

By the end of the test, the data for each well approach a horizontal line with time indicating a source of recharge (leakage).
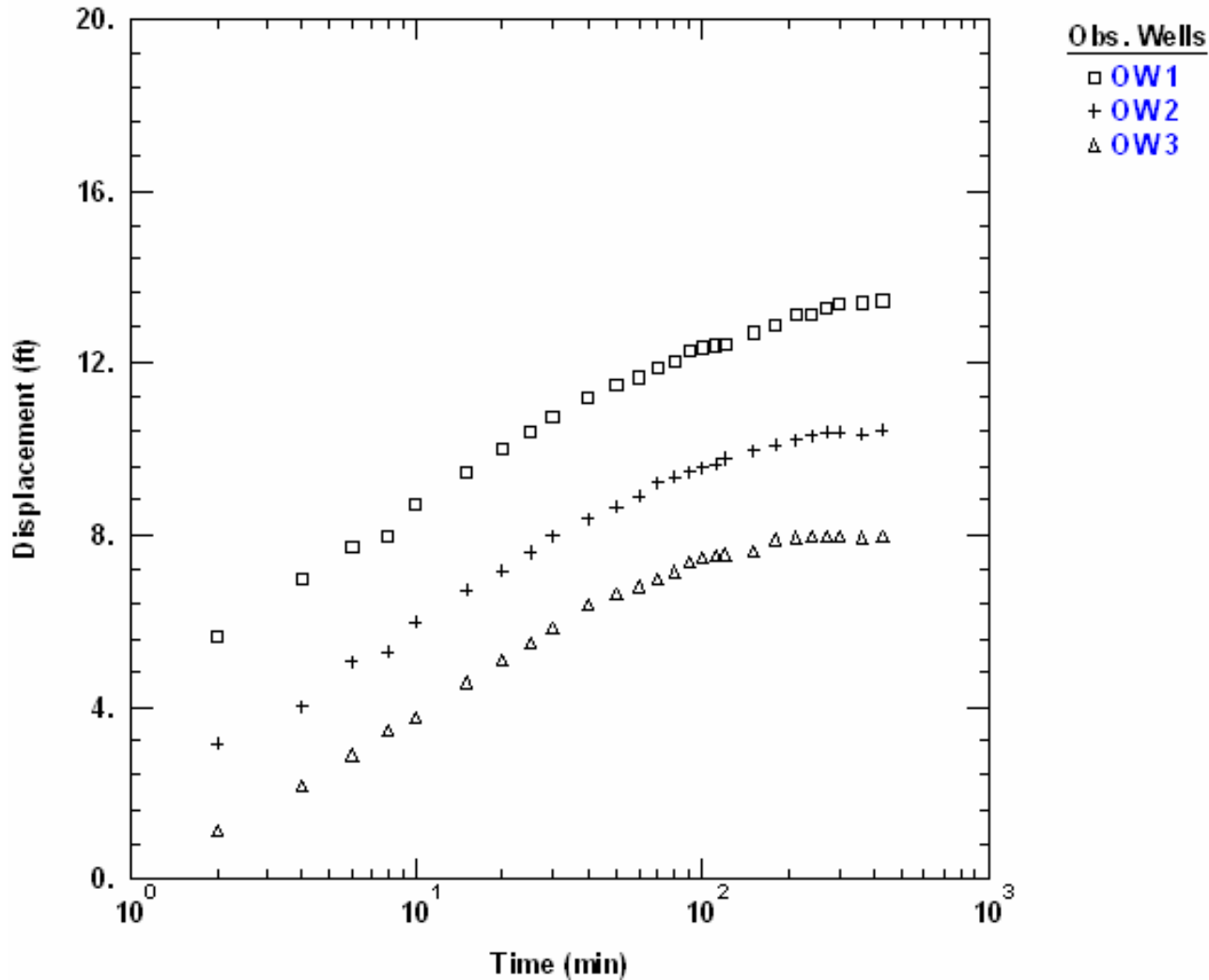
Derivative analysis is another useful diagnostic tool for evaluating aquifer conditions.

1. Choose Composite from the **View** menu to display a plot of the test data on log-linear axes.

A composite plot normalizes time by the radius squared (t/r^2). For fully penetrating wells in a homogeneous and isotropic leaky confined aquifer, the composite plot facilitates visual curve matching because data from more than one observation well plot along a single curve until the onset of leakage.

2. Choose Log Axes from the **View** menu to display the plot on log-log axes.

3. Select Options from the **View** menu. In the **Plots** tab, check **Derivative curves**. In the **Derivative** tab, select the option for **Bourdet** and enter **0.4** for the differentiation interval. Click **OK**.

View Derivative Plot

As the test progresses, the derivatives approach zero, i.e, the slope of the time drawdown data becomes horizontal, which is characteristic of recharge
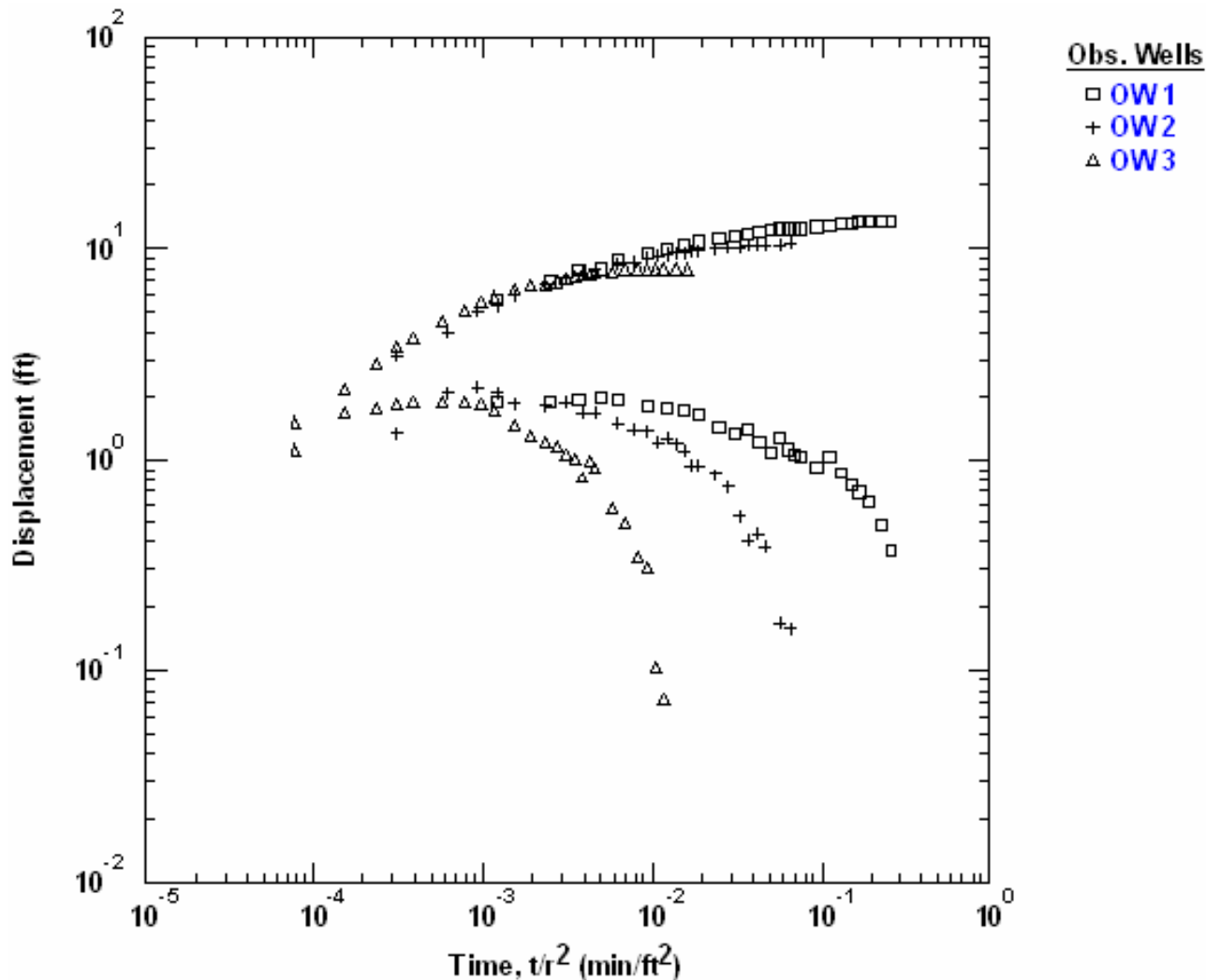
Estimate Aquifer Properties

To start our analysis, we can use the Cooper-Jacob (1946) solution for a confined aquifer to obtain preliminary estimates of transmissivity and storativity.

1. Choose Solution from the **Match** menu to select a method for analyzing the data.

2. Remove the check from **Solution is inactive**. Click the **+** next to **Confined Aquifers** to expand the list of available solutions for confined aquifers. Select **Cooper-Jacob (1946)** and click **OK**.

3. Choose Composite from the **View** menu to display a composite plot of the data.

4. Choose Options from the **View** menu. In the **Plots** tab, remove the check from **Derivative curve(s)** and check **Valid time for Cooper-Jacob approximation**. In the **Valid Time** tab, enter **0.05** for the critical value of u. Click **OK**.

5. Choose Visual from the **Match** menu to perform visual curve matching with the Cooper-Jacob solution.

To perform visual matching, move the mouse to a point where you wish to begin drawing a new line with the Cooper-Jacob solution.

 Click and hold down the left mouse button to anchor the new line at this point.

 Continue to hold the mouse button down and move the mouse to match a new straight line to your data. As you move the mouse, AQTESOLV draws a straight line between the anchor point and the position of the mouse.

 Release the left mouse button when you have finished matching a new straight line. AQTESOLV automatically updates the plot legend to reflect changes in parameter values.

---

6. Repeat the previous step as needed to achieve a satisfactory match.

View Visual Match With Cooper-Jacob

Note that very few data points near the end of the test meet the validity criterion (u 0.05) for the Cooper-Jacob solution.
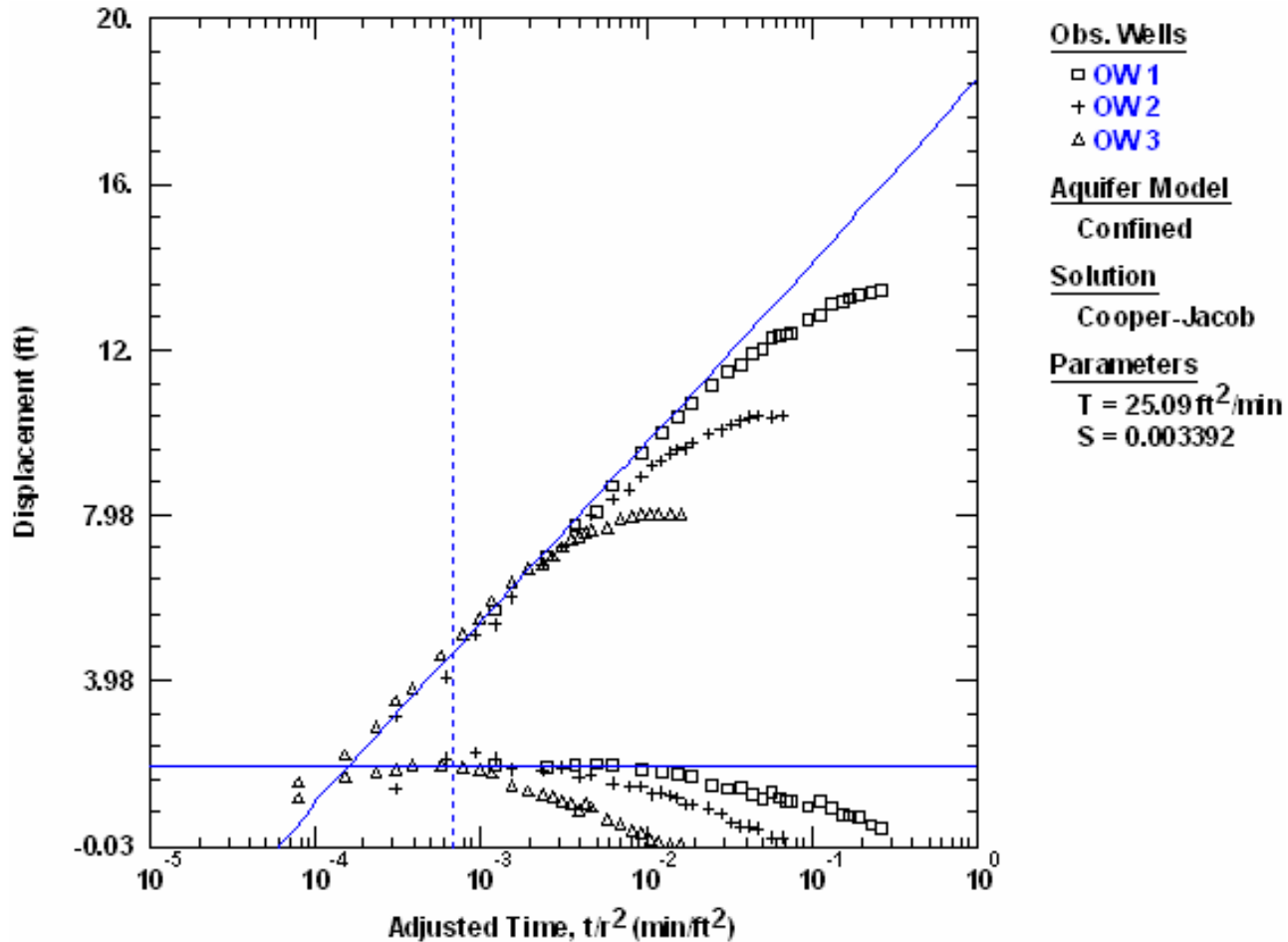
Now you will use the Hantush-Jacob (1955) solution for a leaky confined aquifer to analyze the drawdown data in all three observation wells simultaneously.

1. Choose Solution from the **Match** menu to select a method for analyzing the data.

2. Click the **+** next to **Leaky Confined Aquifers** to expand the list of available solutions for leaky confined aquifers. Select **Hantush-Jacob (1955)/Hantush (1964)** and click **OK**.

3. Choose Log Axes from the **View** menu to display the plot on log-log axes.

4. Choose Options from the **View** menu. In the **Plots** tab, check **Derivative curve(s)**. Click **OK**.

5. Choose Automatic from the **Match** menu and click **Estimate** to perform automatic curve matching.

   During the iterative estimation procedure, AQTESOLV displays a progress window and updates the curves displayed on the plot in the background.

6. When estimation has finished, click **OK** and then **Close**. Click **OK** to view the new position of the type curve.

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View Automatic Match With Hantush-Jacob

7. Use residual-time, residual-simulated and normal probability plots to evaluate the fit of the curve by examining residuals. The diagnostics report also presents residual statistics for curve fitting. The complete report shows estimates of aquitard properties derived from the leakage parameter, r/B.

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

Perform Distance-Drawdown Analysis

In addition to time-drawdown analyses, you can use AQTESOLV to evaluate distance-drawdown data.

1. Choose Distance Drawdown from the **View** menu to plot drawdown versus distance at a specified time.

2. Choose Options from the **View** menu. In the **Distance** tab, enter **420** for the time used in distance-drawdown calculations. Click **OK**.

3. The plot shows drawdown for the three observation wells at the end of the test (420 minutes). You may use automatic estimation to match the curve to just the distance-drawdown data points.

   View Distance-Drawdown Plot

Obs. Wells
□ OW1
+ OW2
△ OW3

Aquifer Model
Leaky

Solution
Hantush-Jacob

Parameters
T = 25.6 ft^2/min
S = 0.003237
$1/B$ = 0.0007852 ft^{-1}
K_z/K_r = 1.
b = 50. ft
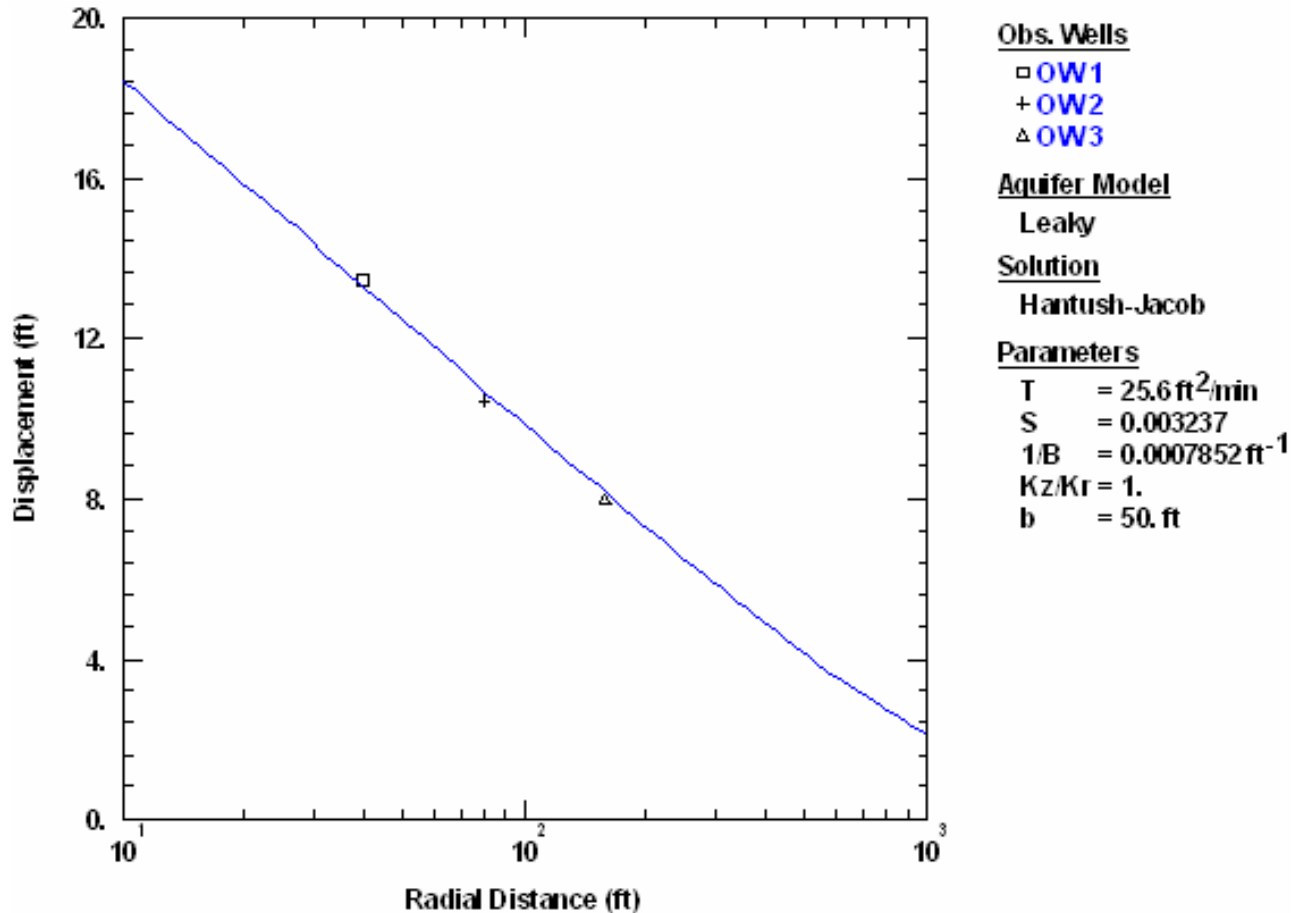
Pumping Test: Unconfined (Saratoga)

In this example, you will analyze data from a pumping test conducted near Saratoga, New York (Greenkorn 1983). The test well (SA 1077) partially penetrated a 16-ft thick water-table aquifer described as interbedded silty fine sand and coarse sand. Pumping continued for nearly two days at a constant rate of 17.2 gallons-per-minute (gpm). Hydraulic response was monitored in an observation well (SA 1072) at a distance of 15.2 ft from the pumped well. Time and drawdown measurements were recorded in days and feet, respectively.

This example will introduce you to the following tasks and features in AQTESOLV:

- Creating a new data set with the Pumping Test Wizard

- Importing data with the Observation Data Import Wizard

- Saving a data set

- Inspecting diagnostic plots (radial flow and derivative)

- Estimating aquifer properties using Cooper-Jacob (1946), Neuman (1974) and Moench (1997) solutions (visual and automatic)

While following the steps in this example, click **Help** or press **F1** to obtain context sensitive help in the AQTESOLV application.

Create a New Data Set with Pumping Test Wizard

The first step in analyzing data from a pumping test is to create a new AQTESOLV data set. In this example, we will use the Pumping Test Wizard to assist us with data entry.

1. Create a new data set by choosing New from the **File** menu.

2. In the **New Data Set** dialog, select **Pumping Test Wizard** from the list. Click **OK**.

3. Choose **Multiwell test** for the type of pumping test. Click **OK**.

4. The **Pumping Test Wizard** prompts you for data required to analyze a pumping test. Click **Next** to begin the wizard.

5. For units of measurement, choose **ft** for length, **day** for time, **gal/min** for pumping rate and **gal/day/sq. ft** for hydraulic conductivity. Click **Next**.

6. For project information, enter **Saratoga, NY** for the location. Click **Next**.

7. For aquifer data, enter **16** for the aquifer thickness. Enter **1** for the anisotropy ratio (i.e., assume hydraulic conductivity is isotropic). Click **Next**.

8. For pumping well data, enter **SA 1077** for the well name. Enter coordinates of X=0 and Y=0. Click **Next**.

9. For pumping well construction, select the option for **vertical, partial penetration**. Enter **9** for the depth to the top of the well screen and **6** for the screen length. Click **Next**.

10. For pumping well radius data, assume **0.333** for casing radius and **0.5** for well radius. Click **Next**.

11. For pumping rates, enter **0** for time and **17.2** for rate in the first row of the spreadsheet. Click **Next**.

12. For observation well data, enter **SA 1072** for the well name. Enter **15.2** and **0** for the X and Y coordinates, respectively. Click **Next**.

13. For observation well construction, select the option for **vertical, partial penetration**. Enter **11** for the depth to the top of the well screen and **3** for the screen length. Click **Next**.

14. For radius data, enter **0.0** for the casing radius to disable delayed observation

well response.

15. For observations, click **Import** to launch the Observation Data Import Wizard for importing data from a file.

    We will import a text file consisting of 44 time-drawdown readings arranged in two columns. The first column is elapsed time since the start of the test. The second column contains drawdown measurements.

> In Step 1 of the wizard, click **Browse**. Select the import file **Saratoga SA 1072.txt** in the AQTESOLV installation folder and click **Open**. Click **Next**.
>
> In Step 2 of the wizard, accept the default entries and click **Next**.
>
> In Step 3 of the wizard, click **Finish**. Inspect the import file summary and click **OK**.
>
> Click **Next** to proceed with the **Pumping Test Wizard**.

16. You have completed the **Pumping Test Wizard**. Click **Finish**.

After completing the **Pumping Test Wizard**, AQTESOLV automatically displays an Error Log to let you know if the data set contains any errors. If the **Error Log** identifies any mistakes, choose options from the Edit menu to correct them.

Save Data Set

At this point, it's a good idea to save your work.

Save the data set by choosing Save As from the **File** menu. Choose a folder, enter **Saratoga SA 1072** for the name of the file and click **Save**. AQTESOLV saves the file with an **.aqt** extension.

Inspect Diagnostic Plots

Before performing curve matching to estimate aquifer properties, you may use diagnostic features in AQTESOLV to evaluate aquifer and flow conditions.

Diagnostic flow plots help you select an appropriate solution method for your pumping test data.

1. Choose Radial Flow from the **View** menu to display a radial flow plot on log-linear axes.

   View Radial Flow Plot

   The response shown on the radial flow plot is characteristic of delayed gravity response in an unconfined aquifer. At late time, data plotting as a straight line indicate radial flow conditions in an infinite-acting aquifer.
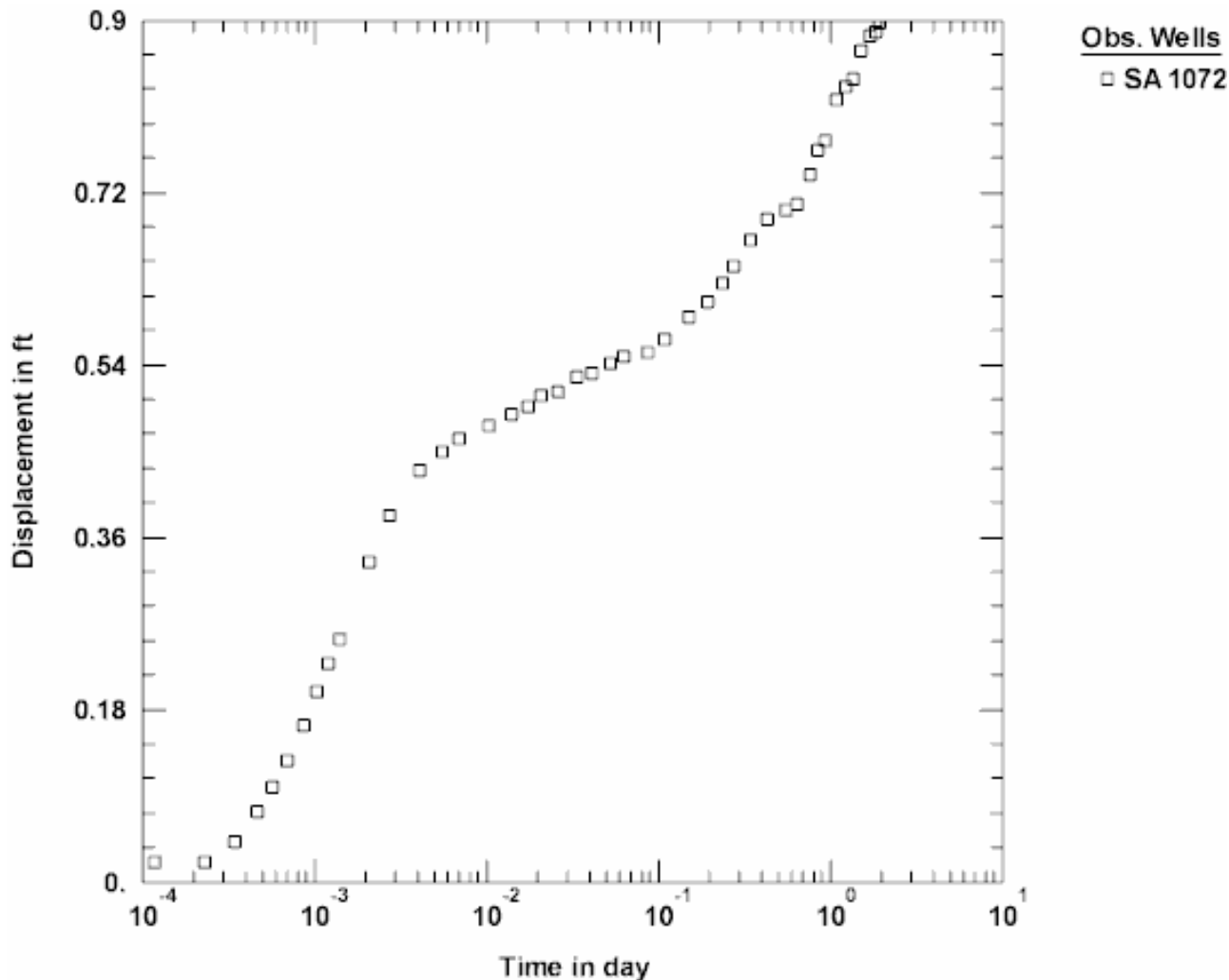
Derivative analysis is another useful diagnostic tool for evaluating aquifer conditions.

1. Choose Displacement-Time from the **View** menu to display a plot of the test data. On semi-log axes, this plot is identical to the radial flow plot above.

2. Choose Wells from the **Edit** menu. Select **SA 1072** from the list and click **Modify**.

   In the **Symbols** tab, remove the check from **Use data symbols properties** and select **cross** for the derivative symbol.

   In the **Curves** tab, remove the check from **Use type curve properties**. Click **Color** for the derivative curve properties, change the color to **red**, and click **OK**.

   Click **OK** and then **Close**.

3. Select Options from the **View** menu. In the **Plots** tab, check **Derivative curves**. In the **Derivative** tab, select the option for **Bourdet** and enter a differentiation interval of **0.3**. Click **OK**.

View Derivative Plot

The form of the derivative plot is characteristic of radial flow in an unconfined aquifer with delayed gravity response. At intermediate time, the derivative approaches zero during the period of delayed gravity response.
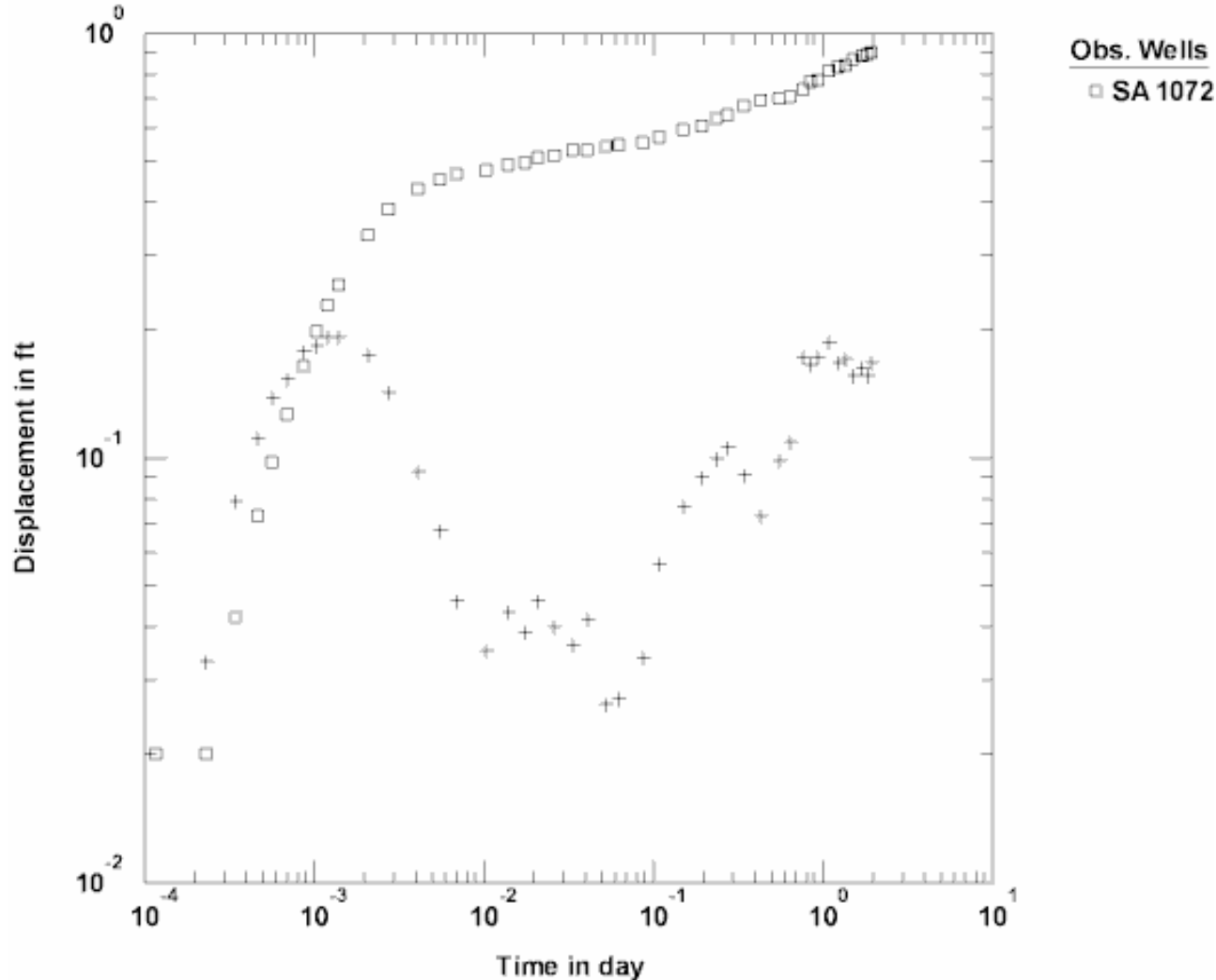
Estimate Aquifer Properties

The radial flow and derivative plots that we have examined for this test confirm the assumption of radial flow in an unconfined aquifer with delayed gravity response. Although the wells in this example are partially penetrating, we can use the Cooper-Jacob (1946) solution, which assumes fully penetrating wells, to obtain first-cut estimates of aquifer properties.

1. Choose Solution from the **Match** menu to select a method for analyzing the data.

2. Remove the check from **Solution is inactive**. Click the **+** next to **Unconfined Aquifers** to expand the list of available solutions for unconfined aquifers. Select **Cooper-Jacob (1946)** and click **OK**.

3. Choose Visual from the **Match** menu to perform visual curve matching with the Cooper-Jacob solution.

   Match the solution to the late-time data to estimate T and Sy. Note that the Cooper-Jacob solution only determines one value for the storative properties of the aquifer (labeled S); however, when you match the straight line to the late-time data, you really are estimating Sy.

To perform visual matching, move the mouse to a point where you wish to begin drawing a new line with the Cooper-Jacob solution.

Click and hold down the left mouse button to anchor the new line at this point.

Continue to hold the mouse button down and move the mouse to match a new straight line to your data. As you move the mouse, AQTESOLV draws a straight line between the anchor point and the position of the mouse.

Release the left mouse button when you have finished matching a new straight line. AQTESOLV automatically updates the plot legend to reflect changes in parameter values.

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4. Repeat the previous step as needed to achieve a satisfactory match to the late-time data. The estimates of T and S should be close to 1.18×10^4 gal/day/ft and 0.15, respectively. Because you have matched the Cooper-Jacob solution to late-time data, you will use 0.15 for your estimate of Sy.

   Note: Because the Cooper-Jacob solution assumes fully penetrating wells, your preliminary estimate of Sy at this stage of the analysis is only a first-order approximation. To obtain a more refined estimate of Sy, you could use the Theis (1935) solution which accounts for partially penetrating wells.

5. Choose Toolbox from the **Match** menu. In the Tweak tab, select **S** from the list of parameters. Use the scroll bar to decrease S until the line matches the early-time data. Your adjusted estimate of S should be near 0.005.

Having completed our preliminary analysis with Cooper-Jacob, let's continue by matching the data with the Neuman (1974) solution for an unconfined aquifer with delayed gravity response.

1. Choose Solution from the **Match** menu to select a method for analyzing the data.

2. From the list of solutions for **Unconfined Aquifers**, select **Neuman (1974)** and click **OK**.

3. Choose Log Axes from the **View** menu to view the data on log-log axes.

4. Choose Toolbox from the **Match** menu. In the Parameters tab, enter , **0.005** and **0.15** for the values of T, S and Sy, respectively. Click **OK**.

5. Visual curve matching with the Neuman solution involves fitting Type A and Type B curves to the data. For a given value of β, match the Type A curve to the early-time data to estimate T and S; match the Type B curve to the late-

time data to determine T and Sy.

Begin visual curve matching by selecting **β=0.1** from the list on the toolbar.

- First, click ▦ on the toolbar to match the Type A curve for β=0.1.

  Click and hold the left mouse button down over a point within the plot area.

  Continue to hold the mouse button down and move the mouse to match the Type A curve to the early-time data. As you move curve, AQTESOLV automatically updates parameter values in the plot legend.

  Release the left mouse button when you have finished matching the curve.

- Next, click ▦ on the toolbar to match the Type B curve for β=0.1.

  Click and hold the left mouse button down over a point within the plot area.

  Continue to hold the mouse button down and move the mouse to match the Type B curve to the late-time data. As you move curve, AQTESOLV automatically updates parameter values in the plot legend.

  Release the left mouse button when you have finished matching the curve.

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6. Repeat the previous step for different values of β until you obtain a satisfactory match.

7. Choose Automatic from the **Match** menu and click **Estimate** to perform automatic curve matching.

   During the iterative estimation procedure, AQTESOLV displays a progress window and updates the curves displayed on the plot in the background.

8. When estimation has finished, click **OK** and then **Close**. Click **OK** to view the new position of the type curve.

View Automatic Match with Neuman Solution

The chart shows the following annotations:

Obs. Wells
SA 1072

Aquifer Model
Unconfined

Solution
Neuman

Parameters
$T = 1.112E+4$ gal/day/ft
$S = 0.01126$
$Sy = 0.3668$
$\beta = 0.1371$

Y-axis: Displacement in ft (10^0, 10^{-1}, 10^{-2})
X-axis: Time in day (10^{-4}, 10^{-3}, 10^{-2}, 10^{-1}, 10^0, 10^1)

9. Use residual-time, residual-simulated and normal probability plots to evaluate the fit of the curve by examining residuals. The diagnostics report also presents residual statistics for curve fitting.

Pro The foregoing analysis with the Neuman (1974) solution assumed a line source for the pumped well. To investigate the effect of a finite-diameter well with wellbore storage, let's match the Moench (1997) solution for an unconfined aquifer with delayed gravity response.

1. Choose Solution from the **Match** menu to select a method for analyzing the data.

2. From the list of solutions for **Unconfined Aquifers**, select **Moench (1997)** and click **OK**.

3. At intermediate and late time, the curves for the Neuman and Moench solutions appear virtually the same; however, at early time, the curve for the Moench solution shifts to the right as a consequence of the finite-diameter pumped well with wellbore storage. As radial distance from the pumped well increases, the difference between the two solutions becomes less pronounced.

4. Choose Automatic from the **Match** menu. In the Parameters tab, select **Inactive** for the estimation status of Sw, r(w), r(c) and alpha. Click **Estimate** to perform automatic curve matching.

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5. When estimation has finished, click **OK** and then **Close**. Click **OK** to view the new position of the type curve.

View Automatic Match with Moench Solution
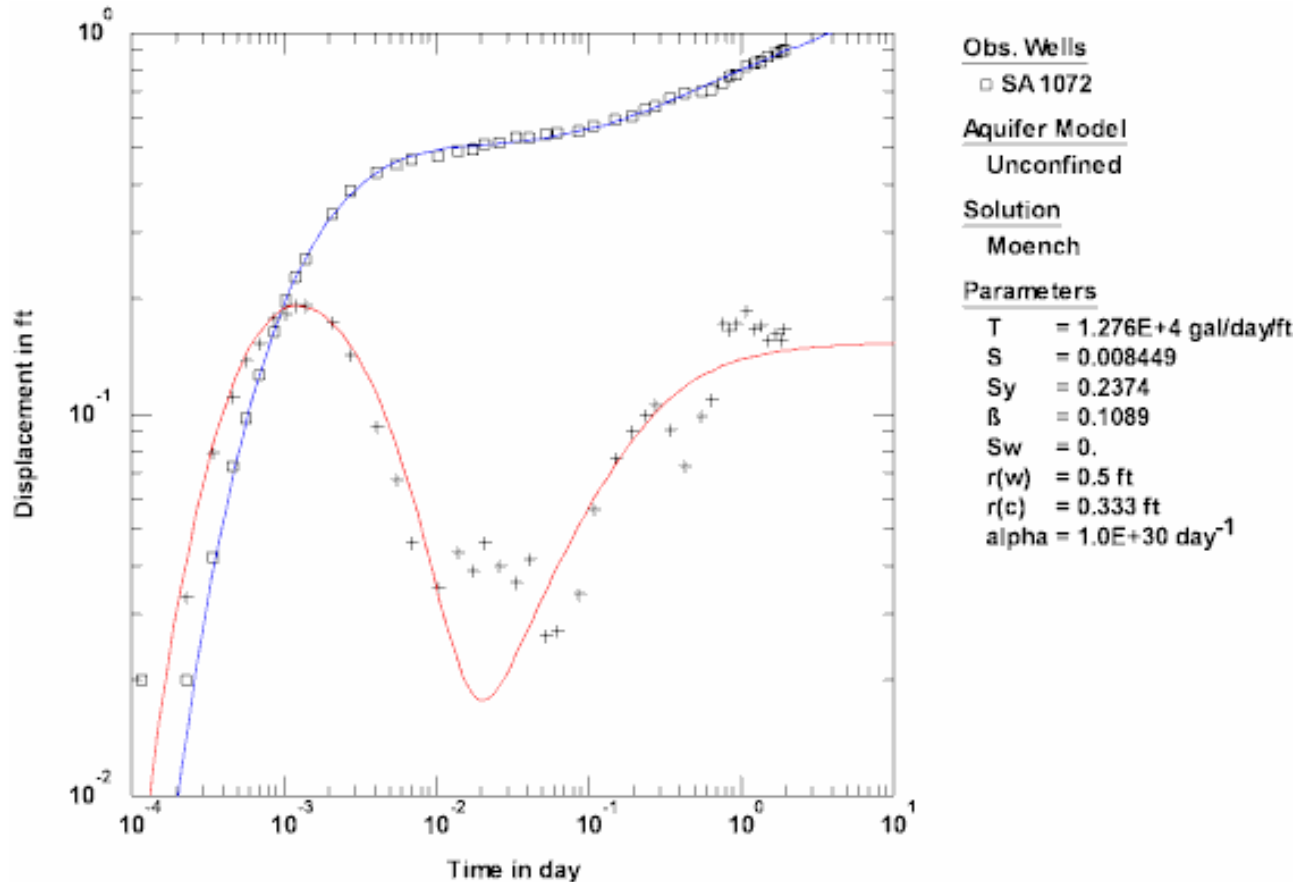
6. In terms of the residual sum of squares (RSS), the objective function minimized by the automatic curve matching procedure, the curve fit with the Moench solution (RSS = 0.003745 ft^2) is superior to the Neuman solution (RSS = 0.00436 ft^2). How do the residual plots compare for the two solutions?

Delayed Observation Well Response

The Moench (1997) solution for a double-porosity aquifer is one of the solutions in AQTESOLV that includes delayed observation well response. To produce delayed response, enter positive nonzero values for the casing radius and well radius of the observation well.

View Effect of Delayed Response

Obs. Wells
- SA 1072 (Delayed)
- SA 1072

Aquifer Model
Unconfined

Solution
Moench

Parameters
T	= 1.276E+4 gal/day/ft
S	= 0.008449
Sy	= 0.2374
Kz/Kr	= 0.1208
Sw	= 0.
r(w)	= 0.5 ft
r(c)	= 0.333 ft
alpha	= 1.0E+30 day^{-1}
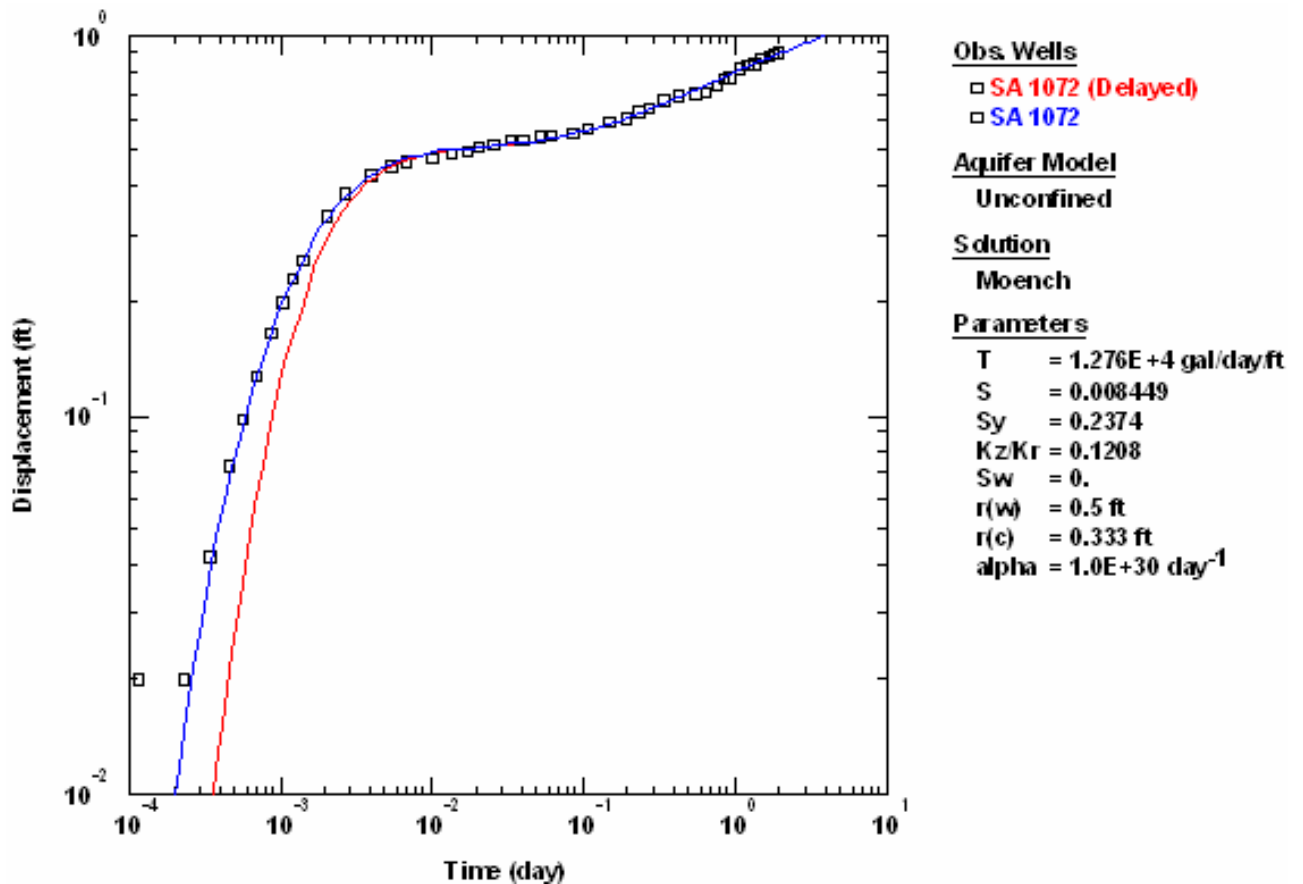
Pumping Test Example: Unconfined (Cape Cod)

In this example, you will analyze data from a pumping test conducted by the USGS at Cape Cod, Massachusetts (Moench et al. 2001). The test well (F507-080) partially penetrated a 170-ft (51.82-m) thick water-table aquifer described as a glacial outwash deposit consisting of sand and gravel. A constant pumping rate of 320 gallons per minute (0.0202 m^3/s) was maintained in the well for 72 hours. Drawdown was monitored in an observation well (F377-037) at a distance of 85.1 ft (25.94 m) from the pumped well. Time and drawdown measurements were recorded in minutes and feet, respectively.

This example will introduce you to the following tasks and features in AQTESOLV:

- Creating a new data set with the Pumping Test Wizard

- Importing data with the Observation Data Import Wizard

- Saving a data set

- Inspecting diagnostic plots (radial flow and derivative)

- Estimating aquifer properties using Cooper-Jacob (1946), Neuman (1974) and Tartakovsky-Neuman (2007) solutions (visual and automatic)

While following the steps in this example, click **Help** or press **F1** to obtain context sensitive help in the AQTESOLV application.

Create a New Data Set with Pumping Test Wizard

The first step in analyzing data from a pumping test is to create a new AQTESOLV data set. In this example, we will use the Pumping Test Wizard to assist us with data entry.

1. Create a new data set by choosing New from the **File** menu.

2. In the **New Data Set** dialog, select **Pumping Test Wizard** from the list. Click **OK**.

3. Choose **Multiwell test** for the type of pumping test. Click **OK**.

4. The **Pumping Test Wizard** prompts you for data required to analyze a pumping test. Click **Next** to begin the wizard.

5. For units of measurement, choose **ft** for length, **min** for time, **gal/min** for pumping rate and **m/sec** for hydraulic conductivity. Click **Next**.

6. For project information, enter **Cape Cod, MA** for the location. Click **Next**.

7. For aquifer data, enter **170** for the aquifer thickness. Enter **1** for the anisotropy ratio (i.e., assume hydraulic conductivity is isotropic). Click **Next**.

8. For pumping well data, enter **F507-080** for the well name. Enter coordinates of X=0 and Y=0. Click **Next**.

9. For pumping well construction, select the option for **vertical, partial penetration**. Enter **13.2** for the depth to the top of the well screen and **47** for the screen length. Click **Next**.

10. For pumping well radius data, assume **0.333** for casing radius and **0.333** for well radius. Click **Next**.

11. For pumping rates, enter **0** for time and **320** for rate in the first row of the spreadsheet. Click **Next**.

12. For observation well data, enter **F377-037** for the well name. Enter **85.1** and **0** for the X and Y coordinates, respectively. Click **Next**.

13. For observation well construction, select the option for **vertical, partial penetration**. Enter **13.3** for the depth to the top of the well screen and **2** for

the screen length. Click **Next**.

14. For observations, click **Import** to launch the Observation Data Import Wizard for importing data from a file.

    We will import a text file consisting of 30 time-drawdown readings arranged in two columns. The first column is elapsed time since the start of the test. The second column contains drawdown measurements.

    In Step 1 of the wizard, click **Browse**. Select the import file **F377-037.txt** in the AQTESOLV installation folder and click **Open**. Click **Next**.

    In Step 2 of the wizard, accept the default entries and click **Next**.

    In Step 3 of the wizard, click **Finish**. Inspect the import file summary and click **OK**.

    Click **Next** to proceed with the **Pumping Test Wizard**.

15. You have completed the **Pumping Test Wizard**. Click **Finish**.

After completing the **Pumping Test Wizard**, AQTESOLV automatically displays an Error Log to let you know if the data set contains any errors. If the **Error Log** identifies any mistakes, choose options from the Edit menu to correct them.

Save Data Set

At this point, it's a good idea to save your work.

Save the data set by choosing Save As from the **File** menu. Choose a folder, enter **F377-037** for the name of the file and click **Save**. AQTESOLV saves the file with an **.aqt** extension.

Pro **Inspect Diagnostic Plots**

Before performing curve matching to estimate aquifer properties, you may use diagnostic features in AQTESOLV to evaluate aquifer and flow conditions.

Diagnostic flow plots help you select an appropriate solution method for your pumping test data.

1. Choose Radial Flow from the **View** menu to display a radial flow plot on log-linear axes.

    View Radial Flow Plot

    The response shown on the radial flow plot shows some characteristics of the Neuman (1974) model for an unconfined aquifer. At intermediate time, the drawdown data only exhibit a moderate delayed gravity response. Late-time data almost appear to plot as a straight line.
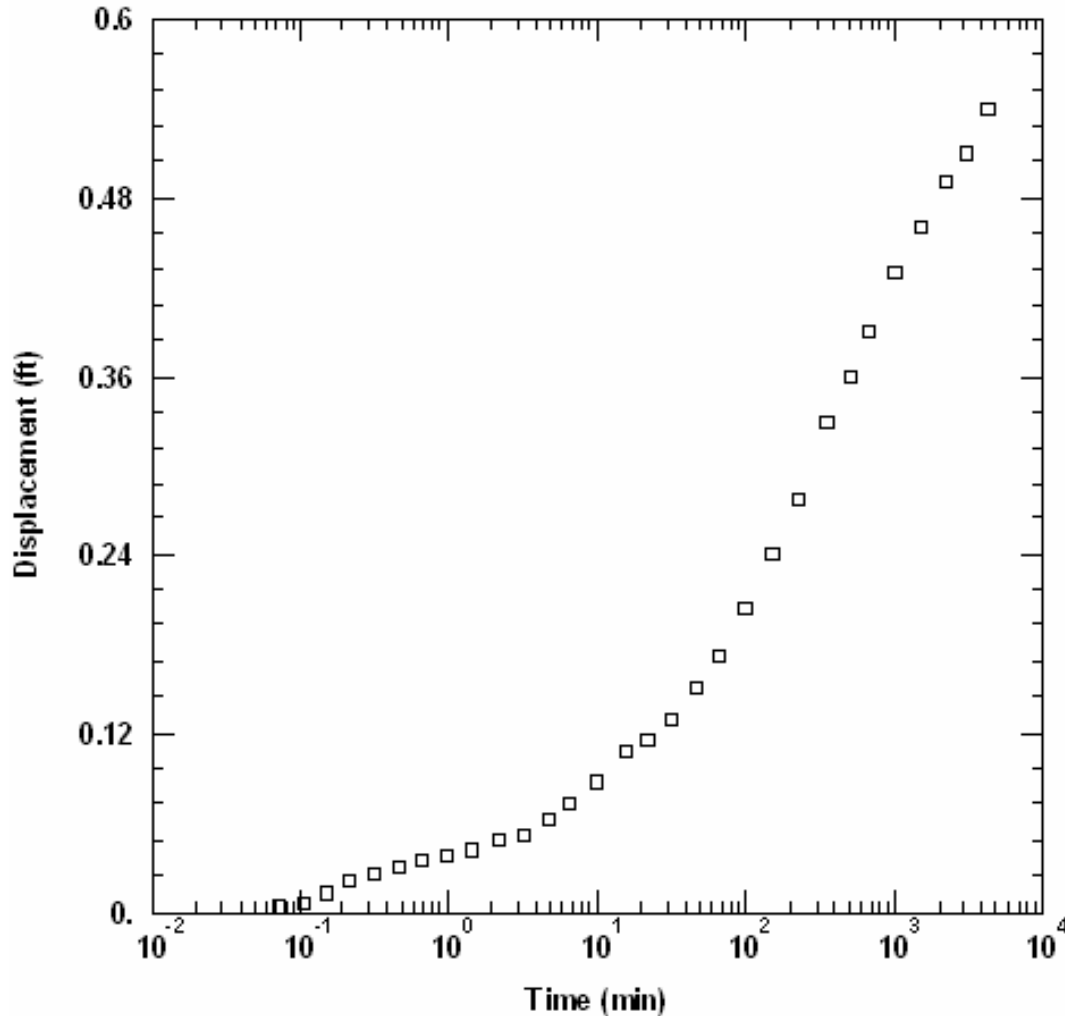
Derivative analysis is another useful diagnostic tool for evaluating aquifer conditions.

1. Choose Displacement-Time from the **View** menu to display a plot of the test data. On semi-log axes, this plot is identical to the radial flow plot above.

2. Choose Wells from the **Edit** menu. Select **F377-037** from the list and click **Modify**.

   In the **Symbols** tab, remove the check from **Use data symbols properties** and select **cross** for the derivative symbol.

   In the **Curves** tab, remove the check from **Use type curve properties**. Click **Color** for the derivative curve properties, change the color to **red**, and click **OK**.

   Click **OK** and then **Close**.

3. Select Options from the **View** menu. In the **Plots** tab, check **Derivative curves**. In the **Derivative** tab, select the option for **Smoothing** and enter a smoothing factor of **1**. Click **OK**.

View Derivative Plot

The form of the derivative plot is not entirely consistent with an unconfined aquifer exhibiting instantaneous drainage at the water table (Neuman 1974 model). With the Neuman model, one expects a pronounced dip in the derivative at intermediate time and a constant derivative at late time. Neither of these characteristics is evident on the derivative plot which suggests that a model with noninstantaneous drainage at the water table (e.g., Tartakovsky-Neuman 2007) may be appropriate for our analysis.
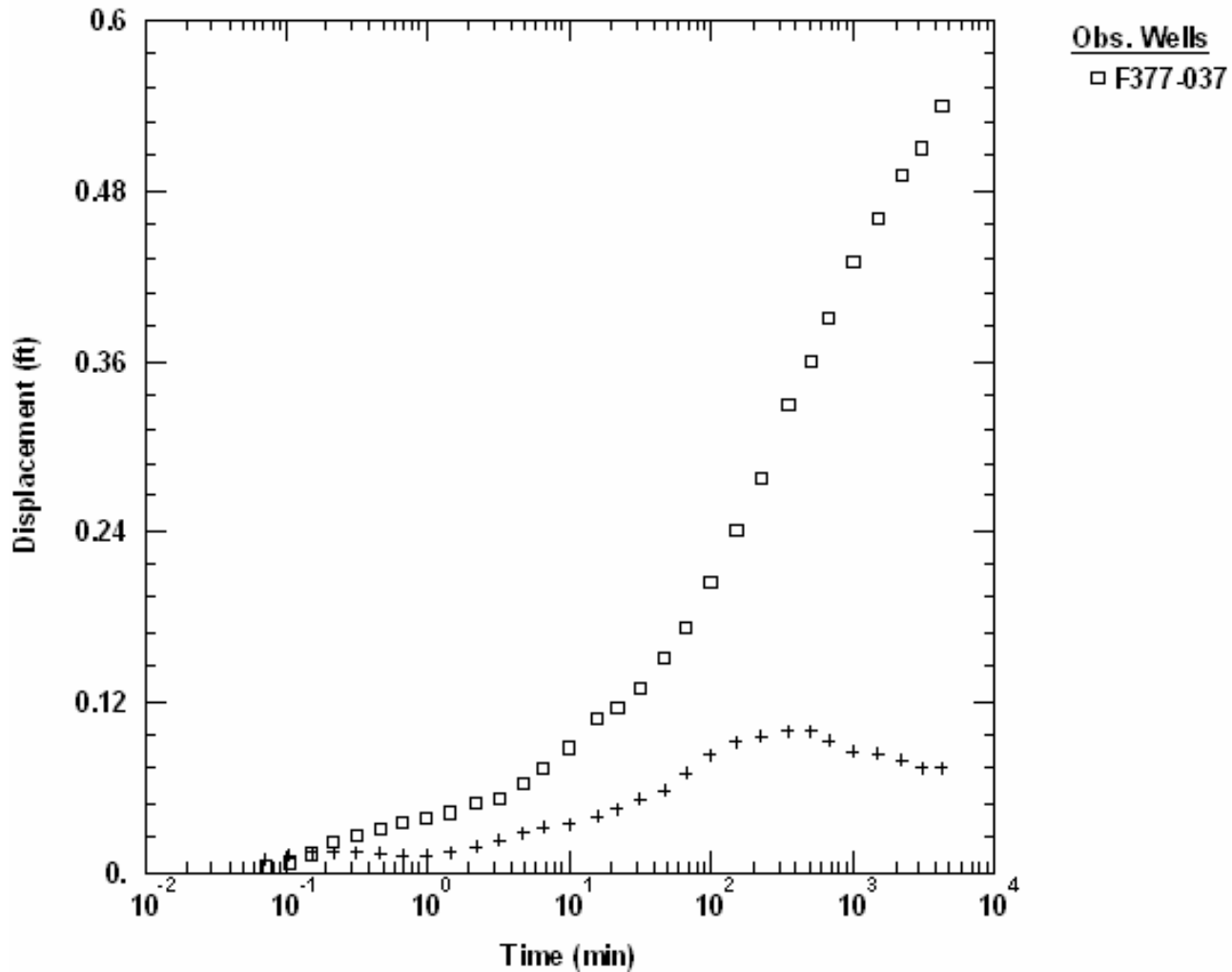
Estimate Aquifer Properties

Although the wells in this example are partially penetrating, we can use the Cooper-Jacob (1946) solution, which assumes fully penetrating wells, to obtain first-cut estimates of aquifer properties.

1. Choose Solution from the **Match** menu to select a method for analyzing the data.

2. Remove the check from **Solution is inactive**. Click the **+** next to **Unconfined Aquifers** to expand the list of available solutions for unconfined

aquifers. Select **Cooper–Jacob (1946)** and click **OK**.

3. Choose Visual from the **Match** menu to perform visual curve matching with the Cooper-Jacob solution.

   Match the solution to the late-time data to estimate T and Sy. Note that the Cooper-Jacob solution only determines one value for the storative properties of the aquifer (labeled S); however, when you match the straight line to the late-time data, you really are estimating Sy.

   To perform visual matching, move the mouse to a point where you wish to begin drawing a new line with the Cooper-Jacob solution.

   Click and hold down the left mouse button to anchor the new line at this point.

   Continue to hold the mouse button down and move the mouse to match a new straight line to your data. As you move the mouse, AQTESOLV draws a straight line between the anchor point and the position of the mouse.

   Release the left mouse button when you have finished matching a new straight line. AQTESOLV automatically updates the plot legend to reflect changes in parameter values.

4. Repeat the previous step as needed to achieve a satisfactory match to the late-time data. Your estimates of T and S should be around 0.06 m^2/sec and 0.1, respectively. Because you have matched the Cooper-Jacob solution to late-time data, you will use 0.1 for your estimate of Sy.

   Note: Because the Cooper-Jacob solution assumes fully penetrating wells, your preliminary estimate of Sy at this stage of the analysis is only a first-order approximation. To obtain a more refined estimate of Sy, you could use the Theis (1935) solution which accounts for partially penetrating wells.

5. Choose Toolbox from the **Match** menu. In the Tweak tab, select **S** from the list of parameters. Use the scroll bar to decrease S until the line matches the early-time data. Your adjusted estimate of S should be on the order of 0.0025.

Having completed our preliminary analysis with Cooper-Jacob, let's continue by matching the data with the Neuman (1974) solution for an unconfined aquifer with delayed gravity response (instantaneous drainage at the water table).

1. Choose Solution from the **Match** menu to select a method for analyzing the data.

2. From the list of solutions for **Unconfined Aquifers**, select **Neuman (1974)** and click **OK**.

3. Choose Log Axes from the **View** menu to view the data on log-log axes.

4. Choose Toolbox from the **Match** menu. In the Parameters tab, enter **0.06**, **0.0025** and **0.1** for the values of T, S and Sy, respectively. Keep the default value of 0.1 for β. Click **OK**.

5. Choose Automatic from the **Match** menu and click **Estimate** to perform automatic curve matching.

   During the iterative estimation procedure, AQTESOLV displays a progress window and updates the curves displayed on the plot in the background.

6. When estimation has finished, click **OK** and then **Close**. Click **OK** to view the new position of the type curve.

   View Automatic Match with Neuman Solution
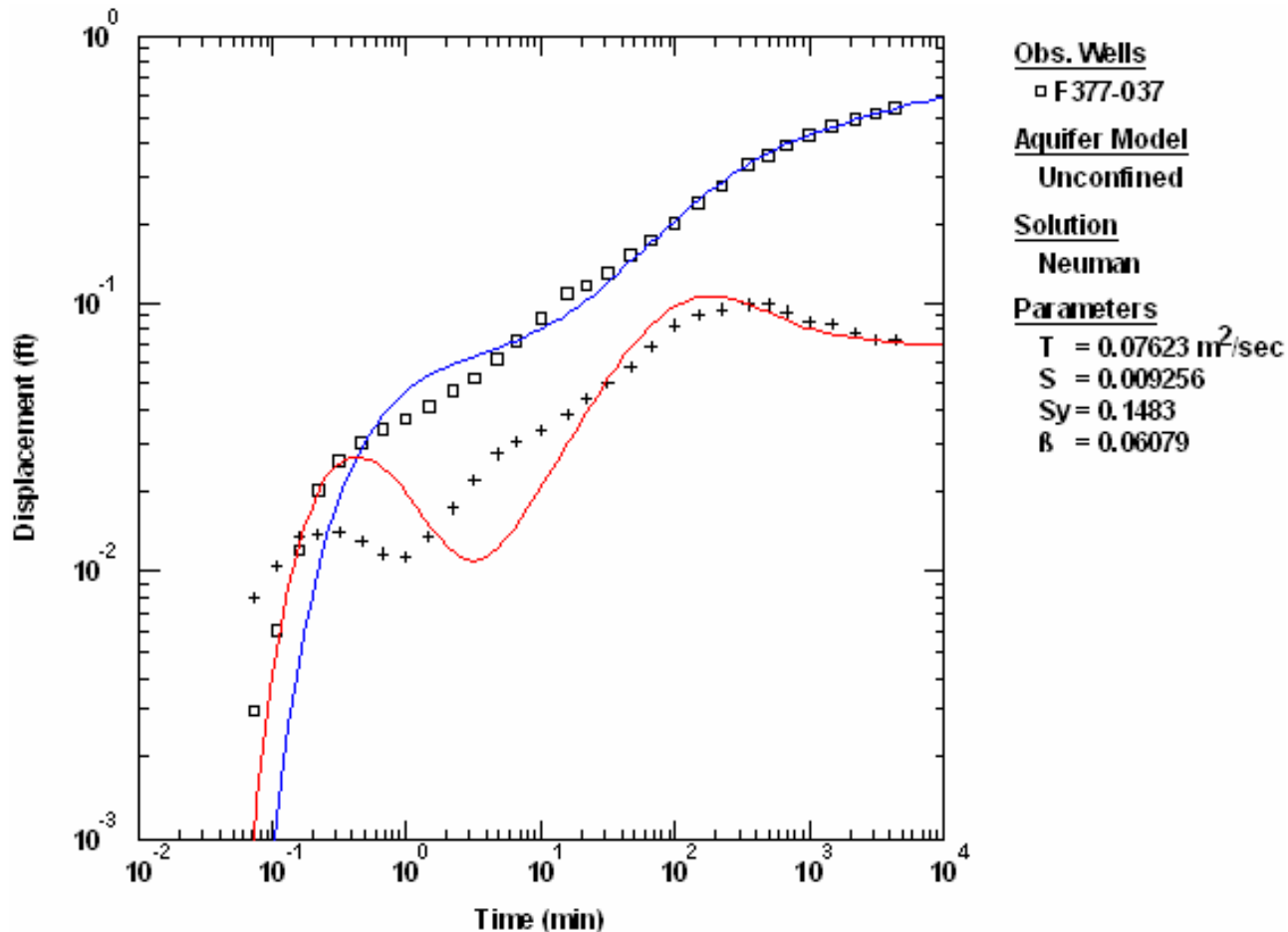
7. The Neuman (1974) solution matches the late-time data well, but gives a poor fit to the data at intermediate time. Choose Aquifer Data from the **Edit** menu to find the estimated value of the hydraulic conductivity anisotropy ratio (Kz/Kr = 0.243).

Pro The foregoing analysis with the Neuman (1974) solution assumed instantaneous drainage at the water table. To investigate the effect of noninstantaneous drainage from the unsaturated zone, let's match the Tartakovsky-Neuman (2007) solution for an unconfined aquifer with 3D flow in the saturated and unsaturated zones.

1. Choose Solution from the **Match** menu to select a method for analyzing the data.

2. From the list of solutions for **Unconfined Aquifers**, select **Tartakovsky-Neuman (2007)** and click **OK**.

3. Choose Automatic from the **Match** menu. In the **Parameters** tab, select **Active** for the estimation status of Kz/Kr. Click **Estimate** to perform automatic curve matching.

4. When estimation has finished, click **OK** and then **Close**. Click **OK** to view the new position of the type curve.

View Automatic Match with Tartakovsky-Neuman Solution
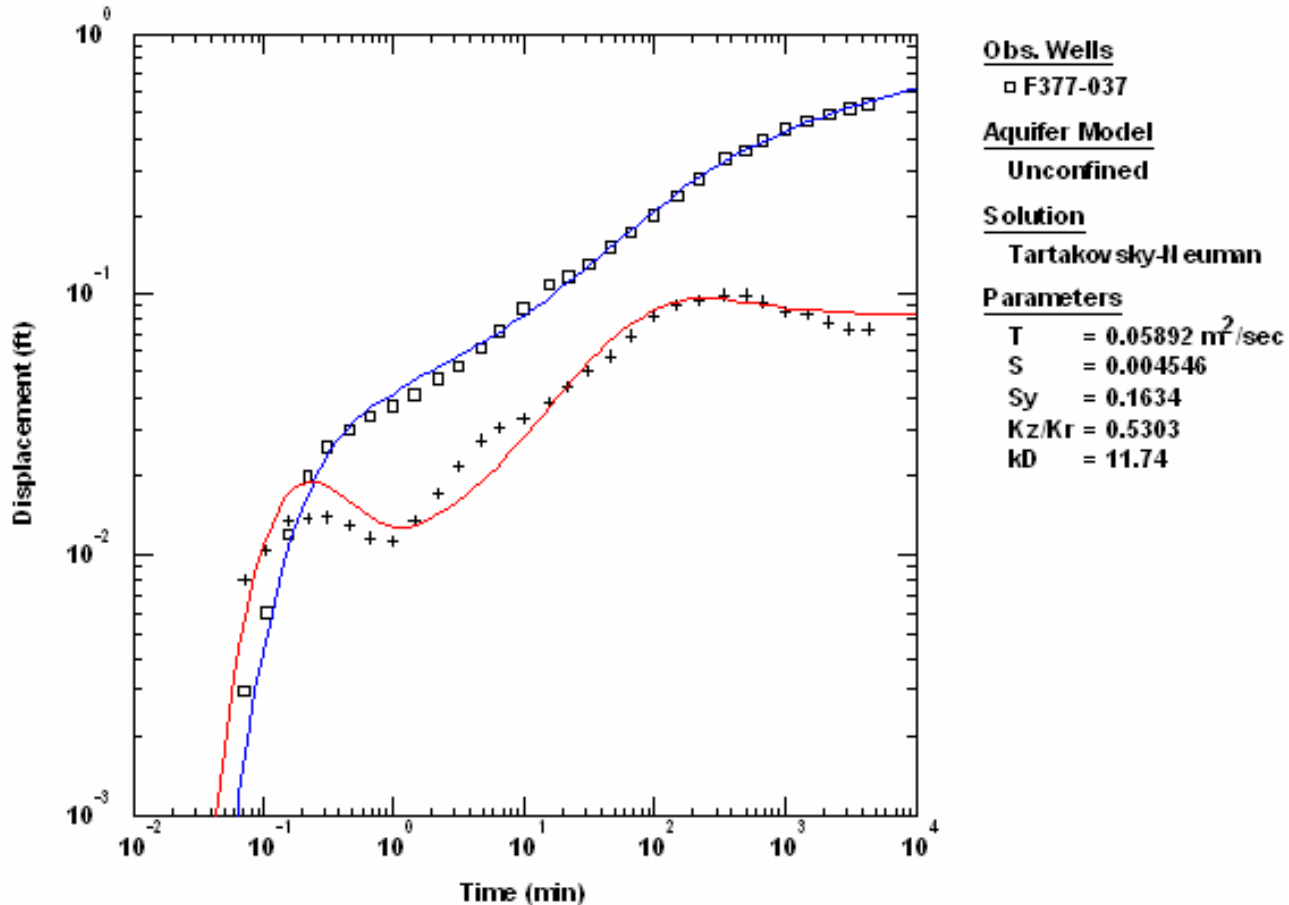
5. Compared to the previous match obtained with the Neuman (1974) model, the Tartakovsky-Neuman (2007) solution yields a lower estimate of T and gives a superior fit to the drawdown data measured at intermediate time.

Note that as the dimensionless Gardner parameter, κ_D, becomes large, the Tartakovsky-Neuman solution is essentially identical to the Neuman (1974) model.

Pumping Test Example: Double Porosity (Nevada)

Moench (1984) presented data from a pumping test conducted at the Nevada Test Site. The test well (UE-25b#1) fully penetrated a fractured aquifer consisting of Tertiary volcanic rocks. Pumping continued for nearly three days at a constant rate of 35.8 liters-per-second (L/sec). Hydraulic response was monitored in an observation well (UE-25a#1) at a distance of 110 m from the pumped well. Time and drawdown measurements were recorded in minutes and meters, respectively.

This example will introduce you to the following tasks and features in AQTESOLV:

- Creating a new data set with the Pumping Test Wizard

- Importing data with the Observation Data Import Wizard

- Saving a data set

- Inspecting diagnostic plots (radial flow and derivative)

- Estimating aquifer properties using the Moench (1984) solution (visual and automatic)

While following the steps in this example, click **Help** or press **F1** to obtain context sensitive help in the AQTESOLV application.

Create a New Data Set with Pumping Test Wizard

The first step in analyzing data from a pumping test is to create a new AQTESOLV data set. In this example, we will use the Pumping Test Wizard to assist us with data entry.

1. Create a new data set by choosing New from the **File** menu.

2. In the **New Data Set** dialog, select **Pumping Test Wizard** from the list. Click **OK**.

3. Choose **Single-well test** for the type of pumping test (we will use the wizard to enter data for the pumping well and add data for the observation well later). Click **OK**.

4. The **Pumping Test Wizard** prompts you for data required to analyze a pumping test. Click **Next** to begin the wizard.

5. For units of measurement, choose **m** for length, **min** for time, **L/sec** for

pumping rate and **m/sec** for hydraulic conductivity. Click **Next**.

6. For project information, enter **Nevada Test Site** for the location. Click **Next**.

7. For aquifer data, assume **400** for the aquifer thickness. Enter **1** for the anisotropy ratio (i.e., assume hydraulic conductivity is isotropic).

   Click **Advanced**. In the Double Porosity tab, enter **80** for the thickness of slab blocks. Click **OK**.

   Click **Next**.

8. For pumping well data, enter **UE-25b#1** for the well name. Enter coordinates of X=0 and Y=0. Click **Next**.

9. For pumping well construction, select the option for **vertical, full penetration**. Click **Next**.

10. For pumping well radius data, assume **0.11** for casing radius and **0.11** for well radius. Click **Next**.

11. For pumping rates, enter **0** for time and **35.8** for rate in the first row of the spreadsheet. Click **Next**.

12. For observations, click **Import** to launch the Observation Data Import Wizard for importing data from a file.

    We will import a text file consisting of 29 time-drawdown readings arranged in two columns. The first column is elapsed time since the start of the test. The second column contains drawdown measurements.

    > In Step 1 of the wizard, click **Browse**. Select the import file **UE25b#1.txt** in the AQTESOLV installation folder and click **Open**. Click **Next**.
    >
    > In Step 2 of the wizard, enter **2** for the number of columns, **1** for the starting row in the file, **1** for the column containing elapsed time and **2** for the column containing displacement. Click **Next**.
    >
    > In Step 3 of the wizard, click **Finish**. Inspect the import file summary and click **OK**.
    >
    > Click **Next** to proceed with the **Pumping Test Wizard**.

13. You have completed the **Pumping Test Wizard**. Click **Finish**.

After completing the **Pumping Test Wizard**, AQTESOLV automatically displays an Error Log to let you know if the data set contains any errors. If the **Error Log** identifies any mistakes, choose options from the Edit menu to correct them.

Add Observation Well

The **Pumping Test Wizard** helped you enter data for the pumped well. Now you will add data for the observation well.

1. Choose Wells from the **Edit** menu and click **New** to add a new well. Select

the new well in the list and click **Modify** to edit the well.

2. In the **General** tab, enter **UE-25a#1** for the well name. Enter **110** and **0** for the X and Y coordinates, respectively.

3. In the **Construction** tab, select the option for **vertical, full penetration**.

4. In the **Radius** tab, enter **0.0** for the casing radius to disable delayed observation well response.

5. In the **Observations** tab, click **Import** to launch the Observation Data Import Wizard for importing data from a file.

   You will import 24 observations from a text file. The first column is elapsed time since the start of the test. The second column contains drawdown measurements for the observation well.

In Step 1 of the wizard, click **Browse**. Select the import file **UE25a#1.txt** in the AQTESOLV installation folder and click **Open**. Click **Next**.   In Step 2 of the wizard, accept the default values determined by the Import Wizard. Click **Next**.   In Step 3 of the wizard, accept the defaults and click **Finish**. Inspect the import file summary and click **OK**.

6. Click **OK** to finish editing well UE-25a#1.

7. Click **Close** to leave the **Wells** window.

Save Data Set

At this point, it's a good idea to save your work.

Save the data set by choosing Save As from the **File** menu. Choose a folder and enter **NTS** for the name of the file. Click **Save**. AQTESOLV saves the file with an **.aqt** extension.

Pro **Inspect Diagnostic Plots**

Before performing curve matching to estimate aquifer properties, you may use diagnostic features in AQTESOLV to evaluate aquifer and flow conditions. Derivative analysis is one useful diagnostic tool for evaluating aquifer conditions.

1. Choose Composite from the **View** menu to display a plot of the test data.

   A composite plot normalizes time by the radius squared (t/r^2).

2. Choose Log Axes from the **View** menu to display the plot on log-log axes.

3. Choose Wells from the **Edit** menu. Select **UE-25a#1** from the list and click **Modify**.

   In the **Symbols** tab, select **cross** for the data symbol.

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In the **Curves** tab, click **Color** for the type curve properties, change the color to **red**, and click **OK**.

Click **OK** and then **Close**.

4. Select Options from the **View** menu. In the **Plots** tab, check **Derivative curves**. In the **Derivative** tab, select the option for **Bourdet** and enter a differentiation interval of **0.2**. Click **OK**.

View Derivative Plot

The form of the derivative plot is characteristic of radial flow in a double-porosity confined aquifer.

Estimate Aquifer Properties

The derivative plot that we have examined for this test suggests a double-porosity fractured aquifer. Before performing automatic curve matching, it's a good idea to obtain preliminary estimates of aquifer properties using visual curve matching with simpler solutions. We will begin our analysis using the Theis (1935) solution for a confined aquifer to estimate fracture properties from the early-time data.

1. Choose Solution from the **Match** menu to select a method for analyzing the data.

2. Remove the check from **Solution is inactive**. Click the **+** next to **Confined Aquifers** to expand the list of available solutions for confined aquifers. Select **Theis (1935)** and click **OK**.

3. Choose Displacement-Time from the **View** menu.

4. Select Options from the **View** menu. In the **Plots** tab, remove the check from **Derivative curves** for now. Click **OK**.

5. Choose Log Axes from the **View** menu to display the plot on log-log axes.

The plot displays two sets of curves. The blue and red curves are drawdown predicted by the Theis solution for the pumped well (UE-25b#1) and the observation well (UE-25a#1), respectively.

6. Choose Visual from the **Match** menu to perform visual curve matching with the Theis solution.

Click and hold the left mouse button down over a point within the plot area.

Continue to hold the mouse button down and move the mouse to match the curves to the drawdown and derivative data. As you move the type curve, AQTESOLV automatically updates the plot legend to reflect changes in parameter values.

Release the left mouse button when you have finished matching the curves.

7. Repeat the previous step as needed to achieve an approximate match of the Theis solution to the early-time data for both wells.

View Visual Match with Theis
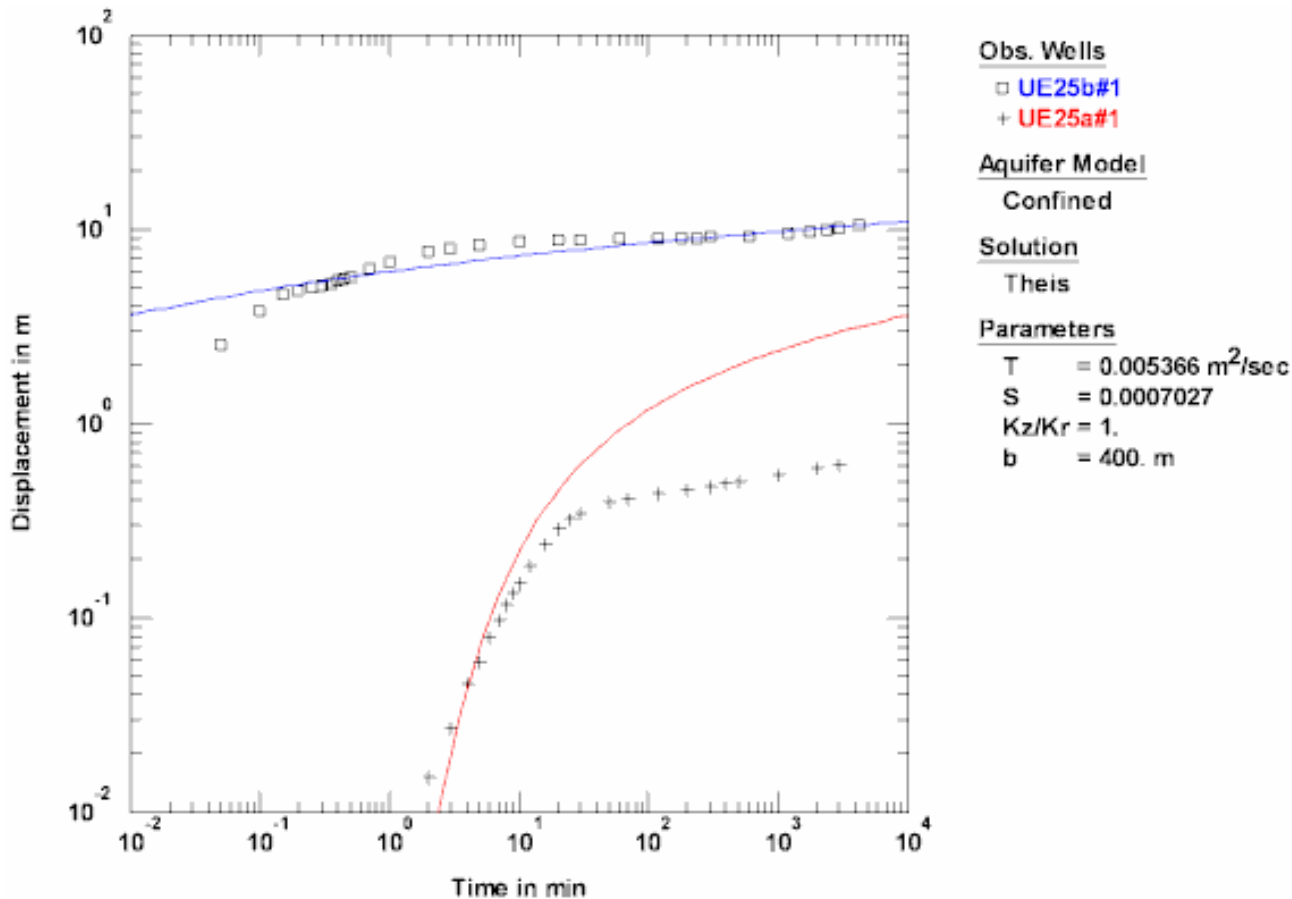
Now we will use automatic curve matching to obtain estimates of aquifer properties with the Moench (1984) solution.

1. Choose Solution from the **Match** menu to select a method for analyzing the data.

2. Remove the check from **Solution is inactive**. Click the **+** next to **Fractured Aquifers (Double Porosity)** to expand the list of available solutions for double-porosity aquifers. Select **Moench (1984) w/slab-shaped blocks** and click **OK**.

3. Choose Composite from the **View** menu to display a plot of the test data.

4. Choose Log Axes from the **View** menu to display the plot on log-log axes.

5. Select Options from the **View** menu. In the **Plots** tab, check **Derivative curves**. Click **OK**.

6. Choose Automatic from the **Match** menu.

   In the **Estimation** tab, enter **75** for the maximum number of iterations.

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Click **Advanced**. Select **Conservative** for the **Updating Method**. Check the option to **Apply SVD** (singular value decomposition). SVD helps to improve convergence of the automatic parameter estimation procedure when starting guesses are poor. For the **Observation Data Weighting Method**, choose **Inverse maximum displacement magnitude**. This weighting scheme gives more weight to the observation well data which have smaller magnitude compared to the pumped well. Click **OK**.

In the **Parameters** tab, enter **1.0** for the value of **Sf** and change its status to **Active**. Set the status of **Sw**, **r(w)** and **r(c)** as **Inactive**.

Click **Estimate** to perform automatic curve matching.

During the iterative estimation procedure, AQTESOLV displays a progress window and updates the curves displayed on the plot.

7. When estimation has finished, click **OK** and then **Close**. Click **OK** to view the new position of the type curve.

View Automatic Match with Moench
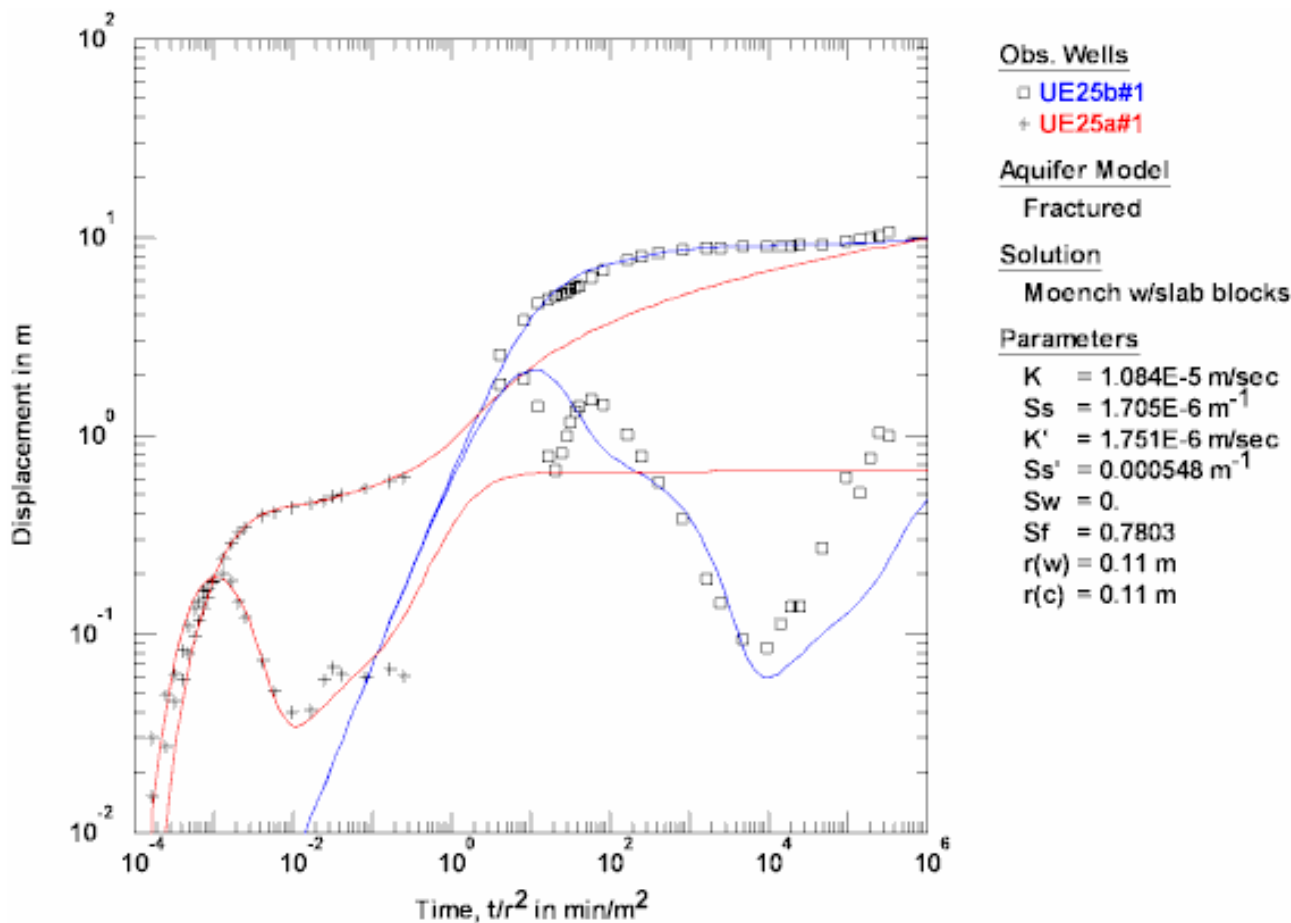
8. Use residual-time, residual-simulated and normal probability plots to evaluate the fit of the curve by examining residuals. The diagnostics report also presents residual statistics for curve fitting.

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

Delayed Observation Well Response

The Moench (1984) solution for a double-porosity aquifer is one of the solutions in AQTESOLV that includes delayed observation well response. Let's examine the effect of delayed response.

1. Choose Wells from the **Edit** menu, select **UE-25a#1** in the list and click **Modify**.

2. In the **Radius** tab, enter **0.05** for casing radius and **0.05** for well radius. Click **OK**. Click **Close**.

   View Effect of Delayed Response

   The effect of delayed response shifts the early-time drawdown in the observation well to the right. No effect is observed at the pumping well. To eliminate delayed response completely, enter zero for the casing radius of the observation well.
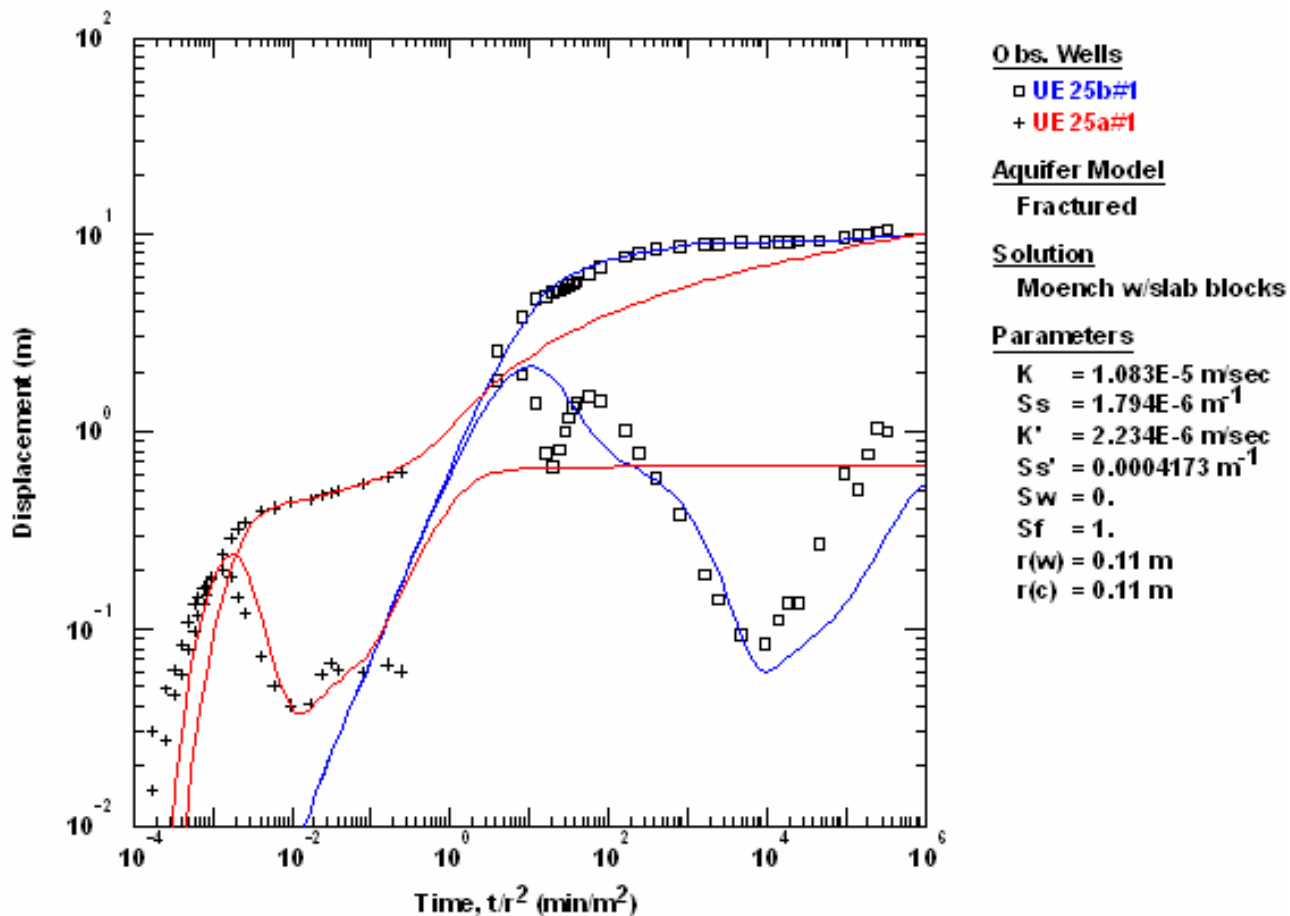
Pumping Test Example: Test Design (Forward Solution)

You can use the Forward Solution Wizard in AQTESOLV to design an aquifer test. In this example, you will predict the drawdown response during a single-well test in a fractured aquifer. A single vertical fracture bisects the pumped well which fully penetrates the aquifer.

This example will introduce you to the following tasks and features in AQTESOLV:

- Creating a new data set with the Forward Solution Wizard

- Saving a data set

- Predicting future response over time and distance using the Theis and Gringarten-Witherspoon solutions (time- and distance-drawdown plots)

While following the steps in this example, click **Help** or press **F1** to obtain context sensitive help in the AQTESOLV application.

Create a New Data Set with Forward Solution Wizard

The first step in designing a pumping test is to create a new AQTESOLV data set. In this example, we will use the Forward Solution Wizard to assist us with entering data needed for prediction.

1. Create a new data set by choosing New from the **File** menu.

2. In the **New Data Set** dialog, select **Forward Solution Wizard** from the list. Click **OK**.

3. Choose **Single-well test** for the type of pumping test. Click **OK**.

4. The **Forward Solution Wizard** prompts you for data required to design a pumping test. Click **Next** to begin the wizard.

5. For units of measurement, choose **ft** for length, **min** for time, **gal/min** for pumping rate and **ft/day** for hydraulic conductivity. Click **Next**.

6. For project information, enter **Aquifer Test Design** for the title. Click **Next**.

7. For aquifer data, enter **200** for aquifer thickness. Enter **1** for anisotropy ratio (i.e., assume hydraulic conductivity is isotropic). Click **Advanced**. In the **Single Fracture tab**, enter **100** for vertical fracture length (Pro Only). Click **OK**. Click **Next**.

8. For pumping well data, enter **PW** for well name. Enter coordinates of X=0 and Y=0. Click **Next**.

9. For pumping well construction, select the option for **vertical, full penetration**. Click **Next**.

10. For pumping well radius data, enter **0.25** for casing radius and **0.25** for well radius. Click **Next**.

11. For pumping rates, enter **0** for time and **100** for rate in the first row of the spreadsheet. Click **Next**.

12. For forward solution data, enter **0.01** and **1440** for the minimum and maximum simulation time, respectively. Enter **100** and **0.001** for T and S, respectively. Click **Next**.

13. You have completed the **Forward Solution Wizard**. Click **Finish**.

After completing the **Forward Solution Wizard**, AQTESOLV automatically displays an Error Log to let you know if the data set contains any errors. If the **Error Log** identifies any mistakes, choose options from the Edit menu to correct them.

Save Data Set

At this point, it's a good idea to save your work.

Save the data set by choosing Save As from the **File** menu. Choose a folder and enter **Forward Solution** for the name of the file. Click **Save**. AQTESOLV saves the file with an **.aqt** extension.

Prediction

Let us start by predicting the response with the Theis (1935) solution for a fully penetrating vertical well in a confined aquifer.

1. Choose Displacement-Time from the **View** menu to display a plot of the test data.

2. Choose Log Axes from the **View** menu to display the plot on log-log axes.

3. Choose Format from the **View** menu. In the **Y Axis tab**, remove the check from **Auto** and enter **1000** for the maximum value. Click **OK**.

4. Choose Solution from the **Match** menu to select a method for analyzing the data.

5. Remove the check from **Solution is inactive**. Click the **+** next to **Confined Aquifers** to expand the list of available solutions for confined aquifers. Select **Theis (1935)** and click **OK**.

6. The curve (blue line) indicates the predicted drawdown for the well.

7. Choose Distance Drawdown from the **View** menu. Enter **1440** for the prediction time and click **OK**.

8. Choose Log Axes from the **View** menu to display the plot on log-log axes.

9. Choose Format from the **View** menu. In the **Y Axis tab**, remove the check from **Auto** and enter **100** for the maximum value. Click **OK**.

10. The plot shows simulated drawdown with increasing radial distance from the pumped well.

Pro Now we will use the Gringarten-Witherspoon (1972) solution to predict the response with a vertical fracture.

1. Choose Displacement-Time from the **View** menu.

2. Choose Log Axes from the **View** menu.

3. Choose Format from the **View** menu. In the **Y Axis tab**, remove the check from **Auto** and enter **1000** for the maximum value. Click **OK**.

4. Choose Solution from the **Match** menu to select a method for analyzing the data.

5. Click the **+** next to **Fractured Aquifers (Single Fracture)** to expand the list of available solutions for single fractures intersecting the pumped well. Select **Gringarten-Witherspoon (1972) uniform-flux vertical fracture** and click **OK**.

6. Note that the slope of the predicted drawdown at early time shows a **unit half-slope**. This behavior is characteristic of linear flow to a fracture.

View Predicted Displacement-Time Plot

Choose Check Slope from the Match menu to measure the slope on a plot. Click and hold the left mouse button down to draw a line over a portion of the plot where you want to measure the slope.
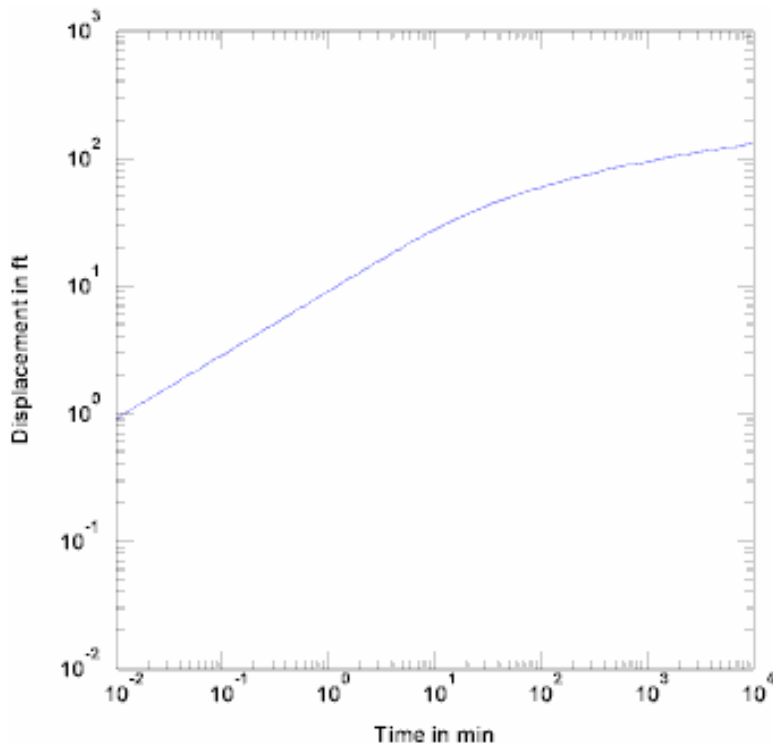
7. Choose Distance Drawdown from the **View** menu. Enter **1440** for the prediction time and click **OK**.

8. Choose Log Axes from the **View** menu to display the plot on log-log axes.

9. Choose Format from the **View** menu. In the **Y Axis tab**, remove the check from **Auto** and enter **100** for the maximum value. Click **OK**.

10. The plot shows simulated drawdown along the x-coordinate axis starting at the pumped well located at the center of the fracture.

View Predicted Distance Drawdown Plot

Press **Ctrl-K** to toggle coordinate tracking as you move the mouse over the plot. This feature is useful for identifying the distance at which drawdown on the plot attains a particular value.
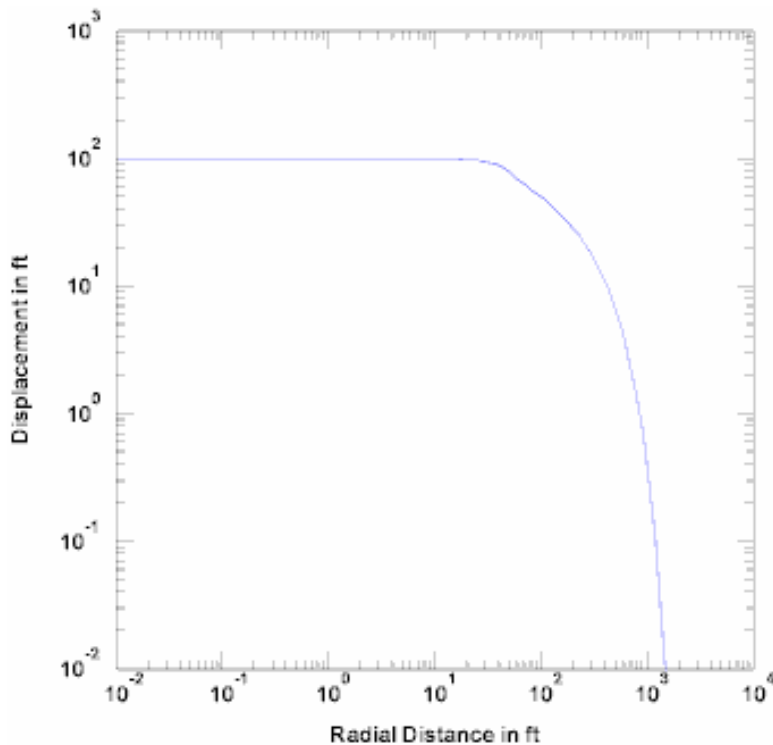
Add Observation Well

So far, we have examined drawdown along the x-coordinate axis in our distance-drawdown analysis. Because flow near the vertical fracture is not radially symmetric, we may add observation wells to the data set to predict drawdown in other directions.

1. Choose Wells from the **Edit** menu and click **New** to add a new well. Select the new well in the list and click **Modify** to edit the well.

2. In the **General** tab, enter **OW** for the well name. Enter **0** and **10** for the X and Y coordinates, respectively (you could enter any value not equal to zero for the y coordinate to predict drawdown along the y axis).

3. In the **Curves** tab, click **Color** for the type curve properties, change the color to **red**, and click **OK**.

4. Click **OK** to finish editing the well.

5. Click **Close** to leave the **Wells** window.

6. The updated plot now shows two curves. The blue and red curves show drawdown along the x- and y-coordinate axes, respectively.

   Note how the two curves merge with distance. When Kx = Ky and radial distance is greater than or equal to about five times the fracture half-length (250 ft in this case), flow around the vertical fracture is essentially radial (i.e., the drawdown contours are nearly circular in shape rather than elliptical).

7. Choose Toolbox from the **Match** menu.

   In the **Tweak** tab, select **Ky/Kx** in the Parameter list and click the left arrow on the scroll bar to decrease its value. As you decrease Ky/Kx, the curves diverge on the distance-drawdown plot.

   Click **Cancel** to discard your changes.

   Use the parameter tweaking feature to perform a sensitivity analysis on individual parameters.

8. You may add more wells to predict drawdown in other directions.

Pumping Test Example: Horizontal Well

In this example, you will analyze data from a hypothetical constant-rate test in a horizontal well used for remediation. The time-drawdown data were developed from published dimensionless type curve values for the horizontal well solution, so this example also serves as a benchmark.

This example will introduce you to the following tasks and features in AQTESOLV:

- Creating a new data set with the Pumping Test Wizard

- Importing data with the Observation Data Import Wizard

- Saving a data set

- Inspecting diagnostic plots (derivative)

- Estimating aquifer properties using the Daviau et al. (1985) solution (automatic)

- Sensitivity analysis (hemiradial and linear flow regimes)

While following the steps in this example, click **Help** or press **F1** to obtain context sensitive help in the AQTESOLV application.

Create a New Data Set with Pumping Test Wizard

The first step in analyzing data from a single-well pumping test is to create a new AQTESOLV data set. In this example, we will use the Pumping Test Wizard to assist us with data entry.

1. Create a new data set by choosing New from the **File** menu.

2. In the **New Data Set** dialog, select **Pumping Test Wizard** from the list. Click **OK**.

3. Choose **Single-well test** for the type of pumping test. Click **OK**.

4. The **Pumping Test Wizard** prompts you for data required to analyze a single-well pumping test. Click **Next** to begin the wizard.

5. For units of measurement, choose **m** for length, **sec** for time, **L/sec** for pumping rate and **consistent** for hydraulic conductivity. Click **Next**.

   Consistent units are based on the units of length and time selected for the data set. In this example, consistent units are m/sec for K (m^2/sec for T).

6. For project information, enter **Horizontal Well** for the title. Click **Next**.

7. For aquifer data, assume **20** for the aquifer thickness. Enter **1** for the anisotropy ratio (i.e., assume hydraulic conductivity is isotropic). Click **Next**.

8. For pumping well data, enter **HW** for the well name. Enter the coordinates for the midpoint of the horizontal well at X=0 and Y=0. Click **Next**.

9. For pumping well construction, select the option for **horizontal**. Enter **10** for zh (depth of well) and **400** for Lh (length of well). Click **Next**.

10. For pumping well radius data, enter **0.1** for casing radius and **0.1** for well radius. Click **Next**.

11. For pumping rates, enter **0** for time and **1.5** for rate in the first row of the spreadsheet. Click **Next**.

12. For observations, click **Import** to launch the Observation Data Import Wizard for importing data from a file.

    We will import a text file consisting of 14 time-drawdown readings arranged in two columns. The first column is elapsed time since the start of the test. The second column contains drawdown measurements.

> In Step 1 of the wizard, click **Browse**. Select the import file **Horizontal Well.txt** in the AQTESOLV installation folder and click **Open**. Click **Next**.
>
> In Step 2 of the wizard, accept the default entries and click **Next**.
>
> In Step 3 of the wizard, click **Finish**. Inspect the import file summary and click **OK**.
>
> Click **Next** to proceed with the **Pumping Test Wizard**.

13. You have completed the **Pumping Test Wizard**. Click **Finish**.

After completing the **Pumping Test Wizard**, AQTESOLV automatically displays an Error Log to let you know if the data set contains any errors. If the **Error Log** identifies any mistakes, choose options from the Edit menu to correct them.

Save Data Set

At this point, it's a good idea to save your work.

Save the data set by choosing Save As from the **File** menu. Choose a folder, enter **Horizontal Well** for the name of the file and click **Save**. AQTESOLV saves the file with an **.aqt** extension.

Inspect Diagnostic Plots

Before performing curve matching to estimate aquifer properties, you may use diagnostic features in AQTESOLV such as derivative analysis to evaluate aquifer and flow conditions.

1. Choose Displacement-Time from the **View** menu to display a plot of the test data.

2. Choose Wells from the **Edit** menu. Select **HW** from the list and click **Modify**.

   In the **Symbols** tab, remove the check from **Use data symbols properties** and select **cross** for the derivative symbol.

   In the **Curves** tab, remove the check from **Use type curve properties**. Click **Color** for the derivative curve properties, change the color to **red**, and click **OK**.

   Click **OK** and then **Close**.

3. Select Options from the **View** menu. In the **Plots** tab, check **Derivative curves**. In the **Derivative** tab, select the option for **Bourdet** and enter a factor of **0.2**. Click **OK**.

   View Derivative Plot

   The plot shows derivative is approximately constant (i.e., horizontal) during two periods, early and late. At early time, radial flow is directed toward the horizontal axis of the well and continues until drawdown reaches the upper and lower impermeable boundaries. At late time and sufficiently large

distances, the well behaves approximately like a point source; hence, assuming no lateral boundaries, flow is nearly radial in a horizontal plane between the upper and lower boundaries.
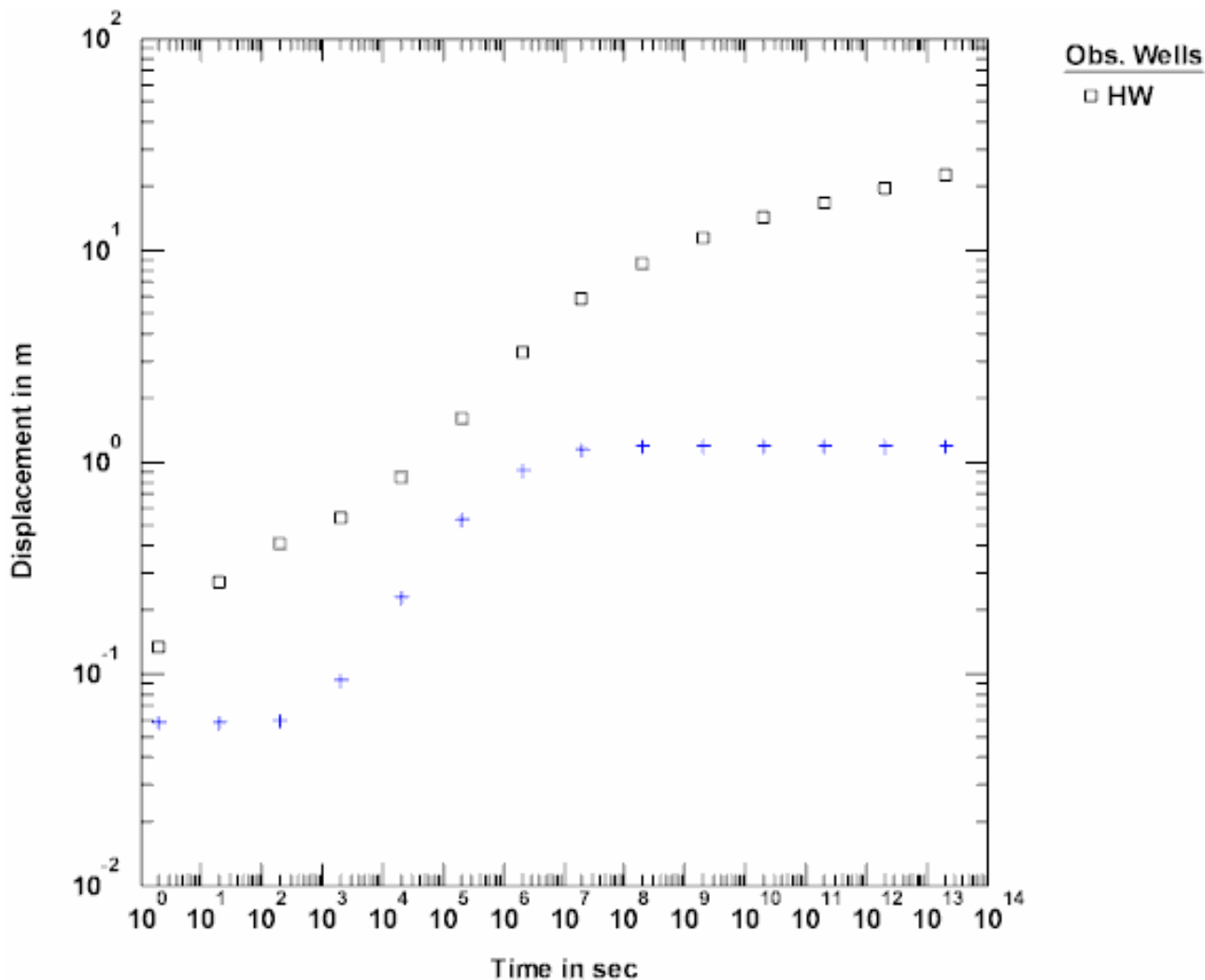
Estimate Aquifer Properties

We will use the Daviau et al. (1985) solution for a horizontal well to obtain estimates of aquifer properties.

1. Choose Solution from the **Match** menu to select a method for analyzing the data.

2. Remove the check from **Solution is inactive**. Click the **+** next to **Confined Aquifers** to expand the list of available solutions for confined aquifers. Select **Daviau et al. (1985) infinite-conductivity horizontal well** and click **OK**.

3. Choose Automatic from the **Match** menu. Click **Estimate** to perform automatic curve matching.

During the iterative estimation procedure, AQTESOLV displays a progress window and updates the curves displayed on the plot in the background.

4. When estimation has finished, click **OK** and then **Close**. Click **OK** to view the new position of the type curve.

View Automatic Match with Daviau et al. Solution
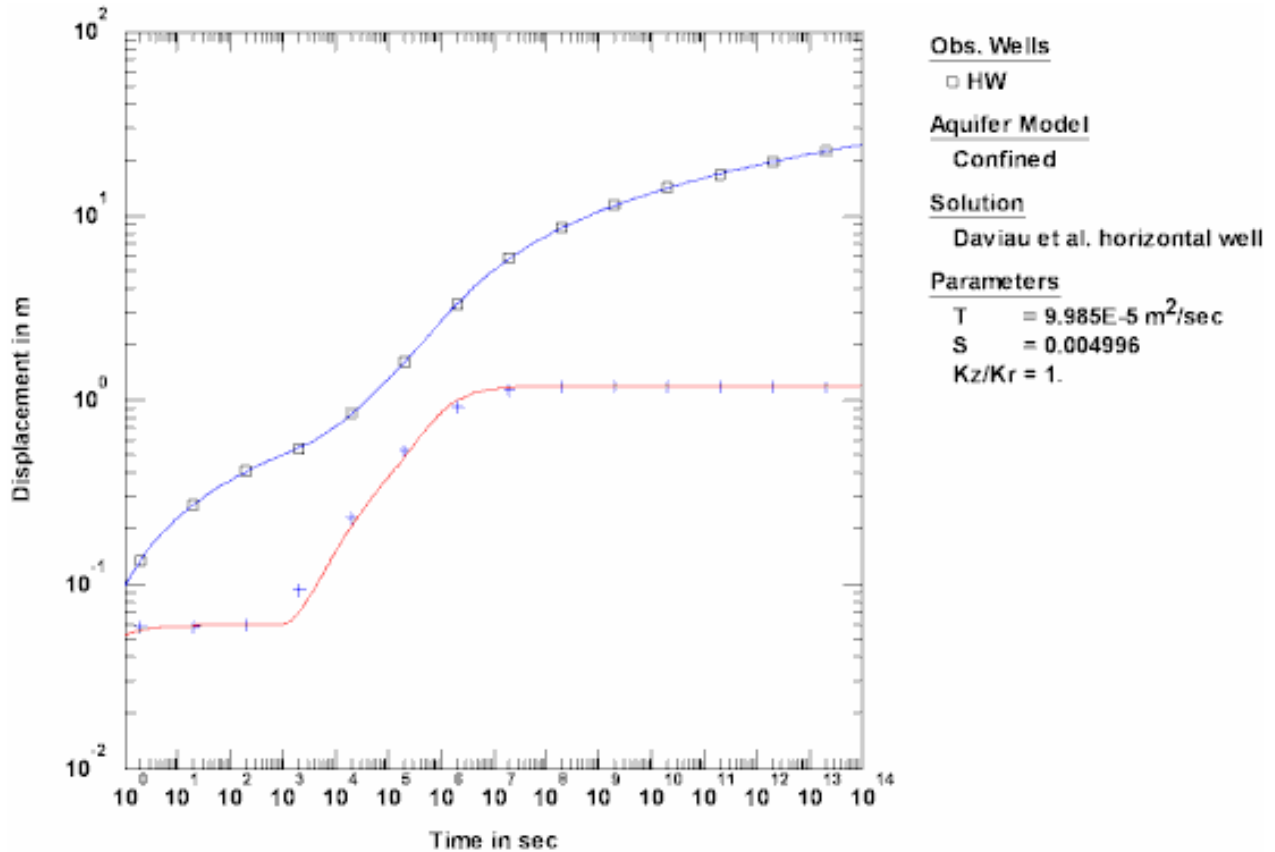
5. Choose Save from the **File** menu to save your work.

Sensitivity Analysis

Thus far, we have identified two radial flow regimes, at early and late time, that may develop in response to discharge from a horizontal well. Under certain conditions, two additional flow regimes may be evident as well.

A horizontal well located near either the upper or lower impermeable boundary of a confined aquifer may result in a **hemiradial flow regime** that follows the initial radial flow period. In the case of a well positioned on or very close to the boundary, hemiradial flow develops immediately and the first period of radial flow is not observed.

In the case of a thin aquifer and a long well, a **linear flow regime** may develop before the late-time radial flow period. Drawdown data on a log-log plot display a unit half-slope during the linear flow period.

Now we will perform a sensitivity analysis to identify hemiradial and linear flow regimes.

1. Choose Wells from the **Edit** menu. Select **HW** from the list and click **Modify**. In the **Construction** tab, enter **0.5** for zh. Click **OK**.

View Contour Plot of Hemiradial Flow

With the well positioned close to the upper no-flow boundary, hemiradial flow occurs at intermediate time between about 100 and 3000 seconds as shown by the constant theoretical derivative curve (i.e., the red line). A brief period of radial flow is present immediately prior to the hemiradial flow regime.
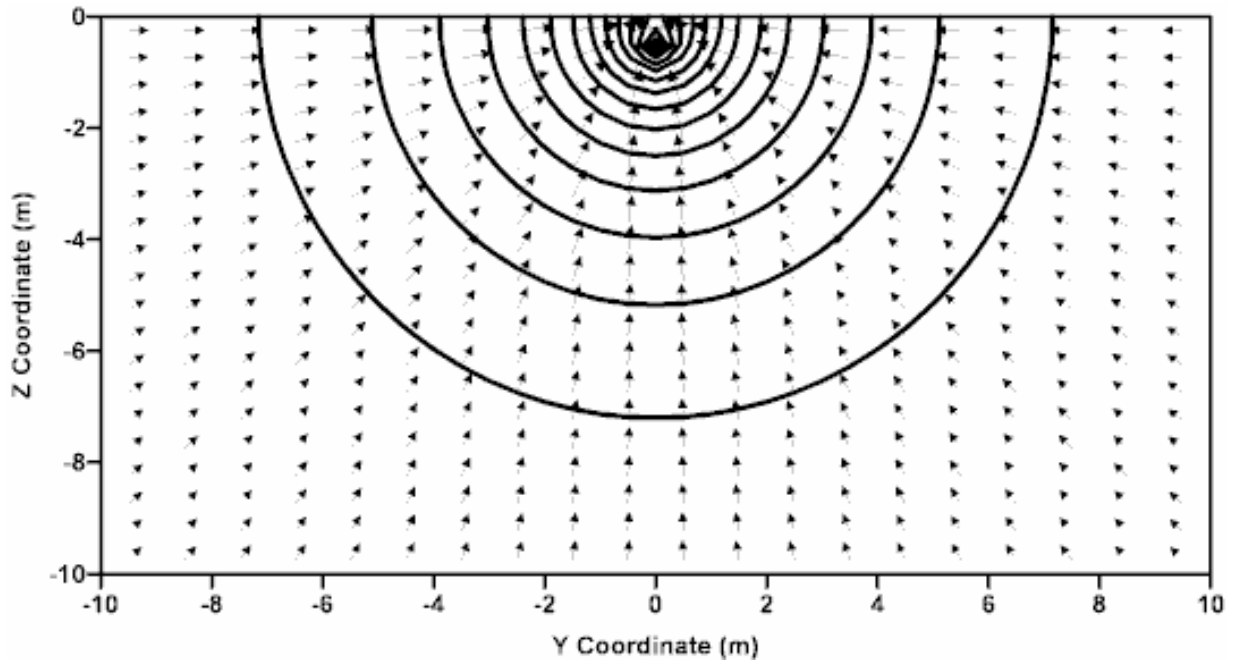
Hemiradial flow in the vicinity of horizontal well near top of confined aquifer

2. Choose Aquifer Data from the **Edit** menu. Enter **10** for the aquifer thickness and click **OK**.

As you decrease the thickness of the aquifer, the theoretical drawdown curve (i.e., the blue line) shows a linear flow regime at intermediate time with a slope approaching 0.5 on the log-log plot. You can choose Check Slope from the **Match** menu to test the slope of the theoretical drawdown curve on the plot.

Slug Tests

Slug Test Example: Unconfined

Batu (1998) presented data for a falling-head slug test in a sandy unconfined aquifer having a saturated thickness of 32.57 ft. The initial displacement in the well was 1.48 ft. The following table provides well construction details for the test.

Well Radius, r_w (inches)	Casing Radius, r_c (inches)	Depth to Top of Screen, d (ft)	Screen Length, L (ft)
5.0	2.0	0.47	13.80

Radius values are measured from the center of the test well. The five-inch well radius reported by Batu (1998) includes a sand filter pack installed in the well annulus. The depth of the well screen, d, is measured from the static water table. From these data, we calculate the static water column height in the well as 14.27 ft (d + L). Elapsed time and depth-to-water measurements were recorded in seconds and feet, respectively.

This example will introduce you to the following tasks and features in AQTESOLV:

- Creating a new data set with the Slug Test Wizard for a single-well test

- Importing data with the Observation Data Import Wizard

- Saving a data set

- Inspecting diagnostic plots (screening data with Cooper et al. solution)

- Estimating aquifer properties with KGS Model and Bouwer-Rice solutions (visual and automatic)

- Performing a discrete sensitivity analysis to evaluate uncertainty in aquifer thickness

- Applying approximate deconvolution approach (Peres et al. solution)

While following the steps in this example, click **Help** or press **F1** to context sensitive help in the AQTESOLV application.

Create a New Data Set with Slug Test Wizard

The first step in analyzing data from a slug test is to create a new AQTESOLV data set. In this example, we will use the Slug Test Wizard to assist us with data entry.

1. Create a new data set by choosing New from the **File** menu.

2. In the **New Data Set** dialog, select **Slug Test Wizard** from the list. Click **OK**.

3. The **Slug Test Wizard** prompts you for data required for a slug test. Click **Next**.

4. For units of measurement, choose **ft** for length, **sec** for time and **cm/sec** for hydraulic conductivity. Click **Next**.

5. For project information, enter **Falling-Head Slug Test** for the title. Click **Next**.

6. For general test well data, enter **1.48** for the initial displacement, **14.27** for static water column height and **Well 1** for the well name. Enter coordinates of X=0 and Y=0. Click **Next**.

7. For aquifer data, enter **32.57** for aquifer thickness. Assume hydraulic conductivity is isotropic and enter **1** for anisotropy ratio. Click **Next**.

8. For screen data, enter **0.47** for depth to top of screen and **13.8** for screen length. Assume the transducer measures the position of the water surface in the well and enter **0** for transducer depth. Click **Next**.

9. For radius data, enter **0.167** for casing radius and **0.417** for well radius. Assume no well skin and enter **0.417** for the skin radius. Click **Next**.

10. Corrections are not required for this test. The gravel pack correction only applies to wells screened across the water table. Click **Next**.

11. For observations, click **Import** to launch the Observation Data Import Wizard for importing data from a file.

We will import a text file consisting of 27 time and water-level readings arranged in two columns. The first column is elapsed time in seconds since the start of the test. The second column contains depth-to-water measurements in feet.

To convert depth-to-water to displacement, we will use the wizard to subtract 10 ft (the static depth-to-water recorded before the test) from all of the measurements in the file. For these test data, the subtraction operation results in negative displacements. To make them positive, we use the wizard to multiply all of the displacement values by -1.

In Step 1 of the wizard, click **Browse**. Select the import file **Falling Head.txt** in the AQTESOLV installation folder and click **Open**. Click **Next**.

In Step 2 of the wizard, enter **2** for the number of columns, **1** for the starting row in the file, **1** for the column containing elapsed time and **2** for

the column containing displacement. Click **Next**.

In Step 3 of the wizard, **check the second box** to subtract a constant from the displacement values and enter **10** for the constant. **Check the fourth box** to multiply displacement values by a constant and enter **-1** for the constant. Click **Finish**. Inspect the import file summary and click **OK**.

Click **Next** to proceed with the **Slug Test Wizard**.

12. You have completed the **Slug Test Wizard**. Click **Finish**.

After completing the **Slug Test Wizard**, AQTESOLV automatically displays an Error Log to let you know if the data set contains any errors. If the **Error Log** identifies any mistakes, choose options from the Edit menu to correct them.

Save Data Set

At this point, it's a good idea to save your work.

Save the data set by choosing Save As from the **File** menu. Choose a folder and enter **Falling Head** for the name of the file. Click **Save**. AQTESOLV saves the file with an **.aqt** extension.

Inspect Diagnostic Plots

Following the guidelines developed by Butler (1998) for a slug test in a well screened below the water table, we will use the Cooper et al. (1967) method to screen our data. An implausibly low storativity (S) value determined from the screening analysis would suggest the presence of vertical flow.

1. Choose Displacement-Time from the **View** menu to display a plot of the test data.

2. Choose Options from the **View** menu. In the **Plots** tab, check **Normalized head** to display data as normalized head. Click **OK**.

3. Choose Log-Linear Axes from the **View** menu.

On these axes, the data show a sigmoidal shape that is typical of solutions based on the fully transient overdamped slug test model, e.g., Hyder et al. (1994).

4. Choose Linear-Log Axes from the **View** menu.

The data show a slightly concave upward appearance which also is characteristic of slug test solutions based on the fully transient overdamped model; however, a good portion of the data give the appearance of a straight line that we may analyze with solutions based on the quasi-steady-state slug test model, e.g., Bouwer-Rice (1976).

5. Choose Solution from the **Match** menu to use the Cooper et al. (1967) method as a screening tool.

6. Remove the check from **Solution is inactive**. Click the **+** next to **Confined Aquifers** to expand the list of available solutions for confined aquifers. Select

Cooper-Bredehoeft-Papadopulos (1967) and click **OK**.

7. Choose Log-Linear Axes from the **View** menu.

8. Choose Automatic from the **Match** menu and click **Estimate** to perform automatic curve matching with the Cooper et al. solution.

 During the iterative estimation procedure, AQTESOLV displays a progress window and updates the curve displayed on the plot in the background.

9. When estimation has finished, click **OK** and then **Close**. Click **OK** to view the new position of the type curve.

10. The estimated values of transmissivity (T) and storativity (S) are 0.3028 cm^2/sec and 0.0007837, respectively.

 According to the Butler (1998) guidelines, a plausible value of S obtained with the Cooper et al. method allows us to assume that flow is essentially constrained to the screened interval of the well (i.e., Kr » Kz). Thus, we can estimate Kr using the well screen length (L) as follows:

 Kr = T/L = (0.3028 cm^2/sec)/(13.8 ft)*(ft/30.48 cm) = 7.20 cm/sec

Match Solutions

 Pro Now we will attempt to use slug test models for unconfined aquifers to see if the water-table boundary has an effect on our results. We will begin by analyzing this slug test with the Hyder et al. (1994) solution (KGS Model) for an unconfined aquifer. The KGS Model is a fully transient solution for overdamped slug tests that accounts for elastic storage in the aquifer.

1. Choose Solution from the **Match** menu to select a method for analyzing the data.

2. Click the **+** next to **Unconfined Aquifers** to expand the list of available solutions for unconfined aquifers. Select **KGS Model (1994)** and click **OK**.

3. Choose Log-Linear Axes from the **View** menu.

4. Choose Automatic from the **Match** menu and click **Estimate** to perform automatic curve matching with the KGS Model.

5. When estimation has finished, click **OK** and then **Close**. Click **OK** to view the new position of the type curve. The estimated value of Ss appears realistic, so we will assume no wellbore skin effect. Compared to the Cooper et al. screening analysis, the value of Kr obtained with the KGS Model is somewhat lower owing to the influence of the water-table boundary condition.

 View Automatic Match

Falling-Head Slug Test

Obs. Wells
  □ Well 1

Aquifer Model
  Unconfined

Solution
  KGS Model

Parameters
  Kr   = 0.0004874 cm/sec
  Ss   = 0.0001738 ft^{-1}
  Kz/Kr = 1.
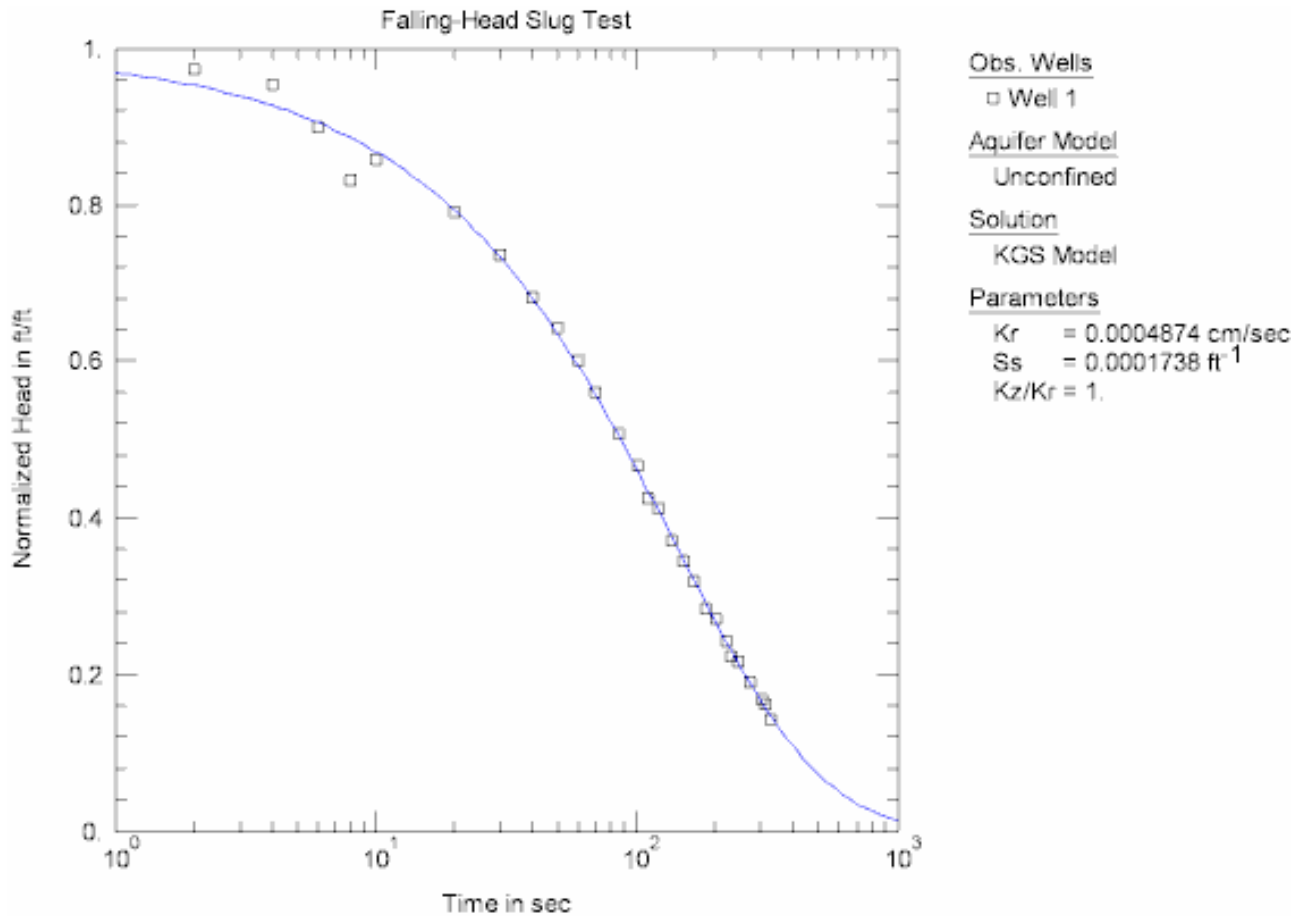
Next let us analyze the test with the Bouwer-Rice (1976) solution for an unconfined aquifer. The Bouwer-Rice solution is based on the quasi-steady-state slug test model that ignores elastic storage in the aquifer.

1. Choose Solution from the **Match** menu to select a method for analyzing the data.

2. From the available solutions for **Unconfined Aquifers**, select **Bouwer-Rice (1976)** and click **OK**.

   With the Bouwer-Rice solution, the plot legend shows two parameters: K (hydraulic conductivity) and y0 (intercept of the line on the y axis).

3. Choose Options from the **View** menu. In the **Plots** tab, check **Recommended head range** to display the range of normalized head recommended by Butler (1998) for matching the Bouwer-Rice solution. Click **OK**.

4. Choose Visual from the **Match** menu to perform visual curve matching with the Bouwer-Rice solution.

   To perform visual matching, move the mouse to a point where you wish to begin drawing a new line.

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> Click and hold down the left mouse button to anchor the new line at this point.
>
> Continue to hold the mouse button down and move the mouse to match a new straight line to your data. As you move the mouse, AQTESOLV draws a straight line between the anchor point and the position of the mouse.
>
> Release the left mouse button when you have finished matching a new straight line. AQTESOLV automatically updates the plot legend to reflect changes in parameter values.

5. Repeat the previous step as needed to estimate K by matching the straight line to the data within the recommended head range. How does your estimate of hydraulic conductivity change if you match the straight line to earlier data?

   View Visual Match

Falling-Head Slug Test

Obs. Wells
□ Well 1

Aquifer Model
  Unconfined

Solution
  Bouwer-Rice

Parameters
  K = 0.0003482 cm/sec
  y0 = 1.063 ft

6. Matching the Bouwer-Rice method to the earlier test data, Batu (1998) estimated K = cm/sec.

7. One could attempt to use automatic estimation to match the Bouwer-Rice solution to these data; however, visual matching is generally more effective for matching straight-line solutions because you can apply your judgment to fit the line to the appropriate range of data.

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

Perform Sensitivity Analysis

In this example, the aquifer thickness is known (32.57 ft); for some slug tests, however, the thickness of the aquifer may not be directly available from drilling or geophysical evidence. In such instances, one approach for evaluating uncertainty is to estimate a reasonable range for aquifer thickness and perform a discrete sensitivity analysis to evaluate the effect of varying thickness on the estimate of hydraulic conductivity.

1. Choose Aquifer Data from the **Edit** menu. In the **General** tab, change the value of aquifer thickness to **40**. Click **OK**.

   Changing the aquifer thickness has little effect on the position of the straight line; hence, increasing the thickness to 40 ft does not greatly influence the estimate of hydraulic conductivity.

2. Repeat the previous step for thickness values of 20 and 50 ft.

Apply Approximate Deconvolution Approach

The close fit between the data from this test and the Cooper et al. solution in the screening analysis suggests that we might be able to match these data using the approximate deconvolution approach of Peres et al. (1989). The Peres et al. method transforms the response data from a slug test into equivalent heads for a constant-rate pumping test. Although the Peres et al. approach is normally applied to confined conditions, we will demonstrate its use with the data from this example.

1. Choose Solution from the **Match** menu.

2. Click the **+** next to **Confined Aquifers** to expand the list of available solutions for confined aquifers. Select **Peres et al. (1989) deconvolution** and click **OK**.

   3. The plot of the data on log-linear axes displays equivalent head (rate-normalized head) on the y axis.

   After applying the Peres et al. deconvolution procedure, the values of equivalent head on the y (vertical) axis of the plot have the peculiar units of **time**.

4. Choose Visual from the **Match** menu to perform visual curve matching with the Peres et al. solution. The curve matching procedure is the same as the familiar Cooper-Jacob (1946) solution for a pumping test.

   To perform visual matching, move the mouse to a point where you wish to begin drawing a new line.
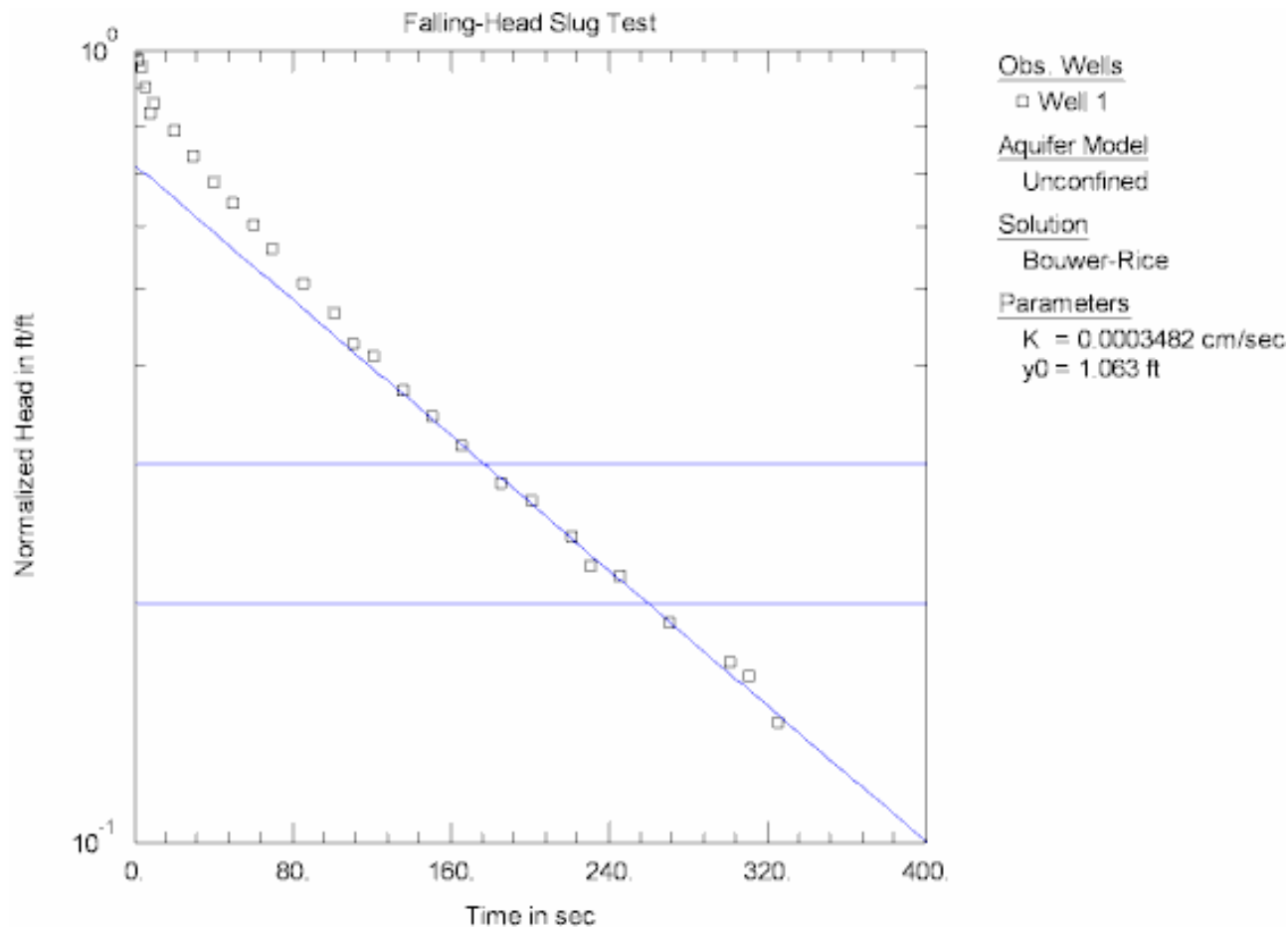
   Click and hold down the left mouse button to anchor the new line at this point.

   Continue to hold the mouse button down and move the mouse to match a new straight line to your data. As you move the mouse, AQTESOLV draws a

straight line between the anchor point and the position of the mouse.

Release the left mouse button when you have finished matching a new straight line. AQTESOLV automatically updates the plot legend to reflect changes in parameter values.

5. Repeat the previous step as needed to estimate T by matching the straight line to the data near the end of the test. Your estimate of T should be close to the value obtained with the Cooper et al. solution.

Slug Test Example: Translation Method

A slug test performed in an unconfined bedrock aquifer allows us to demonstrate the use of the translation method of data analysis. Well BR2 partially penetrates an 83-ft thick limestone aquifer that behaves as an equivalent porous medium. The following table provides construction details for the test well.

Well Radius, r_w (ft)	Casing Radius, r_c (ft)	Depth to Top of Screen, d (ft)	Screen Length, L (ft)
0.245	0.255	21	42

In this test, a solid slug introduced in the well resulted in noninstantaneous test initiation as shown in the figure below.
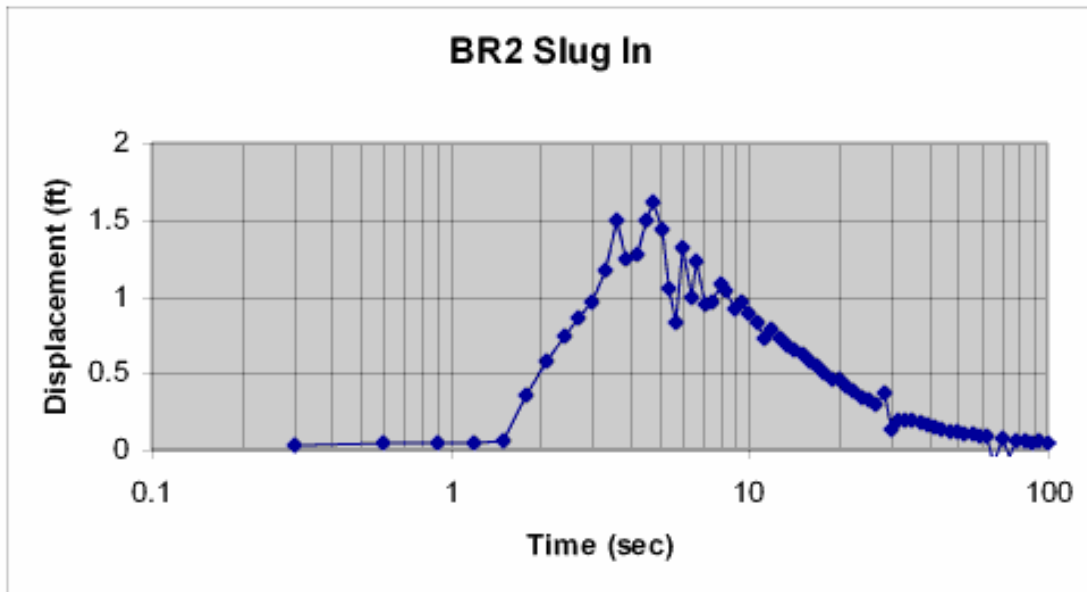
Data collection in well BR2 started just prior to the introduction of the solid slug. The effect of noninstantaneous test initiation is evident from the rising limb of the displacement data that begins shortly after one second and continuing through the subsequent period of noisy data. The peak displacement shown on the graph is 1.615 ft. At 10 seconds, the data begin to stabilize; therefore, you will translate the start of the test to coincide with the reading at 10 seconds before analyzing these data.

According to Butler (1998), the translation method is appropriate when a plot of log displacement vs. time is approximately linear (i.e., the data conform to the

This example will introduce you to the following tasks and features in AQTESOLV:

- Creating a new data set with the Slug Test Wizard for a single-well test

- Importing data with the Observation Data Import Wizard

- Applying the translation method to observation data

- Saving a data set

- Estimating aquifer properties with Bouwer-Rice solution (visual)

While following the steps in this example, click **Help** or press **F1** to context sensitive help in the AQTESOLV application.

Create a New Data Set with Slug Test Wizard

The first step in analyzing data from a slug test is to create a new AQTESOLV data set. In this example, we will use the Slug Test Wizard to assist us with data entry.

1. Create a new data set by choosing New from the **File** menu.

2. In the **New Data Set** dialog, select **Slug Test Wizard** from the list. Click **OK**.

3. The **Slug Test Wizard** prompts you for data required for a slug test. Click **Next**.

4. For units of measurement, choose **ft** for length, **sec** for time and **cm/sec** for hydraulic conductivity. Click **Next**.

5. For project information, enter **March 3, 2003** for the date. Click **Next**.

6. For general test well data, assume **1.615** for the initial displacement. Enter **83** for static water column height and **BR2** for the well name. Enter coordinates of X=0 and Y=0. Click **Next**.

7. For aquifer data, enter **83** for aquifer thickness. Assume hydraulic conductivity is isotropic and enter **1** for anisotropy ratio. Click **Next**.

8. For screen data, enter **21** for depth to top of screen and **62** for screen length. Assume the transducer measures the position of the water surface in the well and enter **0** for transducer depth. Click **Next**.

9. For radius data, enter **0.255** for casing radius and **0.245** for well radius. Assume no well skin and enter **0.245** for the skin radius. Click **Next**.

10. Corrections are not required for this test. Click **Next**.

11. For observations, click **Import** to launch the Observation Data Import Wizard for importing data from a file.

We will import a text file from an In-Situ MiniTroll. Data in the file are arranged in five columns. Column three contains elapsed time and column five contains displacement. Elapsed time and displacement are recorded in seconds and feet, respectively.

In Step 1 of the wizard, click **Browse**. Select the import file **BR2.txt** in the AQTESOLV installation folder and click **Open**. Click **Next**.

In Step 2 of the wizard, enter **5** for the column containing displacement and accept the remaining default values. Click **Next**.

In Step 3 of the wizard, accept the default values and click **Finish**. Inspect the import file summary and click **OK**.

Click **Next** to proceed with the **Slug Test Wizard**.

12. You have completed the **Slug Test Wizard**. Click **Finish**.

After completing the **Slug Test Wizard**, AQTESOLV automatically displays an Error Log to let you know if the data set contains any errors. If the **Error Log** identifies any mistakes, choose options from the Edit menu to correct them.

Save Data Set

At this point, it's a good idea to save your work.

Save the data set by choosing Save As from the **File** menu. Choose a folder and enter **BR2** for the name of the file. Click **Save**. AQTESOLV saves the file with an **.aqt** extension.

Apply Translation Method

1. Choose Displacement-Time from the **View** menu to display a plot of the test data.

2. Choose Options from the **View** menu. In the **Plots** tab, remove the check from **Normalized head** (if necessary). Click **OK**.

3. Choose Log-Linear Axes from the **View** menu.

4. Choose Format from the **View** menu. In the **Graph** tab, check **Show Graph Paper** and select the option for **Major ticks only**. Click **OK**.

View Plot

We can see from the graph that the noisy data associated with noninstantaneous test initiation become stable after 10 seconds. Therefore,

we will use the translation method to translate the start of the test to the reading at 10 seconds.
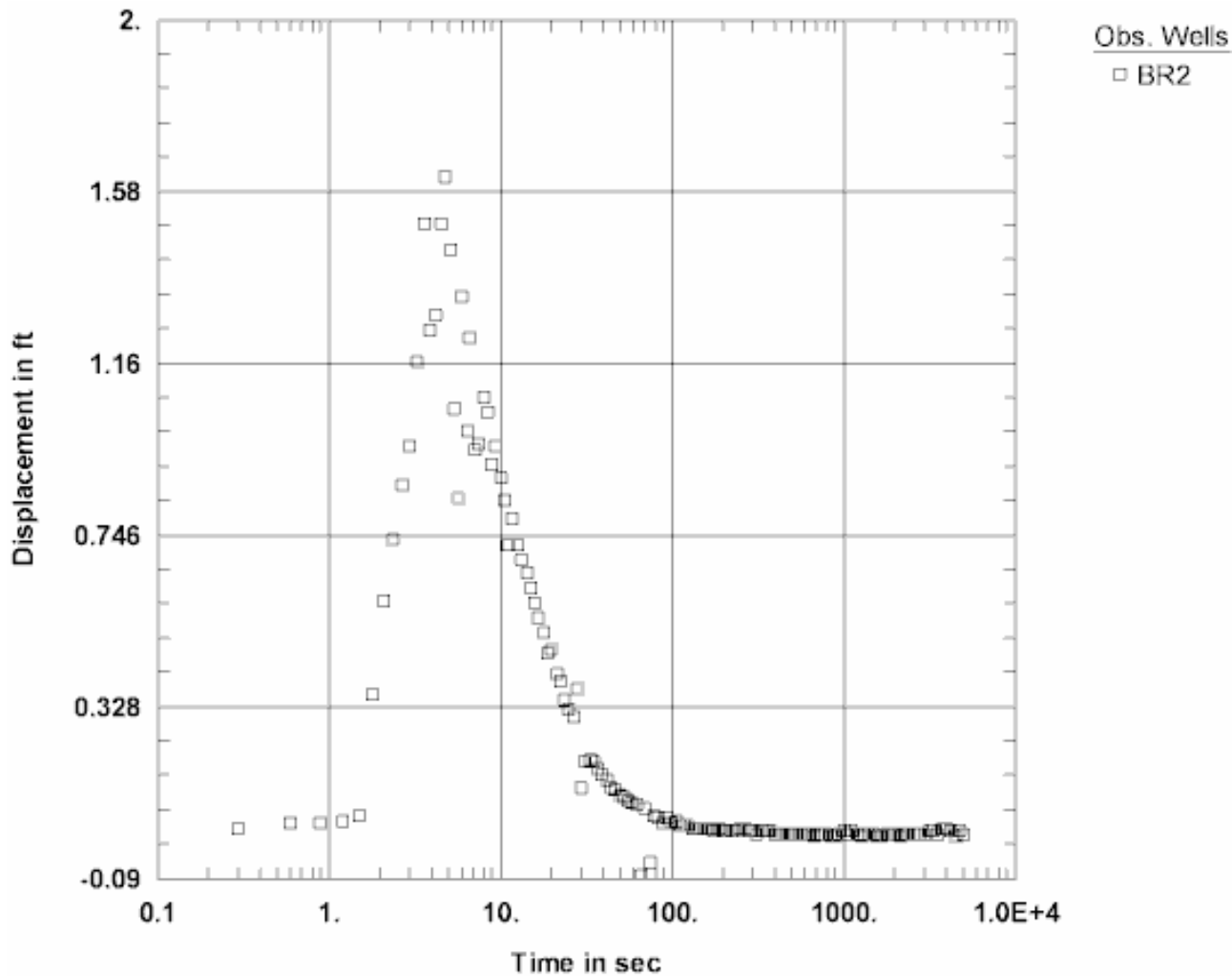
5. Choose Wells from the **Edit** menu. Select **BR2** from the list and click **Modify**. We will apply the translation method to the data.

    In the **Observations** tab, click **Select All**. Click **Math** and check **Perform transformation**. Select **Time** for the data, **-** (subtract) for the operation and enter **10** for the constant. Click **OK** and **Yes** to proceed with the math operations.

    After translating the start of the test, the observations spreadsheet shows that the displacement at elapsed time t = 0 is now 0.885 ft (i.e., the displacement reading originally measured at 10 seconds). Click the **General** tab and enter **0.885** for the initial displacement.
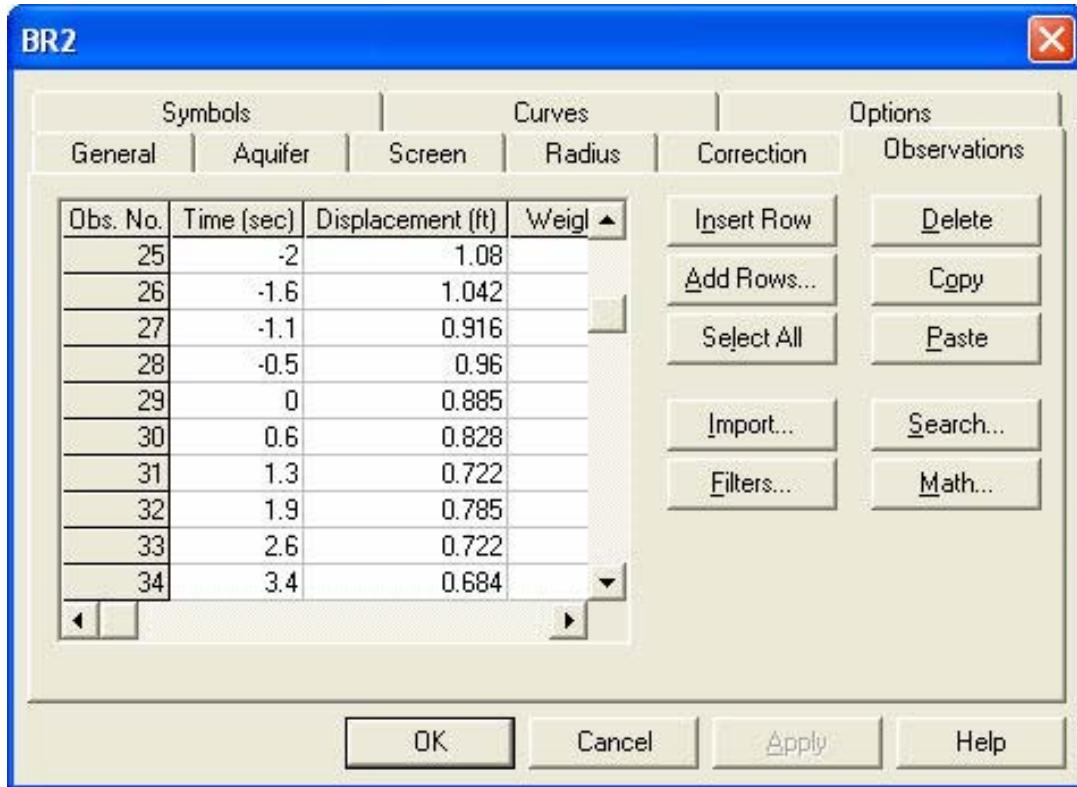
Click **OK** and **Close** to finish editing the well data.

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

Match Solution

After having translated the start of the test, we are ready to analyze the test with the Bouwer-Rice (1976) solution for an unconfined aquifer.

1. Choose Solution from the **Match** menu to select a method for analyzing the data.

2. Remove the check from **Solution is inactive**. Click the **+** next to **Unconfined Aquifers** to expand the list of available solutions for unconfined aquifers. Select **Bouwer-Rice (1976)** and click **OK**.

    With the Bouwer-Rice solution, the plot legend shows two parameters: K (hydraulic conductivity) and y0 (intercept of the line on the y axis).

3. Choose Options from the **View** menu. In the **Plots** tab, check **Normalized head** and **Recommended head range**. Click **OK**.

4. Choose Format from the **View** menu. In the **X Axis** tab, remove the check from **Auto** and enter **0** and **100** for the min and max values, respectively. In the **Y Axis** tab, remove the check from **Auto** and enter **0.01** for the min value.

5. Choose Visual from the **Match** menu to perform visual curve matching with

the Bouwer-Rice solution.

Normally, we would attempt the match the straight line within the head range recommended by Butler (1998) for the Bouwer-Rice solution; however, because we have altered the initial displacement through the application of the translation method, we will ignore the recommended range (shown as two horizontal lines on the plot) in this analysis.

To perform visual matching, move the mouse to a point where you wish to begin drawing a new line.

Click and hold down the left mouse button to anchor the new line at this point.

Continue to hold the mouse button down and move the mouse to match a new straight line to your data. As you move the mouse, AQTESOLV draws a straight line between the anchor point and the position of the mouse.

Release the left mouse button when you have finished matching a new straight line. AQTESOLV automatically updates the plot legend to reflect changes in parameter values.

6. Repeat the previous step as needed to estimate K by matching the straight line to the data.

View Visual Match
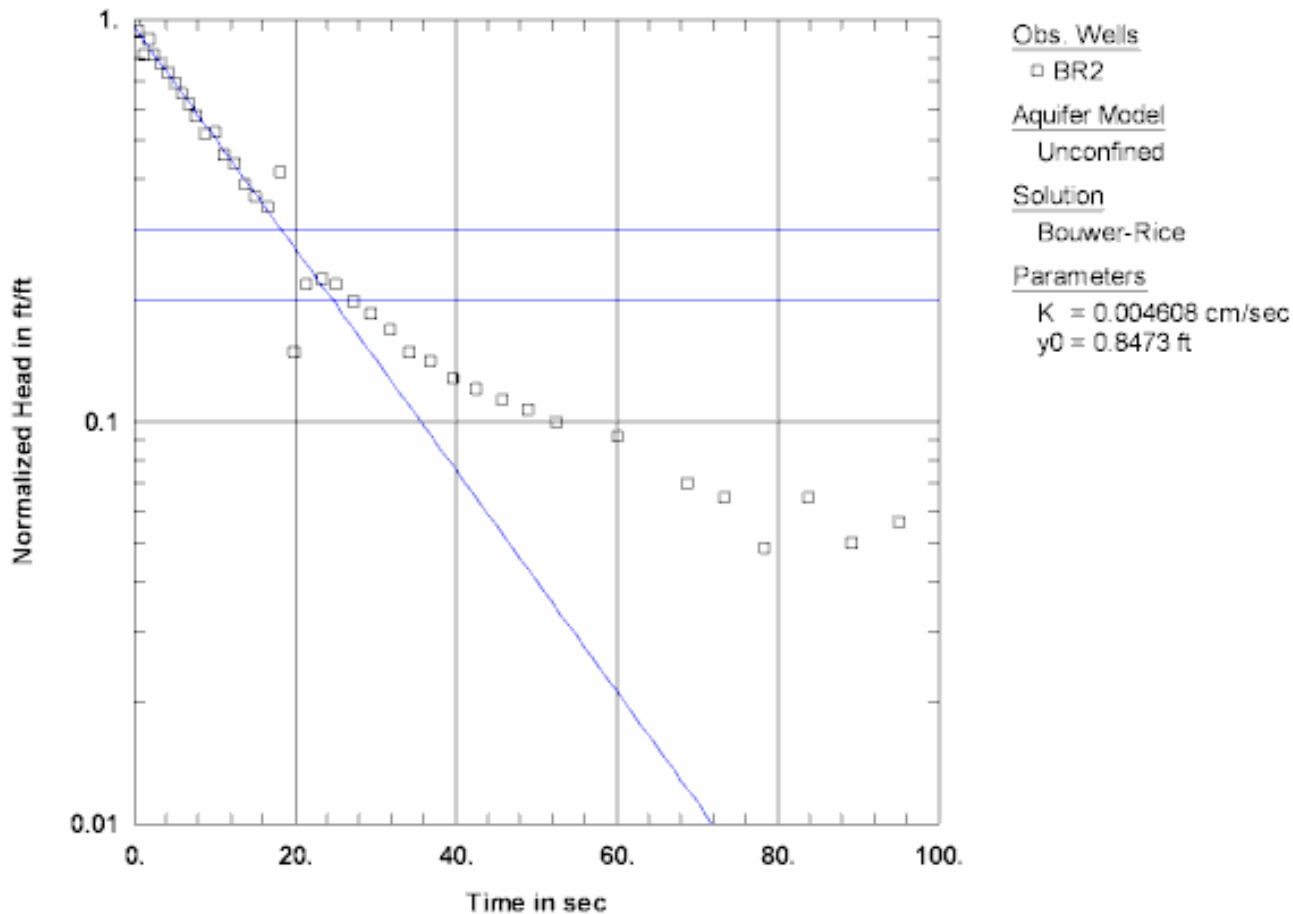
Obs. Wells
□ BR2

Aquifer Model
Unconfined

Solution
Bouwer-Rice

Parameters
K = 0.004608 cm/sec
y0 = 0.8473 ft

7. One could attempt to use automatic estimation to match the Bouwer-Rice solution to these data; however, visual matching is generally more effective for matching straight-line solutions because you can apply your judgment to fit the line to the appropriate range of data.

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

Slug Test: Double Straight-Line Effect (Dallas)

In this example, we will analyze a slug test conducted in a fully penetrating well screened across the water table that exhibits the "double straight-line effect" (Bouwer 1989) due to drainage from the filter pack. The test was conducted in an unconfined aquifer having an estimated saturated thickness of 8 ft. The initial displacement in the well was 3.792 ft. The following table provides well construction details for the test. Data for this example provided courtesy of G. Zemansky.

Well Radius, r_w (ft)	Casing Radius, r_c (ft)	Depth to Top of Screen, d (ft)	Screen Length, L (ft)
0.344	0.0861	0.0	8.0

Radius values are measured from the center of the test well. The well radius includes a filter pack installed in the well annulus. Elapsed time and depth-to-water measurements were recorded in minutes and feet, respectively.

This example will introduce you to the following tasks and features in AQTESOLV:

- Creating a new data set with the Slug Test Wizard for a single-well test

- Importing data with the Observation Data Import Wizard

- Saving a data set

- Displaying data

- Estimating aquifer properties with Bouwer-Rice solution (visual)

While following the steps in this example, click **Help** or press **F1** to context sensitive help in the AQTESOLV application.

Create a New Data Set with Slug Test Wizard

The first step in analyzing data from a slug test is to create a new AQTESOLV data set. In this example, we will use the Slug Test Wizard to assist us with data entry.

1. Create a new data set by choosing New from the **File** menu.

2. In the **New Data Set** dialog, select **Slug Test Wizard** from the list. Click **OK**.

3. The **Slug Test Wizard** prompts you for data required for a slug test. Click **Next**.

4. For units of measurement, choose **ft** for length, **min** for time and **cm/sec** for hydraulic conductivity. Click **Next**.

5. For project information, enter **Well Screened Across Water Table** for the title. Click **Next**.

6. For general test well data, enter **3.792** for the initial displacement, **8.0** for static water column height and **MW-2** for the well name. Enter coordinates of X=0 and Y=0. Click **Next**.

7. For aquifer data, enter **8.0** for aquifer thickness. Assume hydraulic conductivity is isotropic and enter **1** for anisotropy ratio. Click **Next**.

8. For screen data, enter **0.0** for depth to top of screen and **8.0** for screen length. Assume the transducer measures the position of the water surface in the well and enter **0** for transducer depth. Click **Next**.

9. For radius data, enter **0.0861** for casing radius and **0.344** for well radius. Assume no well skin and enter **0.344** for the skin radius. Click **Next**.

10. For correction data, check the option to **Apply correction for effective casing radius**. Select **Bouwer-Rice (1976)** for the correction method and enter **0.28** for the effective porosity of the filter pack. Click **Next**.

11. For observations, click **Import** to launch the Observation Data Import Wizard for importing data from a file.

    We will import a text file consisting of 144 time and water-level readings arranged in two columns. The first column is elapsed time in minutes since the start of the test. The second column contains depth-to-water measurements in feet.

    > In Step 1 of the wizard, click **Browse**. Select the import file **MW-2.txt** in the AQTESOLV installation folder and click **Open**. Click **Next**.
    >
    > In Step 2 of the wizard, accept the default values and click **Next**.
    >
    > In Step 3 of the wizard, accept the default values and click **Finish**. Inspect the import file summary and click **OK**.
    >
    > Click **Next** to proceed with the **Slug Test Wizard**.

12. You have completed the **Slug Test Wizard**. Click **Finish**.

After completing the **Slug Test Wizard**, AQTESOLV automatically displays an Error Log to let you know if the data set contains any errors. If the **Error Log** identifies any mistakes, choose options from the Edit menu to correct them.

Save Data Set

At this point, it's a good idea to save your work.

Save the data set by choosing Save As from the **File** menu. Choose a folder and enter **MW-2** for the name of the file. Click **Save**. AQTESOLV saves the file with an **.aqt** extension.

Display Data

1. Choose Displacement-Time from the **View** menu to display a plot of the test data.

2. Choose Options from the **View** menu. In the **Plots** tab, check **Normalized head** to display data as normalized head. Click **OK**.

3. Choose Linear-Log Axes from the **View** menu.

   The data display the classic "double straight-line" pattern (Bouwer 1989) that is commonly associated with drainage from the filter pack when a slug test is conducted in a well screened across the water table. Bouwer (1989) recommends fitting the Bouwer-Rice (1976) solution to the second (later) straight-line segment when this phenomenon occurs.

Match Solutions

Let us analyze this test with the Bouwer-Rice (1976) solution for an unconfined

aquifer. The Bouwer-Rice solution is based on the quasi-steady-state slug test model that ignores elastic storage in the aquifer.

1. Choose Solution from the **Match** menu to select a method for analyzing the data.

2. From the available solutions for **Unconfined Aquifers**, select **Bouwer-Rice (1976)** and click **OK**.

3. Choose Options from the **View** menu. In the **Plots** tab, check **Recommended head range** to display the range of normalized head recommended by Butler (1998) for matching the Bouwer-Rice solution. Click **OK**.

4. Choose Visual from the **Match** menu to perform visual curve matching with the Bouwer-Rice solution.

   To perform visual matching, move the mouse to a point where you wish to begin drawing a new line.

   Click and hold down the left mouse button to anchor the new line at this point.

   Continue to hold the mouse button down and move the mouse to match a new straight line to your data. As you move the mouse, AQTESOLV draws a straight line between the anchor point and the position of the mouse.

   Release the left mouse button when you have finished matching a new straight line. AQTESOLV automatically updates the plot legend to reflect changes in parameter values.

5. Repeat the previous step as needed to estimate K by matching the straight line to data falling on the second (less steep) straight-line segment. In this particular case, the recommended head range doesn't help much in fitting the line because of the filter pack drainage. How does your estimate of hydraulic conductivity change if you match the solution to the first (steeper) straight-line segment in the data?

   View Visual Match

Well Screened Across Water Table
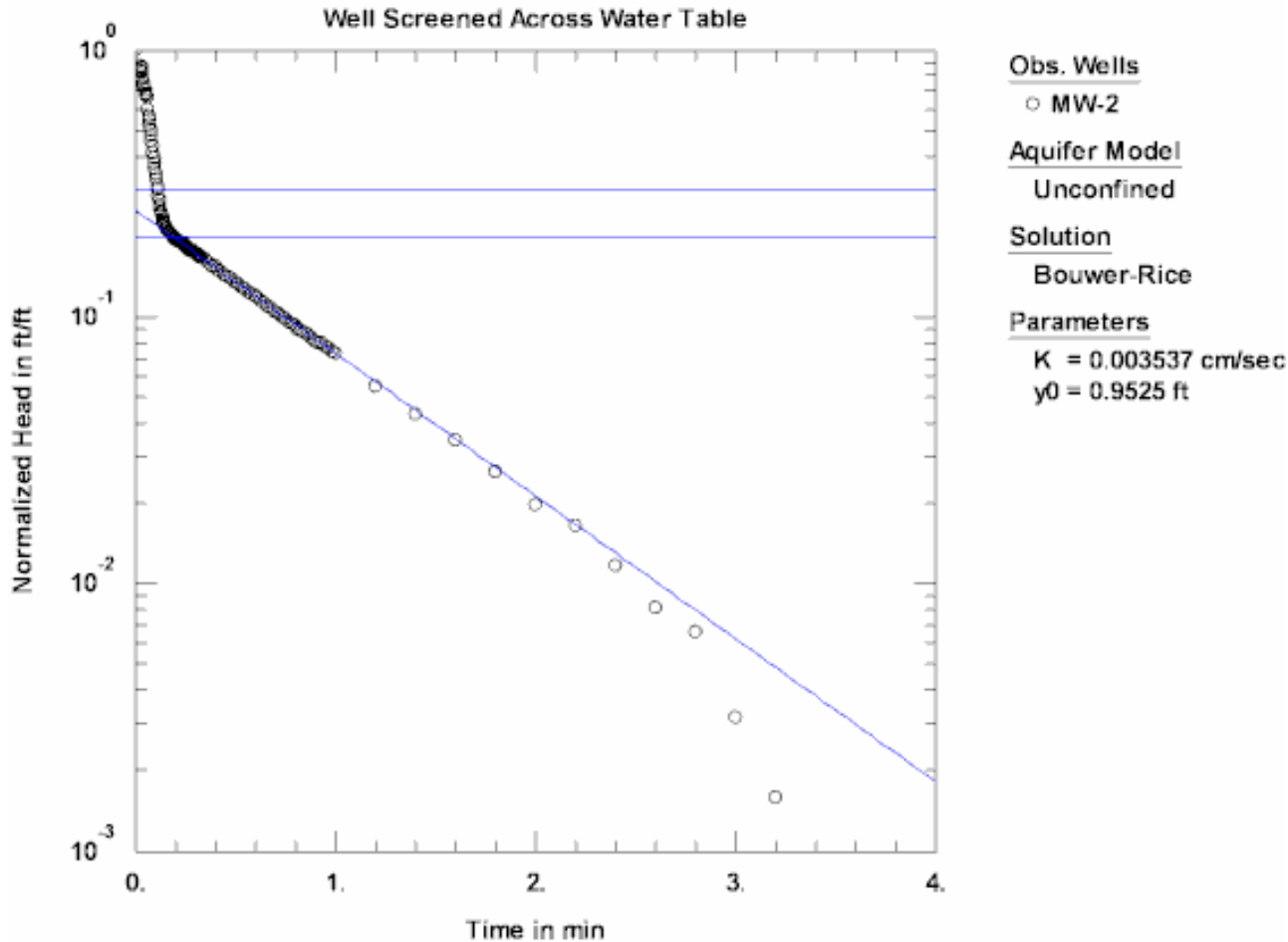
6. One could attempt to use automatic estimation to match the Bouwer-Rice solution to these data; however, visual matching is generally more effective for matching straight-line solutions because you can apply your judgment to fit the line to the appropriate range of data. Using automatic curve matching to fit the solution to the entire set of data would be clearly inappropriate for this example.

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

Slug Test Example: High-K Aquifer

Butler (2002) described a slug test in a high hydraulic conductivity (high-K) confined aquifer having a saturated thickness of 10.6 m. The initial displacement in the well was 0.094 m. The following table provides well construction details for the test.

Well Radius, r_w (m)	Casing Radius, r_c (m)	Depth to Top of Screen, d (m)	Screen Length, L (m)
0.0127	0.0074	4.92	0.61

Radius values are measured from the center of the test well. The depth of the well screen, d, is measured from the top of the aquifer. The static water column height is 11.13 m. Elapsed time and displacement measurements were recorded in seconds and m, respectively.

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This example will introduce you to the following tasks and features in AQTESOLV:

- Creating a new data set with the Slug Test Wizard for a single-well test

- Importing data with the Observation Data Import Wizard

- Saving a data set

- Displaying data

- Estimating aquifer properties with Butler (1998) solution (visual and automatic)

While following the steps in this example, click **Help** or press **F1** to context sensitive help in the program.

Create a New Data Set with Slug Test Wizard

The first step in analyzing data from a slug test is to create a new AQTESOLV data set. In this example, we will use the Slug Test Wizard to assist us with data entry.

1. Create a new data set by choosing New from the **File** menu.

2. In the **New Data Set** dialog, select **Slug Test Wizard** from the list. Click **OK**.

3. The **Slug Test Wizard** prompts you for data required for a slug test. Click **Next**.

4. For units of measurement, choose **m** for length, **sec** for time and **m/day** for hydraulic conductivity. Click **Next**.

5. For project information, enter **DP43C - 0.61 m Screen** for the title. Click **Next**.

6. For general test well data, enter **0.094** for the initial displacement, **11.13** for static water column height and **DP43C** for the well name. Enter coordinates of X=0 and Y=0. Click **Next**.

7. For aquifer data, enter **10.6** for aquifer thickness. Assume hydraulic conductivity is isotropic and enter **1** for anisotropy ratio. Click **Next**.

8. For screen data, enter **4.92** for depth to top of screen and **0.61** for screen length. Assume the transducer measures the position of the water surface in the well and enter **0** for transducer depth. Click **Next**.

9. For radius data, enter **0.0074** for casing radius and **0.0127** for well radius. Assume no well skin and enter **0.0127** for the skin radius. Click **Next**.

10. For corrections, check **Apply correction for frictional (viscous) well loss** to correct for well loss in a small diameter well. Click **Next**.

11. For observations, click **Import** to launch the Observation Data Import Wizard for importing data from a file.

    We will import a text file consisting of 197 time and displacement readings arranged in two columns. The first column is elapsed time in seconds since the start of the test. The second column contains displacement in m.

    > In Step 1 of the wizard, click **Browse**. Select the import file **DP43CT1.txt** in the AQTESOLV installation folder and click **Open**. Click **Next**.
    >
    > In Step 2 of the wizard, enter **2** for the number of columns, **1** for the starting row in the file, **1** for the column containing elapsed time and **2** for the column containing displacement. Click **Next**.
    >
    > In Step 3 of the wizard, click **Finish**. Inspect the import file summary and click **OK**.
    >
    > Click **Next** to proceed with the **Slug Test Wizard**.

12. You have completed the **Slug Test Wizard**. Click **Finish**.

After completing the **Slug Test Wizard**, AQTESOLV automatically displays an Error Log to let you know if the data set contains any errors. If the **Error Log** identifies any mistakes, choose options from the Edit menu to correct them.

Save Data Set

At this point, it's a good idea to save your work.

Save the data set by choosing Save As from the **File** menu. Choose a folder and enter **DP43CT1** for the name of the file. Click **Save**. AQTESOLV saves the file with an **.aqt** extension.

Display Data

1. Choose Displacement-Time from the **View** menu to display a plot of the test data.

2. Choose Options from the **View** menu. In the **Plots** tab, check **Normalized head** to display data as normalized head. Click **OK**.

3. Choose Linear Axes from the **View** menu.

    The data show an oscillatory pattern that is typical of an underdamped slug tests in a high-K aquifer.

Estimate Aquifer Properties

We will begin by analyzing this slug test with the Butler (1998) solution for a

confined aquifer. The Butler solution is an undamped model that accounts for inertial effects in the test well.

1. Choose Solution from the **Match** menu to select a method for analyzing the data.

2. Remove the check from **Solution is inactive**. Click the **+** next to **Confined Aquifers** to expand the list of available solutions for unconfined aquifers. Select **Butler (1998) inertial** and click **OK**.

3. Choose Options from the **View** menu. In the **Plots** tab, check **Solution critically damped when C(D)=2**. Click **OK**.

4. Choose Active Curves from the **Match** menu to perform visual curve matching with the active type curves feature.

   To perform visual matching, move the mouse over the plot.

   Click and hold down the left mouse button to anchor the new line at this point.

   Continue to hold the mouse button down and move the mouse up and down or left and right to adjust the shape of the curve.

   Release the left mouse button when you have finished matching the curve. AQTESOLV automatically updates the plot legend to reflect changes in parameter values.

5. Repeat the previous step as needed to refine the estimate K. As you adjust the curve, Le (estimated effective water column length) should be close to L (theoretical effective water column length). Butler (2002) estimated K = 88.2 m/day.

   View Visual Match
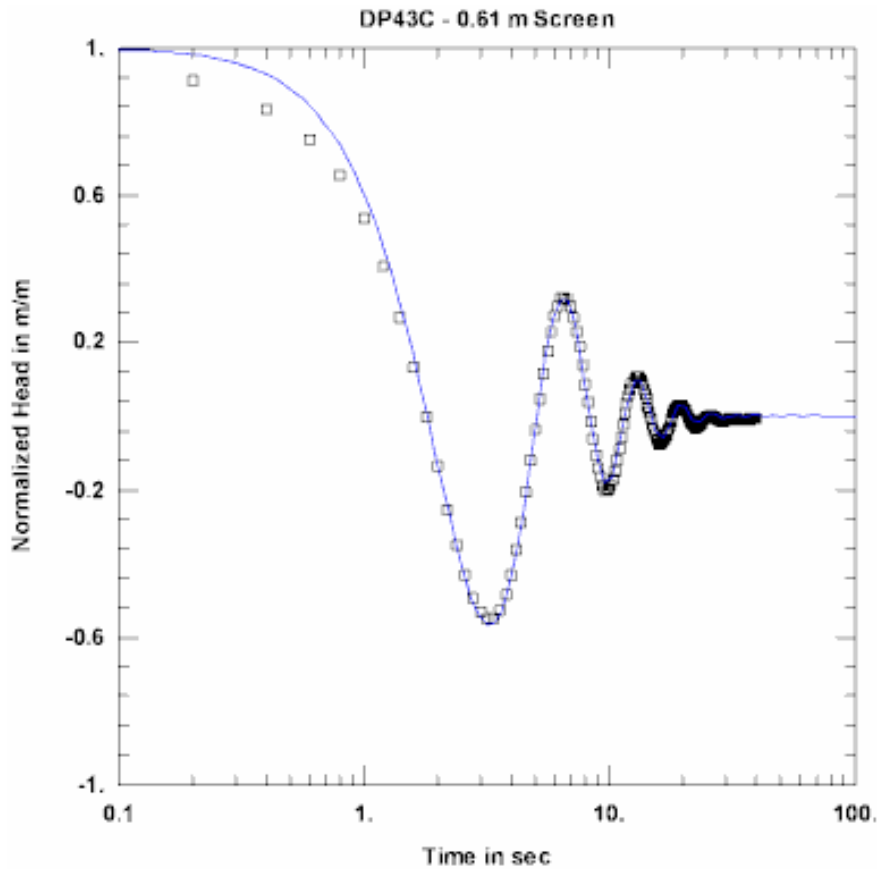
DP43C - 0.61 m Screen

Obs. Wells
□ DP43C

Aquifer Model
Confined

Solution
Butler
Critically damped when C(D)=2

Parameters
K   = 87.55 m/day
Le   = 10.19 m
C(D) = 0.3534
L   = 10.56 m

6. Choose Automatic from the **Match** menu and click **Estimate** to perform automatic curve matching with the Butler solution.

During the iterative estimation procedure, AQTESOLV displays a progress window and updates the curve displayed on the plot in the background.

7. When estimation has finished, click **OK** and then **Close**. Click **OK** to view the new position of the type curve.

Visual and automatic curve matching yield very similar results.

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

Slug Test Example: Multiwell Test (Lincoln County, KS)

Butler (1998) presented data for a slug test in a semiconsolidated sand aquifer in Lincoln County, Kansas. Transducers monitored water levels in the test well (Ln-2) and an observation well (Ln-3) located at a radial distance of 6.45 m from Ln-2. Both wells fully penetrated the 6.1-m thick aquifer. Inflatable packers were used during the test to eliminate the effect of wellbore storage in Ln-3. The initial displacement in Ln-2 was 2.798 m. The following table provides well construction details for the test.

Well	Well Radius, r_w (m)	Casing Radius, r_c (m)
Ln-2	0.102	0.051
Ln-3	0.071	0.025

Radius values are measured from the center of each well. Elapsed time and depth-to-water measurements were recorded in seconds and meters, respectively.

This example will introduce you to the following tasks and features in AQTESOLV:

- Creating a new data set with the Slug Test Wizard for a single-well test

- Importing data with the Observation Data Import Wizard

- Saving a data set

- Displaying data

- Estimating aquifer properties with KGS Model solution (visual and automatic)

Create a New Data Set with Slug Test Wizard

The first step in analyzing data from a slug test is to create a new AQTESOLV data set. In this example, we will use the Slug Test Wizard to assist us with data entry for the test well (we will add data for the observation well later).

1. Create a new data set by choosing New from the **File** menu.

2. In the **New Data Set** dialog, select **Slug Test Wizard** from the list. Click **OK**.

3. The **Slug Test Wizard** prompts you for data required for a slug test. Click **Next**.

4. For units of measurement, choose **m** for length, **sec** for time and **m/day** for hydraulic conductivity. Click **Next**.

5. For project information, enter **Multi-Well Slug Test** for the title. Click **Next**.

6. For general test well data, enter **2.798** for the initial displacement, **10** for static water column height and **Ln-2** for the well name. Enter coordinates of X=0 and Y=0. Click **Next**.

7. For aquifer data, enter **6.1** for aquifer thickness. Assume hydraulic

conductivity is isotropic and enter **1** for anisotropy ratio. Click **Next**.

8. For screen data, enter **0** for depth to top of screen and **6.1** for screen length. Assume the transducer measures the position of the water surface in the well and enter **0** for transducer depth. Click **Next**.

9. For radius data, enter **0.051** for casing radius and **0.102** for well radius. Assume no well skin and enter **0.102** for the skin radius. Click **Next**.

10. Corrections are not required for this test. The gravel pack correction only applies to wells screened across the water table. Click **Next**.

11. For observations, click **Import** to launch the Observation Data Import Wizard for importing data from a file.

    We will import a text file consisting of 81 time and water-level readings arranged in two columns. The first column is elapsed time in seconds since the start of the test. The second column contains depth-to-water measurements in meters.

    > In Step 1 of the wizard, click **Browse**. Select the import file **Ln-2.txt** in the AQTESOLV installation folder and click **Open**. Click **Next**.
    >
    > In Step 2 of the wizard, accept the default values determined by the Import Wizard. Click **Next**.
    >
    > In Step 3 of the wizard, accept the defaults and click **Finish**. Inspect the import file summary and click **OK**.
    >
    > Click **Next** to proceed with the **Slug Test Wizard**.

12. You have completed the **Slug Test Wizard**. Click **Finish**.

After completing the **Slug Test Wizard**, AQTESOLV automatically displays an Error Log to let you know if the data set contains any errors. If the **Error Log** identifies any mistakes, choose options from the Edit menu to correct them.

Add Observation Well

The **Slug Test Wizard** helped you enter data for the test well. Now you will add data for the observation well.

1. Choose Wells from the **Edit** menu and click **New** to add a new well. Select the new well in the list and click **Modify** to edit the well.

2. In the **General** tab, enter **Ln-3** for the well name. Enter **6.45** and **0** for the X and Y coordinates, respectively.

3. In the **Screen** tab, enter **0** for depth to top of screen and **6.1** for screen length.

4. In the **Observations** tab, click **Import** to launch the Observation Data Import Wizard for importing data from a file.

    You will import 81 observations from a text file. The first column is elapsed

time since the start of the test. The second column contains drawdown measurements for the observation well.

> In Step 1 of the wizard, click **Browse**. Select the import file **Ln-3.txt** in the AQTESOLV installation folder and click **Open**. Click **Next**.
>
> In Step 2 of the wizard, accept the default values determined by the Import Wizard. Click **Next**.
>
> In Step 3 of the wizard, accept the defaults and click **Finish**. Inspect the import file summary and click **OK**.

5. Click **OK** to finish editing well Ln-3.

6. Click **Close** to leave the **Wells** window.

Save Data Set

At this point, it's a good idea to save your work.

Save the data set by choosing Save As from the **File** menu. Choose a folder and enter **Lincoln County** for the name of the file. Click **Save**. AQTESOLV saves the file with an **.aqt** extension.

Inspect Diagnostic Plots

Following the guidelines developed by Butler (1998) for a slug test in a fully penetrating well in a confined aquifer, we use the Cooper et al. (1967) method to screen the data in the test well. An implausibly low storativity (S) value determined from the screening analysis would suggest the presence of wellbore skin in the well.

1. Choose Displacement-Time from the **View** menu to display a plot of the test data.

2. Choose Options from the **View** menu. In the **Plots** tab, check **Normalized head** to display data as normalized head. Click **OK**.

3. Choose Log-Linear Axes from the **View** menu.

   On these axes, the test well data show a sigmoidal shape that is typical of solutions based on the fully transient overdamped slug test model, e.g., Hyder et al. (1994).

4. Choose Solution from the **Match** menu to use the Cooper et al. (1967) method as a screening tool for the test well (Ln-2) data.

5. Remove the check from **Solution is inactive**. Click the **+** next to **Confined Aquifers** to expand the list of available solutions for confined aquifers. Select **Cooper-Bredehoeft-Papadopulos (1967)** and click **OK**.

6. Choose Automatic from the **Match** menu and click **Estimate** to perform automatic curve matching with the Cooper et al. solution to the data for the test well.

   During the iterative estimation procedure, AQTESOLV displays a progress

7. When estimation has finished, click **OK** and then **Close**. Click **OK** to view the new position of the type curve.

8. The estimated value of storativity (S) appears plausible; therefore, we assume that wellbore skin is not a factor at the test well.

Match Solution

We will analyze this slug test with the Hyder et al. (1994) solution (KGS Model) for a confined aquifer. The KGS Model is a fully transient solution for multiwell slug tests that accounts for elastic storage in the aquifer. For fully penetrating wells in a confined aquifer without wellbore skin, the KGS Model is equivalent to the Cooper et al (1967) and Dougherty-Babu (1984) solutions.

1. Choose Solution from the **Match** menu to select a method for analyzing the data.

2. From the available solutions for **Confined Aquifers**, select **KGS Model (1994)** and click **OK**.
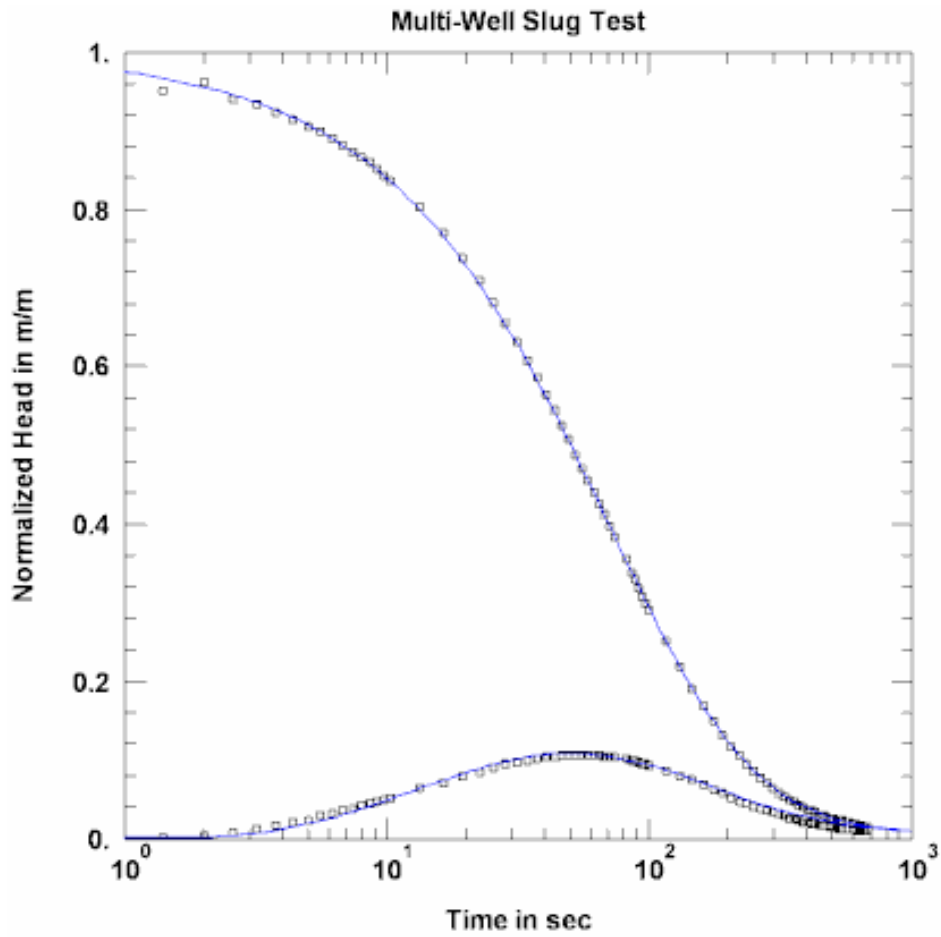
3. Choose Automatic from the **Match** menu and click **Estimate** to perform automatic curve matching with the KGS Model.

During the iterative estimation procedure, AQTESOLV displays a progress window and updates the curve displayed on the plot in the background.

4. When estimation has finished, click **OK** and then **Close**. Click **OK** to view the new position of the type curve.

View Automatic Match

Multi-Well Slug Test

Obs. Wells
Ln-2
Ln-3

Aquifer Model
Confined

Solution
KGS Model

Parameters
Kr = 1.166 m/day
Ss = 9.369E-6 m^{-1}
Kz/Kr = 1.

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

Constant-Head Test Example: Flow and Recovery (Grand Junction)

Lohman (1972) presents data from a constant-head test conducted on September 22, 1948 near Grand Junction, Colorado. The Artesia Heights test well (Well 28) fully penetrates an artesian aquifer and has a radius of 0.276 ft. A two-inch gate valve capping the well regulated flow. After a shut-in period of several days, the static head in the well just prior to the test was 92.33 ft above the discharge point (94.55 ft above the measuring point). With the valve open, the well was allowed to flow freely for 114 minutes. At the end of the test, the gate valve was closed and head in the well during recovery was monitored for an additional 41 minutes. Lohman (1972) reported head values in feet above land surface. The measuring point was 0.5 ft above land surface (Lohman 1965); hence, the static head above land surface was 95.05 ft.

Lohman (1965) describes Well 28 as tapping the Jurassic Entrada Sandstone which serves as the most widely used and productive artesian aquifer in the Grand Junction area. The Summerville and Morrison Formations overlying the Entrada are described as relatively impermeable; however, the underlying Triassic Kayenta Formation may not provide complete hydraulic separation between the Entrada and Wingate Sandstones (an underlying artesian aquifer) in the area (Lohman 1965). Therefore, our analysis will consider the possibility of leakage.

This example will introduce you to the following tasks and features in AQTESOLV:

- Creating a new data set with the Constant-Head Test Wizard

- Importing data with the Pumping Rate Data Import Wizard and the Observation Data Import Wizard

- Saving a data set

- Estimating aquifer properties using Jacob-Lohman (1952) straight-line and type curve solutions for a confined aquifer (visual and automatic)

- Estimating aquifer properties from recovery data using Hantush (1959) solution for a leaky aquifer (automatic)

While following the steps in this example, click **Help** or press **F1** to obtain context sensitive help in the AQTESOLV application.

Create a New Data Set with Constant-Head Test Wizard

The first step in analyzing data from a constant-head test is to create a new AQTESOLV data set. In this example, we will use the Constant-Head Test Wizard to assist us with data entry.

1. Create a new data set by choosing New from the **File** menu.

2. In the **New Data Set** dialog, select **Constant-Head Test Wizard** from the list. Click **OK**.

3. The **Constant-Head Test Wizard** prompts you for data required for a constant-head test. Click **Next**.

4. For units of measurement, choose **ft** for length, **min** for time, **gal/min** for pumping rate and **ft/day** for hydraulic conductivity. Click **Next**.

5. For project information, enter **Grand Junction, Colorado** for the location and **September 22, 1948** for the test date. Click **Next**.

6. For aquifer data, assume **150** for the aquifer thickness. Enter **1** for the anisotropy ratio (i.e., assume hydraulic conductivity is isotropic). Click **Next**.

7. For pumping well data, enter **Well 28** for the well name. Enter coordinates of X=0 and Y=0. Click **Next**.

8. For pumping well construction, select the option for **vertical, full penetration**. Click **Next**.

9. For pumping well radius data, we will assume a negligible casing radius. Enter **0.00001** for casing radius and **0.276** for well radius. Click **Next**.

Wellbore storage plays no role in a constant-head test when the well is flowing and the head in the well is constant; however, depending on well configuration, wellbore storage may affect recovery because the boundary condition changes at the test well. For this particular test, the action of closing the gate valve seals the well at the end of the flow test and head in the well recovers without storage in the casing. A suitable packer arrangement in a well could produce the same effect. To perform recovery calculations without wellbore storage, enter a negligible value for casing radius.

10. For pumping rates, click **Import** to launch the Pumping Rate Data Import Wizard for importing data from a file.

We will import a text file consisting of 20 time-rate readings arranged in two columns. The first column is elapsed time since the start of the test. The second column contains flow rate measurements.

In Step 1 of the wizard, click **Browse**. Select the import file **Grand Junction Rates.txt** in the AQTESOLV installation folder and click **Open**. Click **Next**.

In Step 2 of the wizard, accept the defaults determined by AQTESOLV (**2** for the number of columns, **8** for the starting row in the file, **1** for the column containing elapsed time and **2** for the column containing rates).

Click **Next**.

In Step 3 of the wizard, click **Finish**. Inspect the import file summary and click **OK**.

Click **Next** to proceed with the **Constant-Head Test Wizard**.

11. For constant-head data, enter **92.33** for the head maintained in the test well. Check the option to **Compute multi-rate Agarwal equivalent time**. Click **Next**.

12. For observations, click **Import** to launch the Observation Data Import Wizard for importing data from a file.

We will import a text file consisting of 21 time-head readings arranged in two columns. The first column is elapsed time since the start of the recovery. The second column contains measurements of head above land surface during recovery.

To convert elapsed time since the start of recovery to elapsed time since the start of the test, we will use the wizard to add 114 minutes (the duration of the test) to each of the imported time values. To transform head during recovery to displacement, we subtract 95.05 ft (the static head above land surface recorded before the test) from all of the head measurements in the file. The subtraction operation results in negative displacements. To make them positive, multiply all of the displacement values by -1.

In Step 1 of the wizard, click **Browse**. Select the import file **Grand Junction Recovery.txt** in the AQTESOLV installation folder and click **Open**. Click **Next**.

In Step 2 of the wizard, accept the defaults determined by AQTESOLV (**2** for the number of columns, **11** for the starting row in the file, **1** for the column containing elapsed time and **2** for the column containing displacement). Click **Next**.

In Step 3 of the wizard, **check the first box** to subtract a constant from the time values and enter **-114** for the constant. **Check the second box** to subtract a constant from the displacement values and enter **94.55** for the constant. **Check the fourth box** to multiply displacement values by a constant and enter **-1** for the constant. Click **Finish**. Inspect the import file summary and click **OK**.

Click **Next** to proceed with the **Constant-Head Test Wizard**.

13. You have completed the **Constant-Head Test Wizard**. Click **Finish**.

After completing the **Pumping Test Wizard**, AQTESOLV automatically displays an Error Log to let you know if the data set contains any errors. If the **Error Log** identifies any mistakes, choose options from the Edit menu to correct them.

Save Data Set

At this point, it's a good idea to save your work.

Save the data set by choosing Save As from the **File** menu. Choose a folder and enter **Grand Junction** for the name of the file. Click **Save**. AQTESOLV saves the file with an **.aqt** extension.

Estimate Aquifer Properties from Flow Test

To start our analysis, we can use the Jacob-Lohman (1952) straight-line solution to obtain preliminary estimates of aquifer properties.

1. Choose Solution from the **Match** menu to select a method for analyzing the data.

2. Remove the check from **Solution is inactive**. Click the **+** next to **Confined Aquifers** to expand the list of available solutions for confined aquifers. Select **Jacob-Lohman (1952) straight-line method** and click **OK**.

3. Choose Displacement-Time from the **View** menu. For the Jacob-Lohman straight-line method, the data are plotted on linear-log axes.

    For a constant-head test, the displacement-time plot shows displacement normalized by discharge, s/Q(t), where s is the constant head maintained in the test well and Q(t) is discharge at time t.

4. Choose Visual from the **Match** menu to perform visual curve matching with the Jacob-Lohman straight-line solution.

> To perform visual matching, move the mouse to a point where you wish to begin drawing a new line with the Jacob-Lohman solution.
>
> Click and hold down the left mouse button to anchor the new line at this point.
>
> Continue to hold the mouse button down and move the mouse to match a new straight line to your data. As you move the mouse, AQTESOLV draws a straight line between the anchor point and the position of the mouse.
>
> Release the left mouse button when you have finished matching a new straight line. AQTESOLV automatically updates the plot legend to reflect changes in parameter values.

5. Repeat the previous step as needed to achieve a satisfactory match.

    View Visual Match With Jacob-Lohman
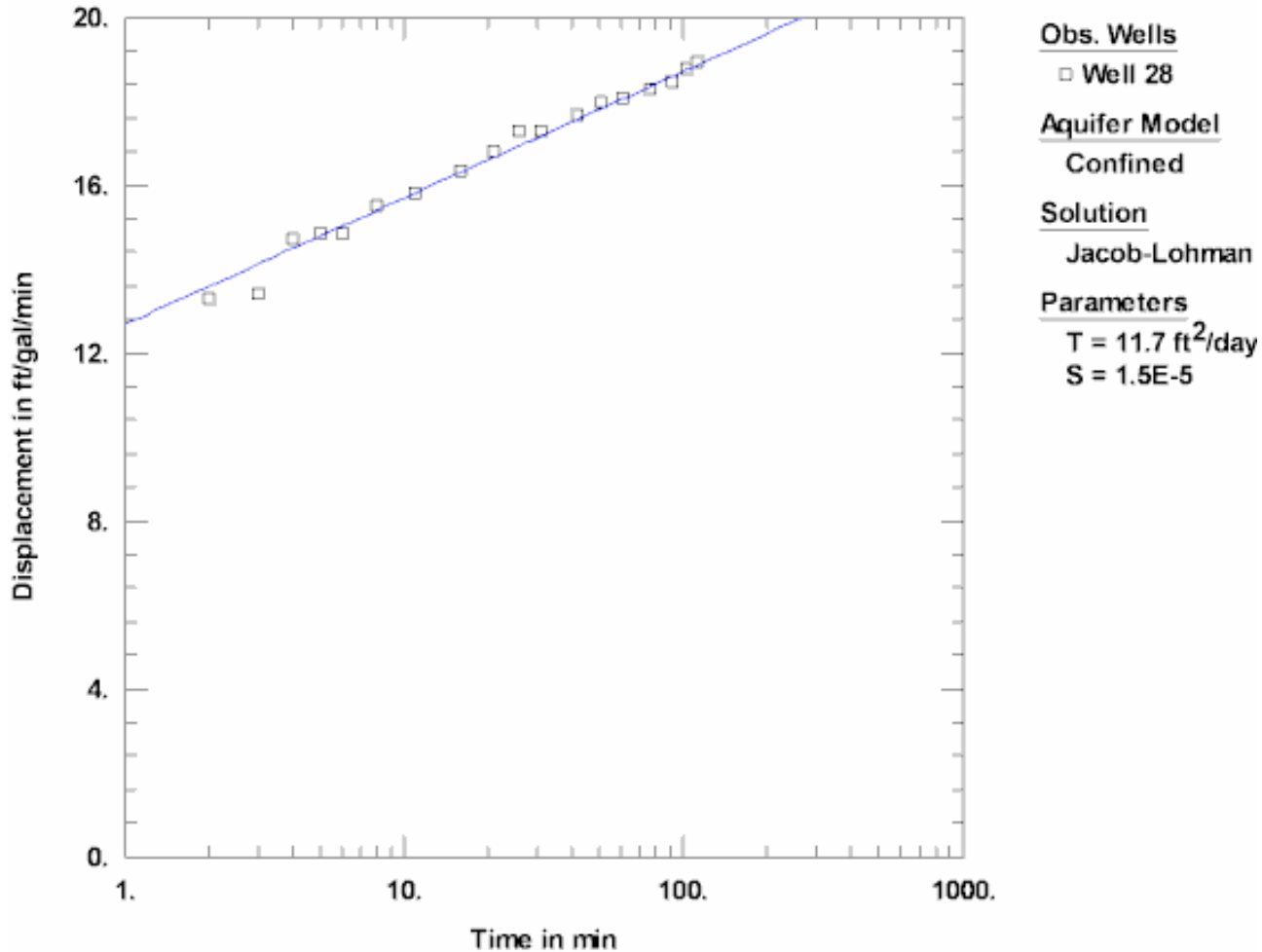
Having completed our preliminary analysis with the Jacob-Lohman straight-line solution, let's refine our match with the Jacob-Lohman (1952) type curve solution for a confined aquifer.

1. Choose Solution from the **Match** menu to select a method for analyzing the data.

2. From the list of solutions for **Confined Aquifers**, select **Jacob-Lohman (1952)** and click **OK**.

3. Choose Log Axes from the **View** menu to change the axes to a log-log format.

4. Choose Automatic from the **Match** menu. In the **Parameters** tab, select **Inactive** for the estimation status of both r(w) and r(c). Click **Estimate** to perform automatic curve matching.

   During the iterative estimation procedure, AQTESOLV displays a progress window and updates the curves displayed on the plot in the background.

5. When estimation has finished, click **OK** and then **Close**. Click **OK** to view the new position of the type curve. The estimated values of T and S from automatic matching are close to the visual estimates.

6. Choose Discharge-Time from the **View** menu to inspect the discharge rate simulated by the Jacob-Lohman solution versus the observed flow rate measurements.

View Automatic Match on Discharge-Time Plot
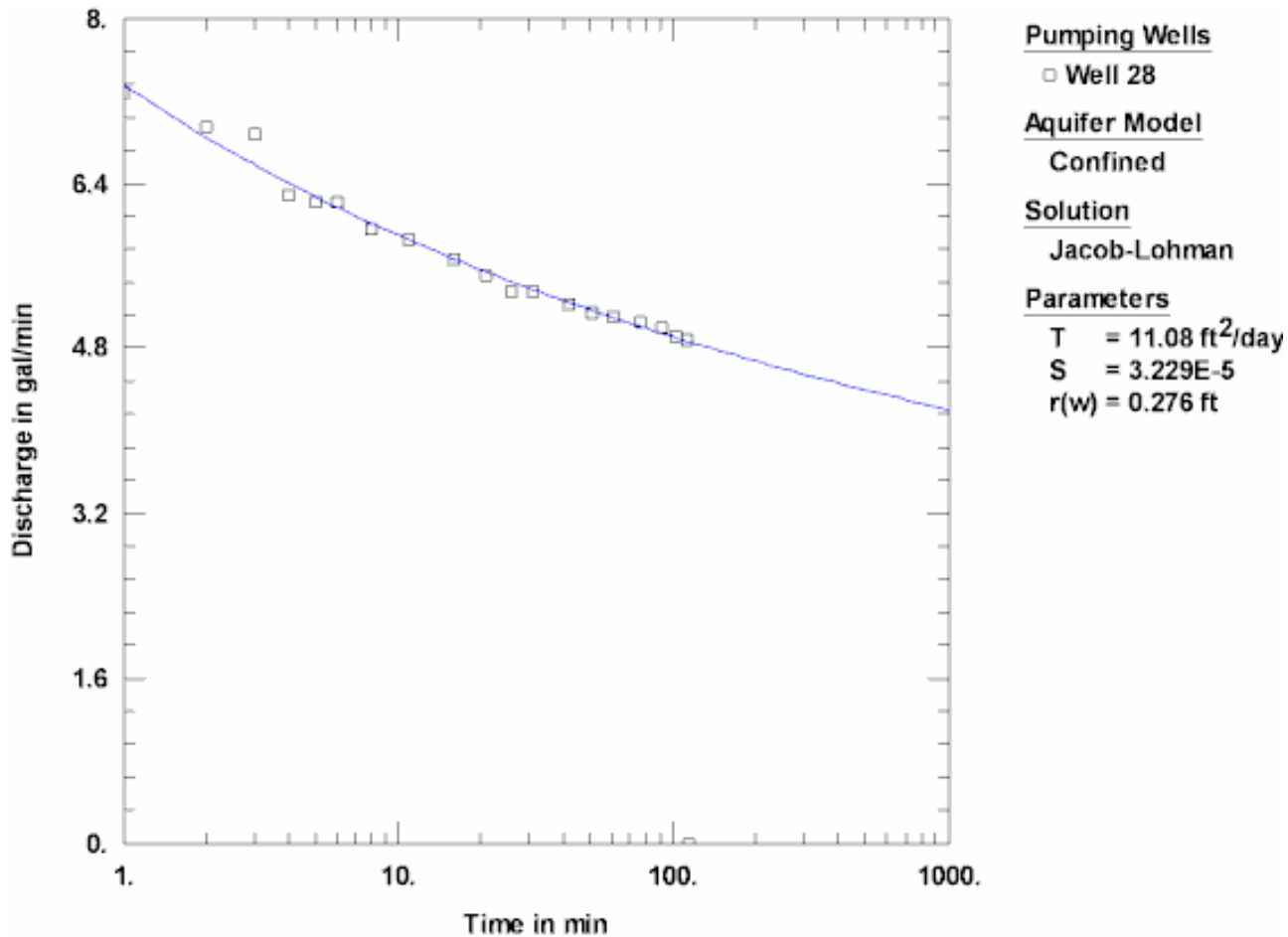
7. Use residual-time, residual-simulated and normal probability plots to evaluate the fit of the solution by examining residuals. The diagnostics report also presents residual statistics for curve fitting.

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

Estimate Aquifer Properties from Recovery Data

AQTESOLV provides an exact method for evaluating recovery data from a constant-head test. We will begin our recovery analysis with the Jacob-Lohman (1952) type curve solution.

1. Choose Residual Drawdown from the **View** menu to plot residual drawdown data on linear-log axes.

    Although we obtained a good curve fit with the Jacob-Lohman solution when matching only the data from the flow test, the residual drawdown plot suggests a source of recharge (e.g., leakage) because the data recover more

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quickly than the predicted curve. In addition, a line through the trend of the data intercepts the x axis at a value greater than 1.

2. Choose Agarwal from the **View** menu. The plot displays recovery as a function of Agarwal equivalent time.

The Agarwal method is an approximate recovery data analysis procedure for constant-head tests (Uraiet and Raghavan 1980). If leakage were a factor in the response for this test, we would observe the data to flatten with increasing recovery time; however, due to the short duration of recovery measurements, the leakage effect is not apparent.

Pro Now let's use the Hantush (1959) solution for a constant-head test in a leaky aquifer to investigate the potential effect of leakage.

1. Choose Solution from the **Match** menu. Click the **+** next to **Leaky Aquifers** to expand the list of available solutions for leaky aquifers. Select **Hantush (1959) constant head** and click **OK**.

2. Choose Displacement-Time from the **View** menu to display the data from the flow test.

3. Choose Automatic from the **Match** menu. In the **Estimation** tab, enter **50** for the maximum iterations. Click **Advanced** and change the lambda updating method to **Conservative**. Click **Estimate** to perform automatic curve matching.

When estimation has finished, click **OK** and then **Close**. Click **OK** to view the new position of the type curve.

The residual sum of squares (RSS) for the leaky aquifer model indicates an improved match compared to the confined aquifer model: RSS = 0.7744 for the confined aquifer model versus RSS = 0.6685 for the leaky aquifer model.

4. Choose Residual Drawdown from the **View** menu.

View Residual Drawdown Plot for Leaky Aquifer Model

The residual drawdown curve predicted with the leaky aquifer model matches the recovery data much more closely than the model for a confined aquifer. If you attempt to use automatic curve matching to estimate the aquifer properties from just the recovery data, T and S are perfectly correlated and the fit is nonunique.
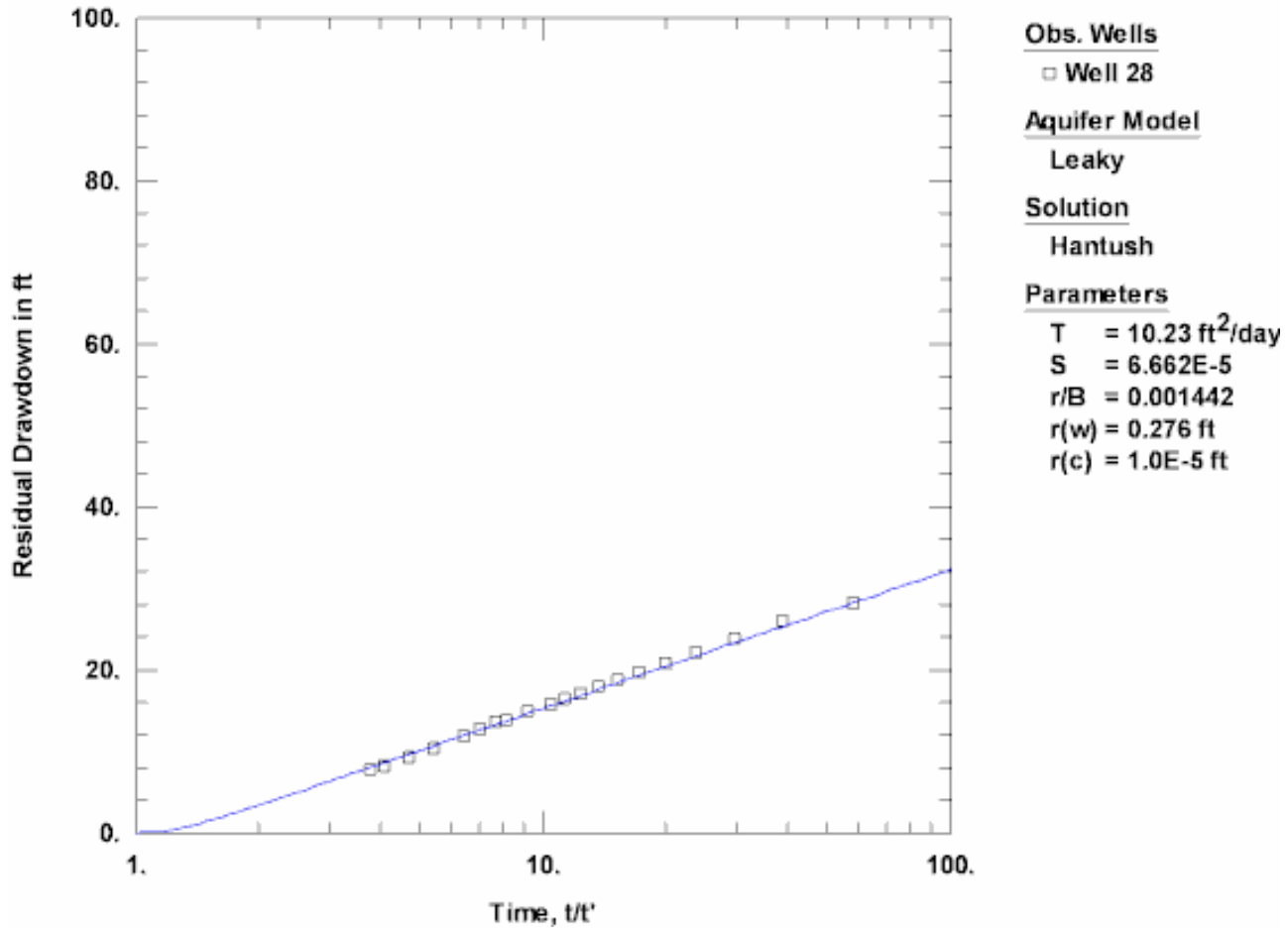
Mounding Example: Rectangular Recharge Area

In this example, you will use AQTESOLV to predict transient rise of the water table beneath a rectangular recharge area using a solution by Hantush (1967). The length and width of the recharge basin are both 100 ft. The hydraulic conductivity of the unconfined aquifer is 0.1 ft/day and the specific yield is 0.1. The initial saturated thickness of the aquifer is 10 ft.

The procedure for applying the **circular recharge area** solution by Hantush (1967) is essentially the same as given below.

This example will introduce you to the following tasks and features in AQTESOLV:

- Creating an empty data set

- Predicting the growth of a groundwater mound using the Hantush solution for a rectangular recharge area

- Saving a data set

While following the steps in this example, click **Help** or press **F1** to obtain context sensitive help in the AQTESOLV application.

Create an Empty Data Set

The first step in performing groundwater mounding simulations is to create a new AQTESOLV data set. In this example, we will create an empty data set before using the groundwater mounding tools in AQTESOLV.

1. Create a new data set by choosing New from the **File** menu.

2. In the **New Data Set** dialog, select **Default** from the list. Click **OK**.

After creating an empty data set, AQTESOLV automatically displays an Error Log to let you know if the data set contains any errors. For the purpose of simulating a groundwater mound, you may ignore any errors shown in the **Error Log**.

Prediction

Now we can use the Hantush (1967) solution to predict the transient growth of a groundwater mound beneath a rectangular recharge area.

1. Choose Units from the **Edit** menu.

2. For units of measurement, choose **ft** for length, **day** for time, **consistent** for

pumping rate and **consistent** for hydraulic conductivity. Click **OK**.

3. Choose Mounding>Rectangular Recharge Area from the **Tools** menu to enter mounding data.

4. For aquifer properties, enter **0.1** for hydraulic conductivity (K), **0.1** for specific yield (Sy) and **10** for initial saturated thickness (h(0)).

5. For recharge area properties, enter **0.01** for recharge rate (w), **100** for the simulation time (t), **100000** for time when recovery begins (t(0)), **0** for x coordinate (X), **0** for y coordinate (Y), **100** for length (l) and **100** for width (a).

To simulate recharge *without* recovery, enter a value for t(0) greater than the simulation time.

6. Click **Contour** to launch the Grid Wizard for preparing a contour plot with Surfer.

Surfer is a popular standalone software package that integrates seamlessly with AQTESOLV to generate contour plots. Install Surfer on your computer to gain access to this feature.

7. In Step 1 of the **Grid Wizard**, enter the name of a **Grid file** to store data for the contour plot. Click Browse if you would like to store the file in a specific folder on your computer. Select **X-Y (Plan)** for the grid orientation. Click **Next**.

8. In Step 2 of the **Grid Wizard**, enter **-100** and **100** for the minimum and maximum dimensions in the X and Y directions. Enter **51** for the number of grid lines in both directions. For the depths, enter **0** and **10**. Enter **100** for the time to predict the growth of the mound. Click **Next**.

9. In Step 3 of the **Grid Wizard**, check **Display grid file with Surfer** and select **Contour**. Click **Finish** to display the contour plot with Surfer. You may use options in Surfer to customize the appearance of the plot.

 View Contour Plot
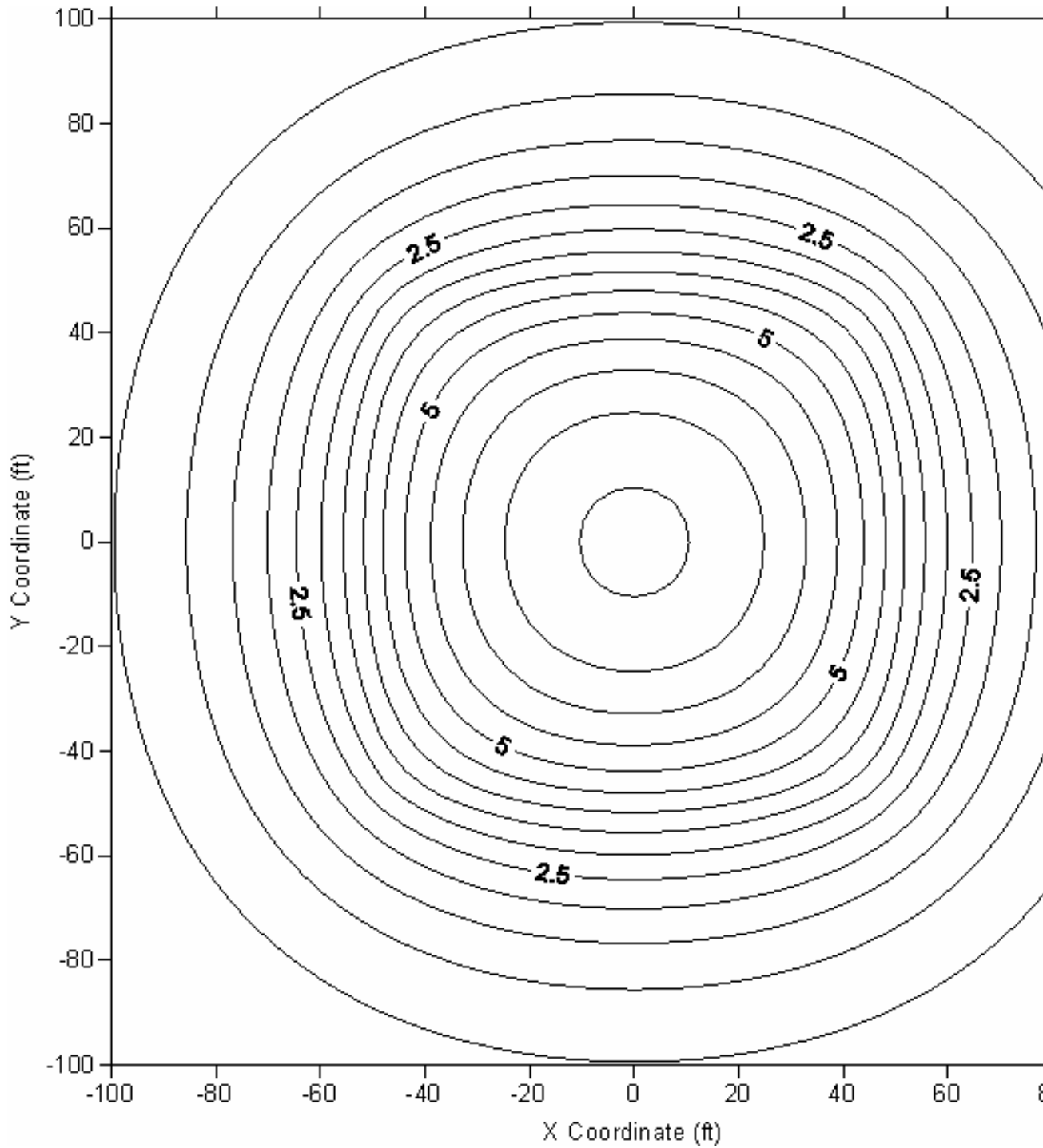
10. Click **Report** to save a file containing groundwater mounding results in text or HTML format.

You may open a text or HTML report in Microsoft Excel to generate a quick chart of the results.

11. Click **OK** when you have finished using the mounding tool for a rectangular recharge area.

Save Data Set

Save the data set by choosing Save As from the **File** menu. Choose a folder and enter **Mound** for the name of the file. Click **Save**. AQTESOLV saves the file with an **.aqt** extension.

More Examples

On the Web

Visit the examples section of the AQTESOLV web site to find more example data sets and tutorials.

Menus

File Menu

Select options in the **File** menu to manage data set files, import and export data, print plots and reports, send data sets as email and exit the application.

New	Create a new data set
Open	Open a file containing a data set
Close	Close the active data set
Save	Save the active data set
Save As	Save the active data set using a specified file name
Export	Export data
Print	Print the plot or report in the active window
Print Preview	Preview the plot or report before printing
Print Setup	Configure printer options
Page Setup	Format the page for printing
Batch Print	Batch print a group of data sets
Send Mail	Send the active data set as an email attachment
MRU	Most recently used files
Exit	Close the AQTESOLV application

Related Topics

Edit Menu

Select options in the **Edit** menu to modify the active data set.

Undo	Undo the last curve adjustment
Redo	Redo the previously undone curve adjustment
Copy	Copy plot or report to Windows clipboard
Units	Select measurement units
Annotations	Edit title, project information and end notes
Aquifer Data	Edit aquifer/aquitard data
Wells	Edit, add or delete wells
Test Type	Change the test type

Related Topics

View Menu

The **View** menu provides options for displaying 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 plots and reports.

Displacement-Time	Display displacement vs. time plot in active window
Composite	Display composite plot in active window
Residual Drawdown	Display residual drawdown plot in active window
Agarwal	Display Agarwal plot in active window
Residual-Time	Display residual vs. time plot in active window
Residual-Simulated	Display residual vs. simulated plot in active window
Normal Probability	Display normal probability plot in active window
Discharge-Time	Display discharge vs. time plot in active window
Derivative-Time	Display derivative plot in active window (Pro only)
Radial Flow	Display radial flow plot in active window (Pro only)
Linear Flow	Display linear flow plot in active window (Pro only)
Bilinear Flow	Display bilinear flow plot in active window (Pro only)
Spherical Flow	Display spherical flow plot in active window (Pro only)
Diagnostics	Display diagnostics report in active window
Report	Display complete report in active window
Error Log	Display error log in active window
Linear Axes	Display plot on linear x and y axes
Log-Linear Axes	Display plot on logarithmic x and linear y axes
Linear-Log Axes	Display plot on linear x and logarithmic y axes
Log Axes	Display plot on logarithmic x and y axes
Format	Format plot or report in active window
Options	Select options for plot or report in active window
Zoom	Select zoom factor for active window
Refresh	Refresh contents displayed in active window
Contour	Generate grid and contour plot
Toolbar	Toggle toolbar on/off
Status Bar	Toggle status bar on/off

- You also may select **plot** and **report** options from the list on the toolbar.

Related Topics

Match Menu

Choose options from the **Match** menu to select an aquifer test solution, perform visual or automatic curve matching, tweak parameters (sensitivity analysis) and edit matching options.

Solution	Choose an aquifer test solution
Automatic	Perform automatic curve matching
Visual	Perform visual curve matching
Toolbox	Open the curve matching toolbox
Check Slope	Test the slope of a range of data
Active Curves	Toggle active type curves on/off
Forward Solution	Toggle forward solution (predictive simulation) on/off

Related Topics

Tools Menu

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

Mounding	Compute transient water-table rise beneath a circular or rectangular recharge area using Hantush (1967) solution
ModelCad	Launch ModelCad for Windows application
TWODAN	Launch TWODAN application
WinSitu	Launch Win-Situ application
Customize	Customize tools and configure application settings

Windows Menu

The **Windows** menu provides options for managing windows. AQTESOLV provides a multi-document interface so you can work on more than one data set at the same time. In addition, you can open more than one window (e.g., showing different plots) for the same data set.

New Window	Open a new window for the active data set
Cascade	Cascade all windows in the application frame
Tile Horizontal	Tile all windows horizontally
Tile Vertical	Tile all windows vertically
Arrange Icons	Arrange window icons at the bottom of the application frame

Related Topics

Help Menu

Choose options from the **Help** menu to access the program's help features and find software support options.

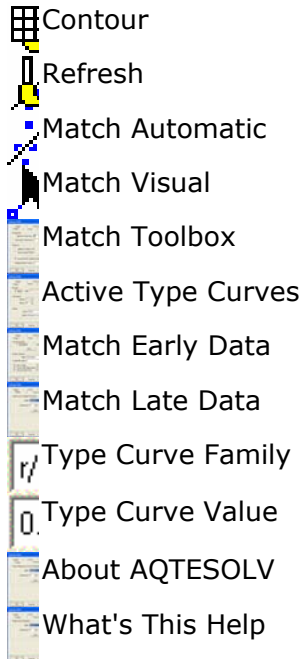| Contents and Index	Display contents of help system
Search	Search the help system
What's This	Get context-sensitive help
Quick Tips	Show/hide quick tips
Tip of the Day	Display *Tip of the Day* window
Examples	Show examples
AQTESOLV on the Web	Find more information at the AQTESOLV web site
Check for Updates	Check for software updates
Register	Register your copy of AQTESOLV
About AQTESOLV	Display program copyright and version information

Toolbar

(View > Toolbar)

Choose **Toolbar** from the **View** menu to show/hide the toolbar.

The toolbar contains buttons for the following commands:

New

Open

Save

Print

Print Preview

Undo

Redo

Aquifer Data

Wells

View

Linear Axes

Log-Linear Axes

Linear-Log Axes

Log Axes

Show Derivative

Contour

Refresh

Match Automatic

Match Visual

Match Toolbox

Active Type Curves

Match Early Data

Match Late Data

Type Curve Family

Type Curve Value

About AQTESOLV

What's This Help

- Move the mouse over a toolbar control and pause for a moment to reveal a **tooltip** that shows the button's function.

- Select plot and report options from the drop-down list of views on the toolbar.

- Change type curve families and curve values from drop-down lists on the toolbar.

Related Topics

Keyboard Shortcuts

AQTESOLV provides the following keyboard shortcuts to program features.

Ctrl-C	Copy
Ctrl-D	Superimpose derivative
Ctrl-K	Toggle cursor coordinate tracking on/off
Ctrl-N	New
Ctrl-O	Open
Ctrl-P	Print
Ctrl-S	Save
Ctrl-T	Toggle type curves on/off
Ctrl-Y	Redo
Ctrl-Z	Undo
F1	Help
Shift-F1	Context help

- Press **ESC** while AQTESOLV is refreshing a type curve to disable the display of type curves. Press **Ctrl-T** to resume type curve display.

Entering, Editing and Importing Data

Overview (Data Sets)

Begin a new analysis in AQTESOLV by creating a new data set. AQTESOLV stores a complete record of each aquifer test analysis in an AQTESOLV data set which contains the following:

- aquifer test data (e.g., aquifer geometry data, well data, pumping data and time-displacement data),

- information concerning the solution method used to analyze the test data (e.g., solution method and aquifer properties), and

- formatting parameters for plots and reports.

Learn more about working with data sets:

➡ How Do I Begin a New Analysis (Creating New Data Sets)?

1. Create a new data set by choosing File>New.

2. Use the Pumping Test Wizard, Constant-Head Test Wizard, Slug Test Wizard to enter test data. These wizards also help you to import data logger files.

3. Use the Forward Solution Wizard to create a data set and predict the response in a pumping test (test design).

4. Use the AQTESOLV for DOS Import Wizard to import a data set created with a DOS version of AQTESOLV.

5. Instead of using a wizard to create a new data set, you also may select the **Default** option when you choose File>New. Choose options from the Edit menu to enter your test data.

➡ How Do I Open an Old Analysis (Opening Data Sets)?

1. Open a file containing an AQTESOLV data set by choosing File>Open. The default file name extension for an AQTESOLV data set is **.aqt**.

2. Select options from the Edit menu to modify the data set.

➡ How Do I Change My Analysis (Editing Data Sets)?

1. Choose options from the Edit menu to modify a data set.

2. Select View>Format to edit the appearance of a plot or report.

3. Choose Match>Solution to select an aquifer test solution.

4. To change aquifer properties for the active solution, choose Match>Toolbox.

➡ How Do I Save My Analysis (Saving Data Sets)?

1. Save the active data set using the current file name by choosing File>Save.

2. To save the active data set with a new file name, choose File>Save As.

3. The file name extension for AQTESOLV data sets is **.aqt**.

- By default, AQTESOLV data sets have an **.aqt** file name extension.

Data Entry Wizards

Pumping Test Wizard

The easiest way to enter data from a pumping test is to use the **Pumping Test Wizard**.

Using the Pumping Test Wizard

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

2. In the **New Data Set** dialog, select **Pumping Test Wizard** from the list to help you create a new data set for a typical pumping test. Click **OK**.

3. Configure the wizard for a **Multiwell Test** or **Single-Well Test**. Click **OK**.

4. Click **Help** in the wizard to get context-sensitive help.

5. Follow the steps in the wizard to enter pumping test data including measurement units, aquifer data, well locations and construction details, pumping rates and water-level observations.

6. In the **Pumping Rates** step of the wizard, click **Import** to import time-rate data from a file or enter rates directly into the spreadsheet.

7. In the **Observations** step of the wizard, click **Import** to import time-displacement data from a data logger file or enter observations directly into the spreadsheet.

8. Click **Finish** at the end of the wizard.

- After completing the **Pumping Test Wizard**, modify a data set using options in the Edit menu.

- Avoid repetitive data entry and save time by using an existing data set as a template for a new test.

  For example, if you conduct multiple pumping tests in a single well, you can use the data set for the first test as a template for the successive tests.

- Choose File>Open to open an existing data set file. Choose options from the Edit menu to modify test data. Choose File>Save As to save the modified data set in a new file.

Related Topics

Constant-Head Test Wizard

The easiest way to enter data from a constant-head test is to use the **Constant-Head Test Wizard**.

Using the Constant-Head Test Wizard

1. Choose New from the **File** menu.
2. In the **New Data Set** dialog, select **Constant-Head Test Wizard** from the list to help you create a new data set for a typical constant-head test. Click **OK**.
3. Click **Help** in the wizard to get context-sensitive help.
4. Follow the steps in the wizard to enter constant-head test data including measurement units, aquifer data, well locations and construction details, pumping rates and water-level observations.
5. In the **Pumping Rates** step of the wizard, click Import to import time-rate data from a file or enter rates directly into the spreadsheet.
6. In the **Observations** step of the wizard, click Import to import time-displacement data from a data logger file or enter observations directly into the spreadsheet.
7. Click **Finish** at the end of the wizard.

- After completing the **Constant-Head Test Wizard**, modify the data set using options in the Edit menu.

- Avoid repetitive data entry and save time by using an existing data set as a template for a new test.

   For example, if you conduct multiple tests in a single well, you can use the data set for the first test as a template for the successive tests.

- Choose File>Open to open an existing data set file. Choose options from the Edit menu to modify test data. Choose File>Save As to save the modified data set in a new file.

Related Topics

Slug Test Wizard

The easiest way to enter data from a slug test is to use the **Slug Test Wizard**.

Using the Slug Test Wizard

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

2. In the **New Data Set** dialog, select **Slug Test Wizard** from the list to help you create a new data set for a typical slug test. Click **OK**.

3. Click **Help** in the wizard to get context-sensitive help.

4. Follow the steps in the wizard to enter slug test data including measurement units, aquifer data, well locations and construction details and water-level observations.

5. In the **Observations** step of the wizard, click **Import** to import time-displacement data from a data logger file or enter observations directly into the spreadsheet.

6. Click **Finish** at the end of the wizard.

- After completing the **Slug Test Wizard**, modify a data set using options in the Edit menu.

- Avoid repetitive data entry and save time by using an existing data set as a template for a new test.

  For example, if you conduct multiple slug tests in a single well, you can use the data set for the first test as a template for the successive tests.

- Choose File>Open to open an existing data set file. Choose options from the Edit menu to modify test data. Choose File>Save As to save the modified data set in a new file.

Related Topics

Forward Solution Wizard

Use the **Forward Solution Wizard** to perform predictive simulations for a pumping test.

Using the Forward Solution Wizard

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

2. In the **New Data Set** dialog, select **Forward Solution Wizard** from the list to help you create a new data set for predictive simulation. Click **OK**.

3. Configure the wizard for a **Multiwell Test** or **Single-Well Test**. Click **OK**.

4. Click **Help** in the wizard to get context-sensitive help.

5. Follow the steps in the wizard to enter test data including measurement units, aquifer data, well locations and construction details and pumping rates.

6. In the **Pumping Rates** step of the wizard, click **Import** to import time-rate data from a file or enter rates directly into the spreadsheet.

7. In the **Forward Solution Data** step of the wizard, enter the range of time for the simulation and estimates of transmissivity and storage coefficient for the aquifer. You can change these estimates later by choosing Match>Toolbox.

8. Click **Finish** at the end of the wizard.

- After completing the **Forward Solution Wizard**, modify a data set using options in the Edit menu.

- Choose Match>Forward Solution to perform predictive simulations with any complete data set.

AQTESOLV for DOS Import Wizard

Choose New from the **File** menu and select **Import AQTESOLV for DOS Wizard** from the **New Data Set** dialog to import an AQTESOLV for DOS data set.

Using the AQTESOLV for DOS Import Wizard

1. Click **Browse** to select a file containing an AQTESOLV for DOS data set to import.

2. Click **Finish** to import the data set.

- After importing an AQTESOLV for DOS data set, you should review the imported data to ensure its completeness using options in the Edit menu. Many new features and data options have been added to AQTESOLV since the release of DOS versions of the software.

- Check **Convert all data sets with .DAT extension in this folder** if you want to convert all AQTESOLV for DOS data sets (with a .DAT extension) into AQTESOLV for Windows data sets (with a .AQT extension) in the folder you have selected.

Related Topics

Editing Data

Editing Test Data

Choose from the following options in the **Edit** menu to enter data into a new data set or modify an existing one.

Units	Select measurement units for the data set
Annotations	Edit the title, project information and end notes for the data set
Aquifer Data	Edit aquifer data
Wells	Edit well data

- Avoid repetitive data entry and save time by using an existing data set as a **template** for a new test.

   For example, if you conduct repeated tests in a single well, you can use the data set for the first test as a template for the successive tests.

- Choose File>Open to open an existing data set file. Choose options from the Edit menu to modify test data. Choose File>Save As to save the modified data set in a new file.

- Choose File>New, select **Default** to create an empty data set, and click **OK**. Choose options from the Edit menu to enter test data. Choose File>Save As to save the new data set.

Importing Data

Overview (Importing Data)

AQTESOLV provides easy-to-use wizards that **import aquifer test data** from external files. When convenient, you also may **copy and paste data** from another application (e.g., Excel) directly into AQTESOLV.

o   Import observation data from data logger files using the Observation Data Import Wizard.

   In some cases, you may find it easier to copy and paste observation data directly from another application into AQTESOLV (e.g., if your data are stored in a spreadsheet such as Excel).

o   Import files containing pumping rate data using the Pumping Rate Data Import Wizard. You also may copy and paste pumping rate data into AQTESOLV.

- Before you import observation or rate data, choose File>New to create a new data set. Select a data set wizard which will assist you with importing data.

- To import observation or rate data into the active data set, choose Edit>Wells to modify well data.

Observation Data Import Wizard

(Edit > Wells > [Modify >] Observations > Import)

Import time and displacement data for a well with the **Observation Data Import Wizard**, a versatile and flexible tool for importing measurements from a file. The wizard works seamlessly with many types of data loggers including In-Situ and Solinst products.

Before you begin importing a data logger file, ascertain the following basic information about the contents of the file:

- Identify the **structure of the file** (number of data columns in the file and order of the columns containing elapsed time and displacement data).

- Note the **static transducer reading** prior to the start of the test (you may need to subtract this value from each imported reading to convert values from depth to water or water column height above the transducer to displacement).

Using the Import Wizard

1. Choose **Wells** from the **Edit** menu, select a well from the list and click **Modify**.

2. In the **Observations** tab, click **Import**.

3. Follow the steps in the wizard: open the import file, identify the file structure and specify transformation and filter operations.

- If no data set is open and the **Edit** menu is not available, create a new data set or open an existing data set.

Related Topics

Pumping Rate Data Import Wizard

(Edit > Wells > [Modify >] Rates > Import)

Import time and displacement data for a well with the **Pumping Rate Data Import Wizard**, a versatile and flexible tool for importing rate measurements from a file.

Using the Import Wizard

1. Choose **Wells** from the **Edit** menu, select a well from the list and click **Modify**.

2. In the **Rates** tab, click **Import**.

3. Follow the steps in the wizard: open the import file, identify the file structure and specify transformation and filter operations.

- If no data set is open and the **Edit** menu is not available, create a new data set or open an existing data set.

Related Topics

Viewing Data

Plots

Overview (Plots)

The **View** menu provides options for plotting data, solutions and estimation results. Other options in the **View** menu allow you to customize the appearance of a plot.

➡ Data Plots

- Plots for viewing aquifer test (displacement) data and matching analytical solutions include displacement-time, composite, residual drawdown and derivative-time plots.

- AQTESOLV also provides discharge-time plots to view the discharge rate history from variable-rate pumping tests.

➡ Diagnostic Flow Plots

- The radial flow, linear flow, bilinear flow and spherical flow plots help you to choose appropriate models for your data set.

- Use diagnostic flow plots to identify behavior produced by wellbore storage, fracture flow and double-porosity phenomena.

- Derivative plots also provide an important diagnostic tool.

➡ Residual Plots

- Use the residual-time, residual-simulated and normal probability plots to examine residuals (i.e., errors between simulated and observed values of displacement)   from visual or automatic curve matching.

- Use residual plots to evaluate how well a solution (type curve) matches your test data.

➡ Customizing Plots

- Format plots to customize axes, labels and curve styles.

- Select plot options to edit items to display on plots, type curve families, derivative options and more.

Related Topics

Data Plots

Displacement-Time Plot

(View > Displacement-Time)

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

➡️ Example: Pumping Test in Unconfined Aquifer (with Derivative)
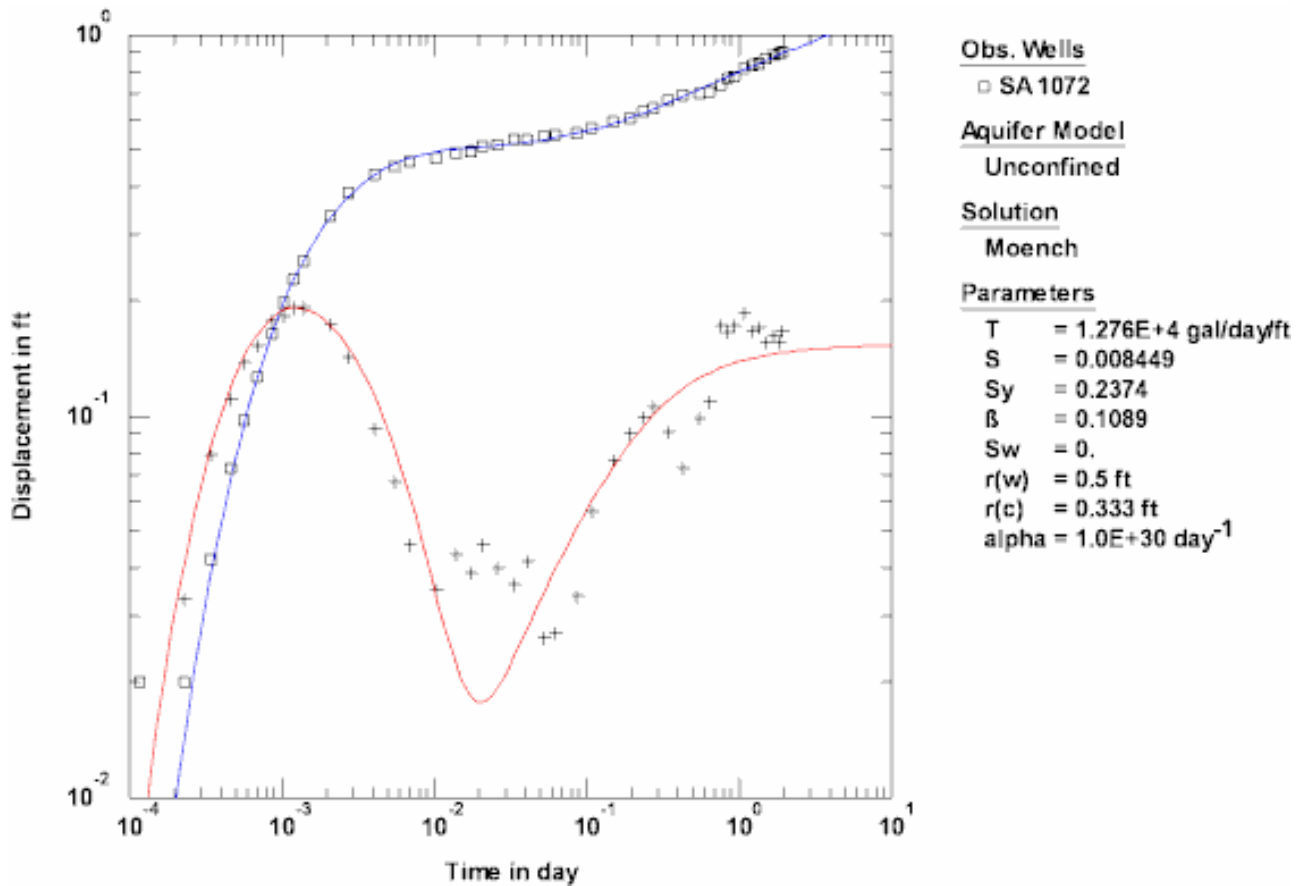
➡️ Example: Slug Test in Confined Aquifer (Multiwell)

Multi-Well Slug Test

Obs. Wells
- Ln-2
- Ln-3

Aquifer Model
Confined

Solution
KGS Model

Parameters
Kr   = 1.166 m/day
Ss   = 9.369E-6 m^{-1}
Kz/Kr = 1.
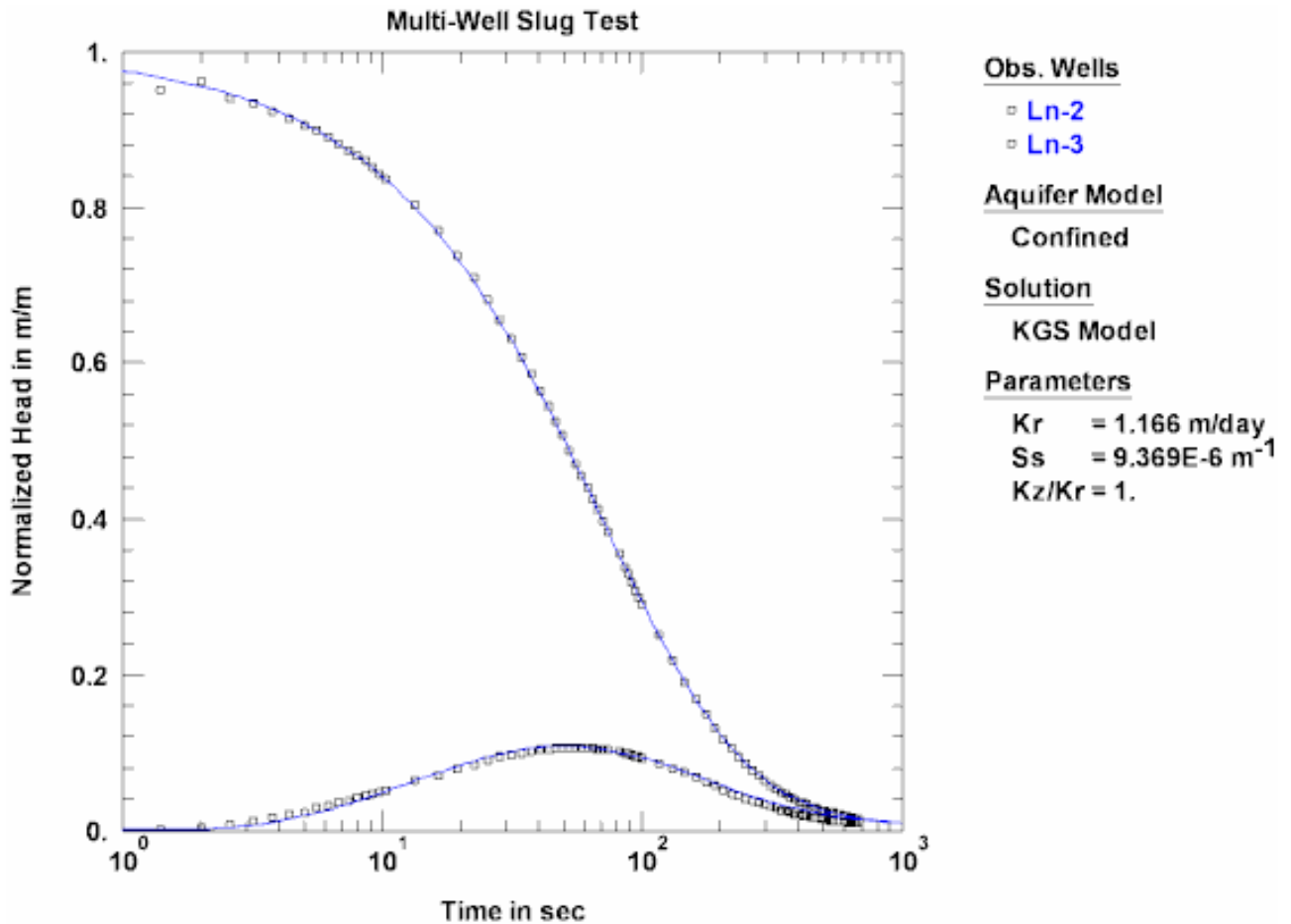
- The displacement-time plot allows you to analyze displacement data from one or more observation wells.

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

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

- Choose Options from the **View** menu and select **Family of Type Curves** to superimpose a type curve family on the plot.

- Choose Options from the **View** menu and select **Derivative Curves** to display displacement and derivative data on a single plot.

- Choose Options from the **View** menu and select **Theis Type Curves** to superimpose the Theis solution on the plot.

- Choose Options from the **View** menu and select **Recommended Head Ranges** to display head ranges recommended by Butler (1998) for the analysis of slug tests.

Related Topics

Composite Plot

(View > Composite)

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).

➡️ Example: Pumping Test in Confined Aquifer (with Derivative)

➡️ Example: Pumping Test in Double-Porosity Aquifer (with Derivative)

Obs. Wells
- UE25b#1
- UE25a#1

Aquifer Model
Fractured

Solution
Moench w/slab blocks

Parameters
$K = 1.084E\text{-}5$ m/sec
$Ss = 1.705E\text{-}6$ m^{-1}
$K' = 1.751E\text{-}6$ m/sec
$Ss' = 0.000548$ m^{-1}
$Sw = 0.$
$Sf = 0.7803$
$r(w) = 0.11$ m
$r(c) = 0.11$ m
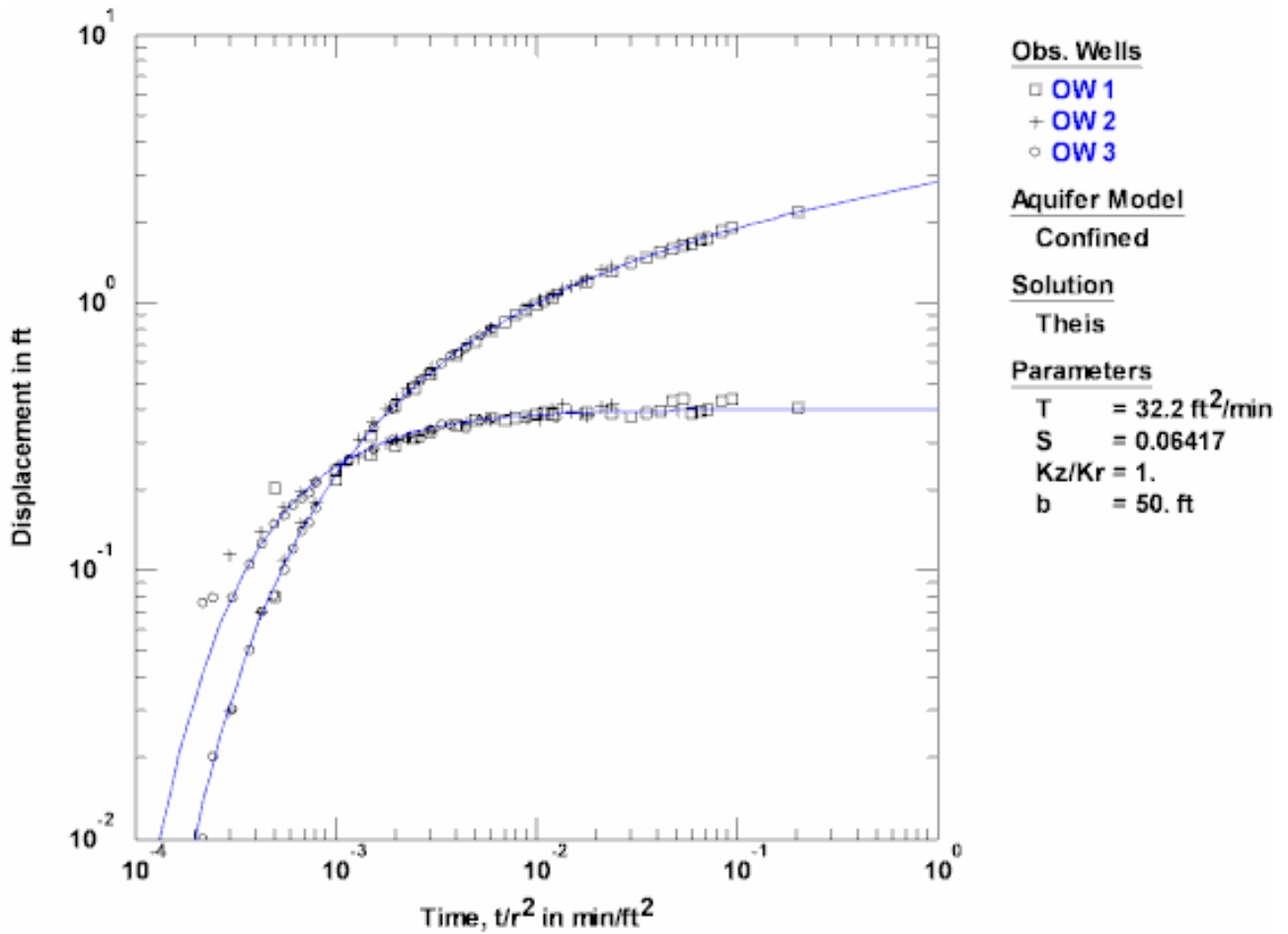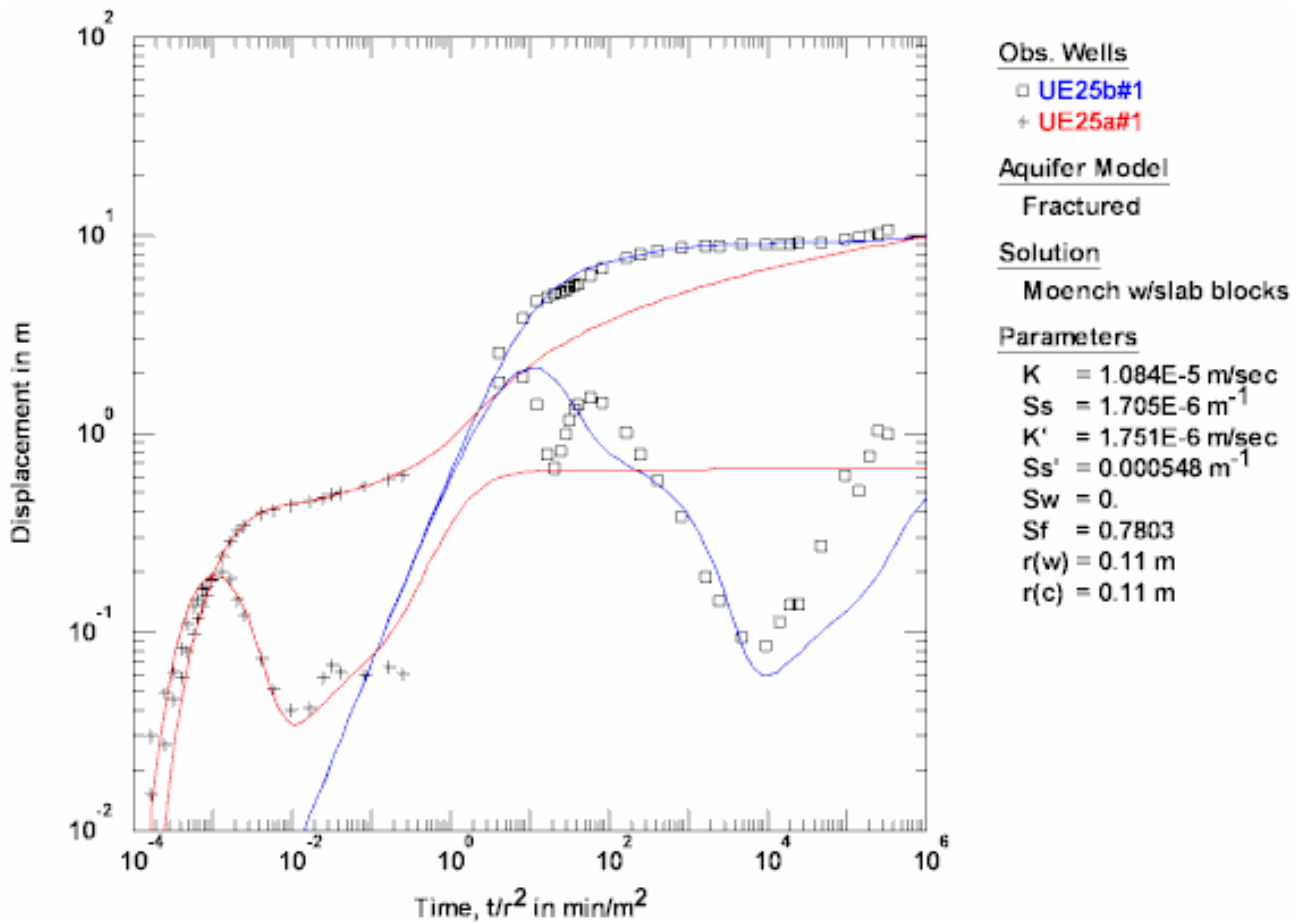
- The composite plot allows you to analyze displacement data from one or more observation wells.

- 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.

Related Topics

Residual Drawdown Plot

(View > Residual Drawdown)

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

➡️ Example: Pumping Test in Confined Aquifer
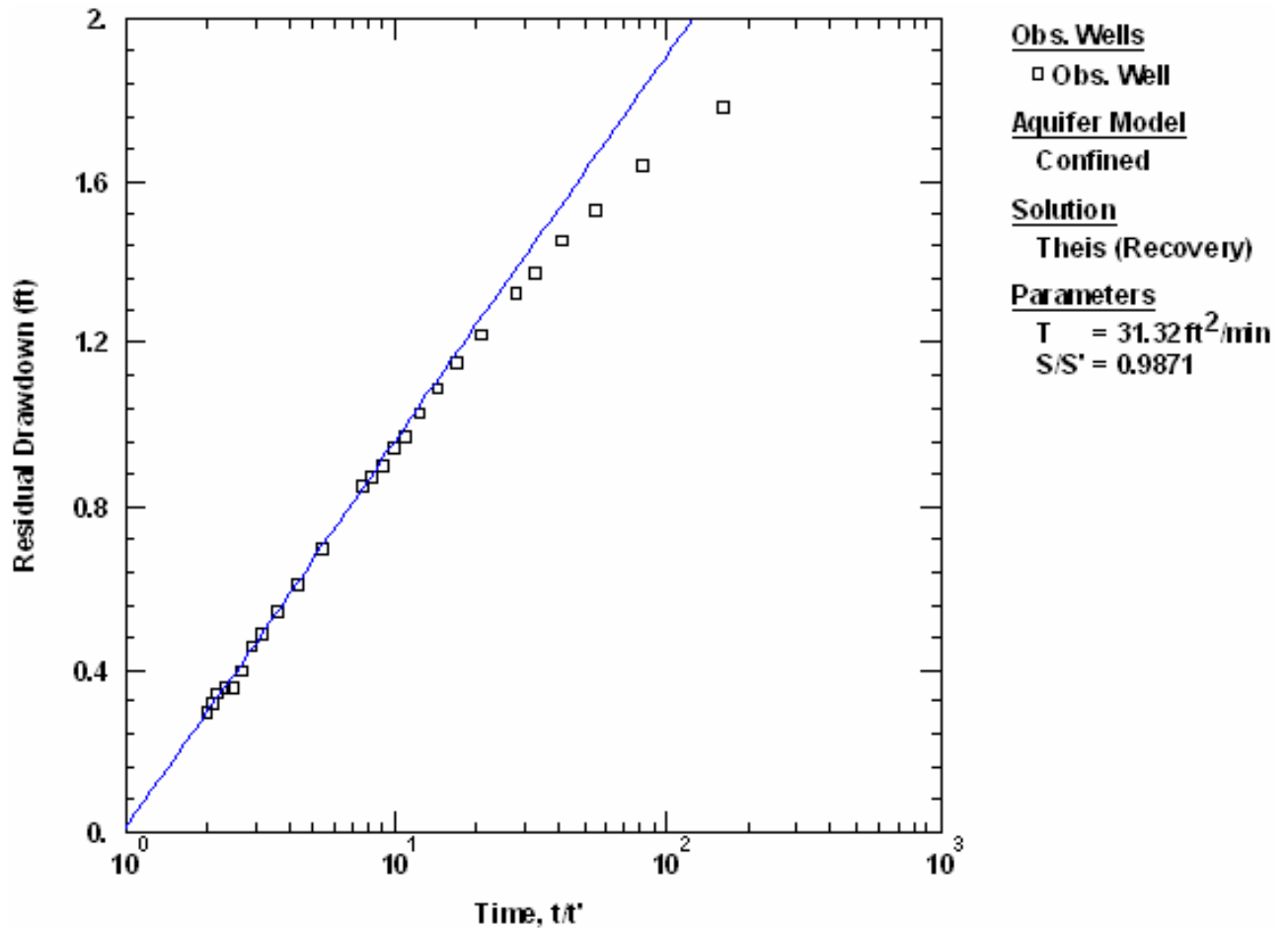
➡️ Example: Constant-Head Test in Leaky Confined Aquifer
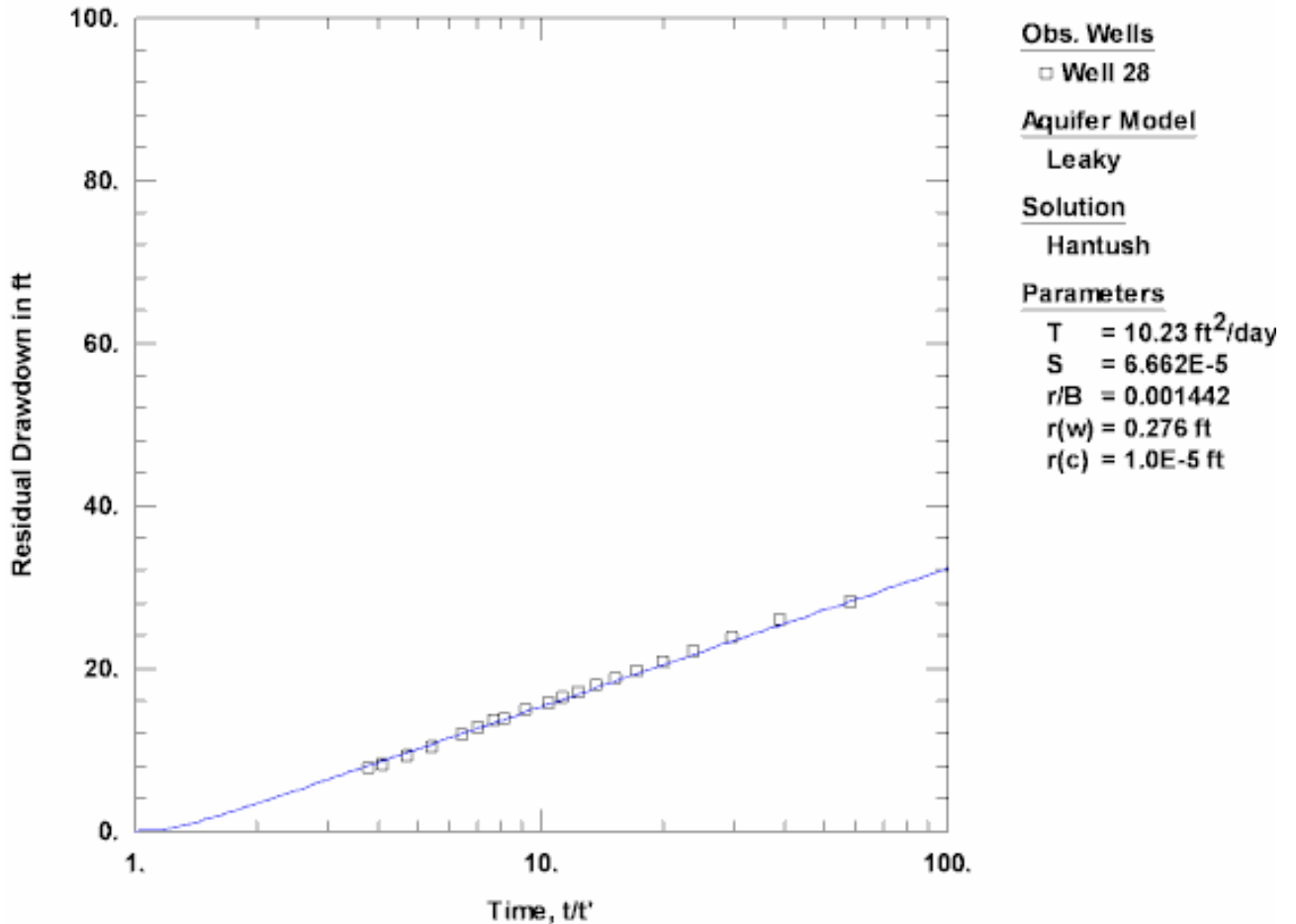
In the petroleum industry, the residual drawdown plot is known as a **Horner plot**.

- A 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 data set includes only one pumping well and the observation 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. Assuming an infinite aquifer, the residual drawdown approaches zero (the pre-pumping or static condition) as the time of recovery increases; hence, the recovery data plot closer to the origin of the residual drawdown plot where t/t' = 1. If the aquifer is bounded or the pre-pumping condition is not static, the residual drawdown will approach a nonzero value as t/t' approaches 1.

- Choose Visual or Toolbox>Tweak from the **Match** menu to match a solution

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to the recovery data.

- Choose Automatic from the **Match** menu to perform automatic estimation for the recovery data.

Related Topics

Agarwal

(View > Agarwal)

Choose **Agarwal** from the **View** menu to plot recovery data as a function of Agarwal equivalent time in the active window.

➡ Example: Recovery Test in Confined Aquifer (with Derivative)
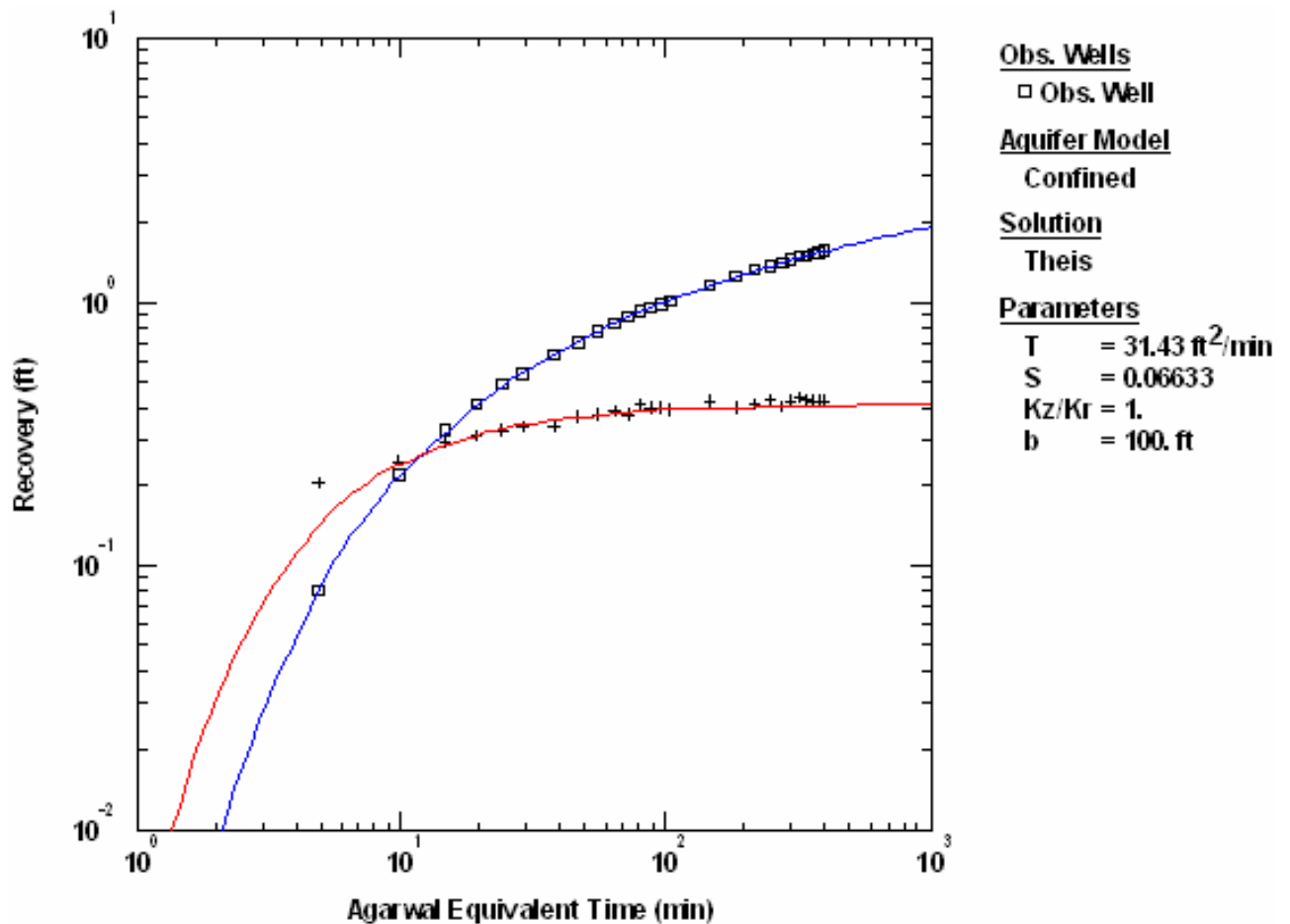
Through a simple transformation of the time variable, Agarwal (1980) devised a procedure that uses solutions developed for drawdown analysis (e.g., the Theis type curve) to analyze recovery data.

- For a **constant-rate test**, Agarwal equivalent time, t_{equiv}, is defined as

$$t_{equiv} = \frac{t_p \cdot t'}{t_p + t'}$$

where t is the elapsed time since pumping began [T], t' is time since pumping stopped [T] and t_p is the total time of pumping [T].

- For a **multi-rate test** consisting of n steps, Agarwal equivalent time is given as follows

$$t_{equiv} = \left[\prod_{j=1}^{n-1} \left(\frac{t_{n-1} - t_{j-1}}{t' + t_{n-1} - t_{j-1}} \right)^{\frac{q_j - q_{j-1}}{q_{n-1} - q_n}} \right] t'$$

where $t_0 = 0$, q is pumping rate [L^3/T], $q_0 = 0$ and $n > 1$.

- Recovery, s_{recov}, is defined as

$$S_{recov} = S_p - S'$$

where s' is residual drawdown in the well at times after pumping stopped [L] and s_p is the drawdown in the well at time t_p [L].

- The Agarwal method assumes that the total time of pumping is larger than the time since pumping stopped ($t_p > t'$).

- The Agarwal plot allows you to analyze recovery data from one or more wells.

- Agarwal plots show one type curve for each well.

- Use of the Agarwal method is limited to tests with one pumping well.

For **constant-head tests**, Uraiet and Raghavan (1980) proposed an approximate method for the analysis of recovery data based on the Agarwal procedure. Their procedure uses the last rate measured prior to recovery and computes Agarwal equivalent time with the constant-rate formula; however, because rates are variable during a constant-head test, AQTESOLV also provides an option to compute Agarwal equivalent time using the multi-rate formula.

- To apply the Agarwal recovery method, your observation data must have a drawdown measurement at t_p, the time when the pump was shut off, to allow computation of s_{recov}.

- Choose Visual or Toolbox>Tweak from the **Match** menu to match a solution to the recovery data.

- Choose Automatic from the **Match** menu to perform automatic estimation for the recovery data.

- Choose View>Options and select **Family of Type Curves** to superimpose a type curve family on the plot.

- Choose View>Options and select **Derivative Curves** to display displacement

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and derivative data on a single plot.

- Choose View>Options and select **Theis Type Curves** to superimpose the Theis solution on the plot.
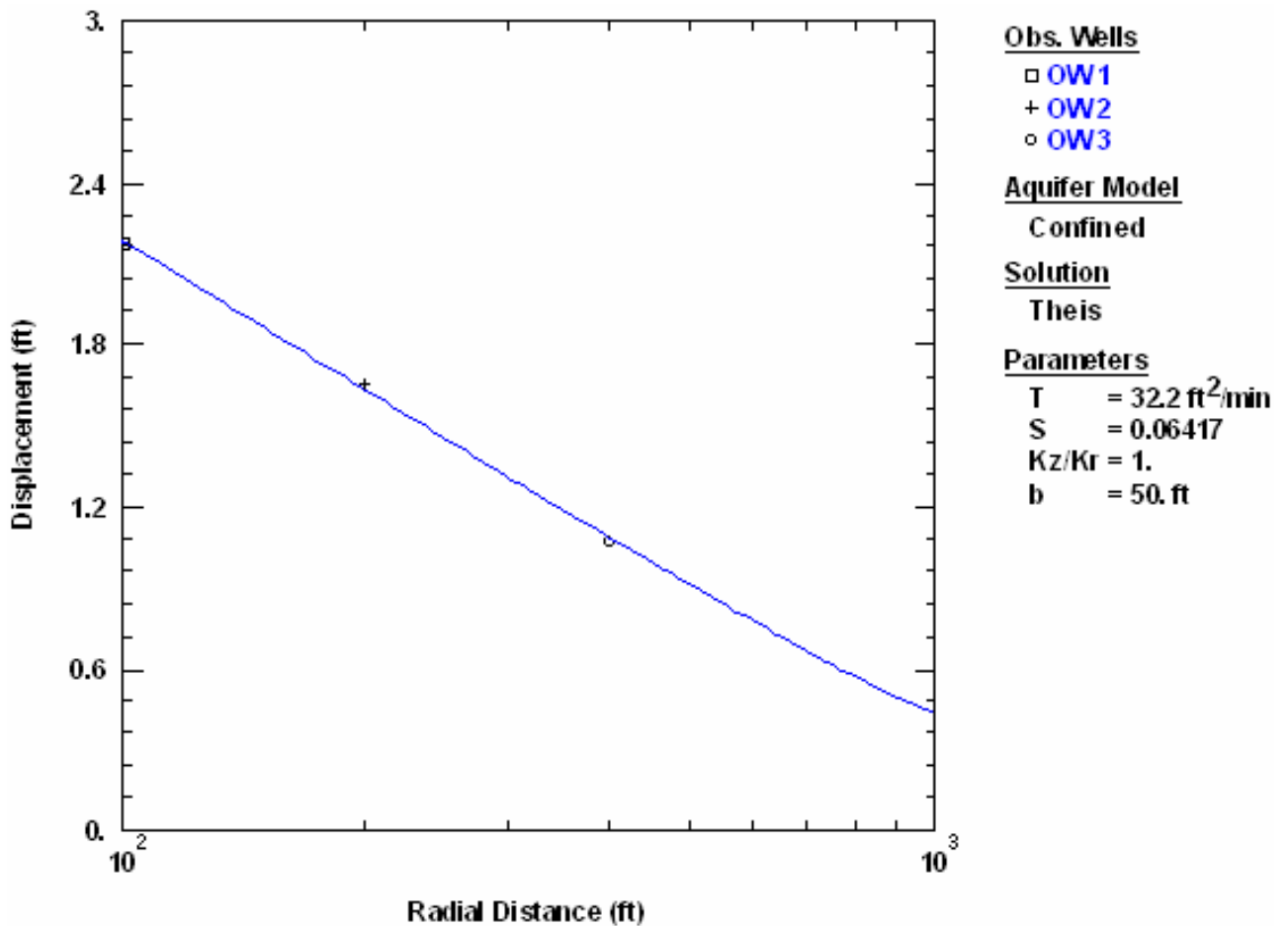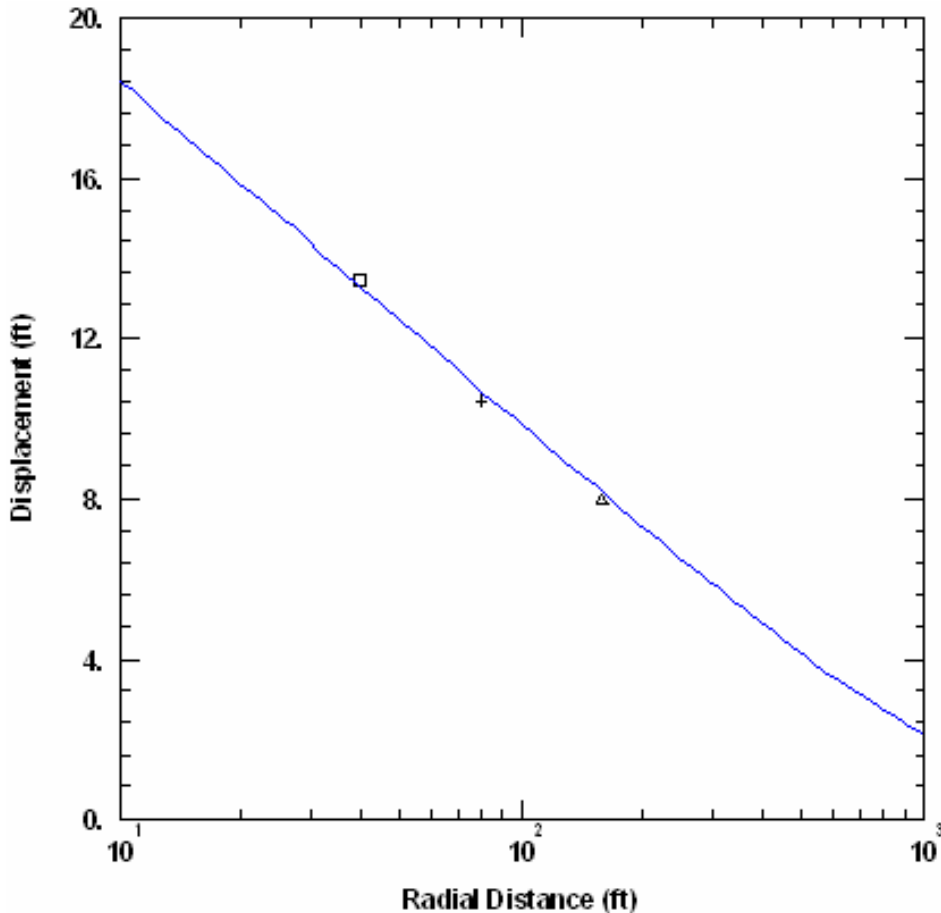
Related Topics

Distance Drawdown Plot

(View > Distance Drawdown)

Choose **Distance Drawdown** from the **View** menu to plot values of displacement as a function of observation well distance in the active window.

➡ Example: Pumping Test in Confined Aquifer

Obs. Wells
□ OW1
+ OW2
○ OW3

Aquifer Model
Confined

Solution
Theis

Parameters
T   = 32.2 ft^2/min
S   = 0.06417
Kz/Kr = 1.
b   = 50. ft

➡ Example: Pumping Test in Leaky Confined Aquifer

Obs. Wells
□ OW1
+ OW2
△ OW3

Aquifer Model
Leaky

Solution
Hantush-Jacob

Parameters
$T = 25.6\,\text{ft}^2/\text{min}$
$S = 0.003237$
$1/B = 0.0007852\,\text{ft}^{-1}$
$Kz/Kr = 1.$
$b = 50.\,\text{ft}$

- The distance-drawdown plot allows you to analyze displacement data from one or more observation wells.

- AQTESOLV automatically interpolates or extrapolates a value of drawdown when a well does not contain an observation at the time specified for the distance-drawdown plot.

TIPS

- Choose Match>Automatic to perform automatic curve matching.

- Choose Match>Toolbox to perform visual curve matching using parameter tweaking.

- Choose View>Option>Distance to enter the time for distance-drawdown plots.

- AQTESOLV draws a curve on a distance-drawdown plot for each observation well in the data set. Each curve may vary according to well construction (e.g., partial penetration) and radial direction from the pumped well. For the pumped well, the distance-drawdown curve is drawn along the x-coordinate axis. For radially symmetric problems and observation wells having identical construction, all curves will overlay each other.

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Derivative-Time Plot

(View > Derivative-Time)

Choose **Derivative-Time** from the **View** menu to perform derivative analysis by displaying the derivative of displacement data as a function of logarithmic time:

$$\frac{\partial s}{\partial \ln t} \ vs \ t$$

If a solution is active, AQTESOLV also plots the derivative curve for the solution.

➡ Example: Pumping Test in Unconfined Aquifer with 3D Saturated/Unsaturated Flow
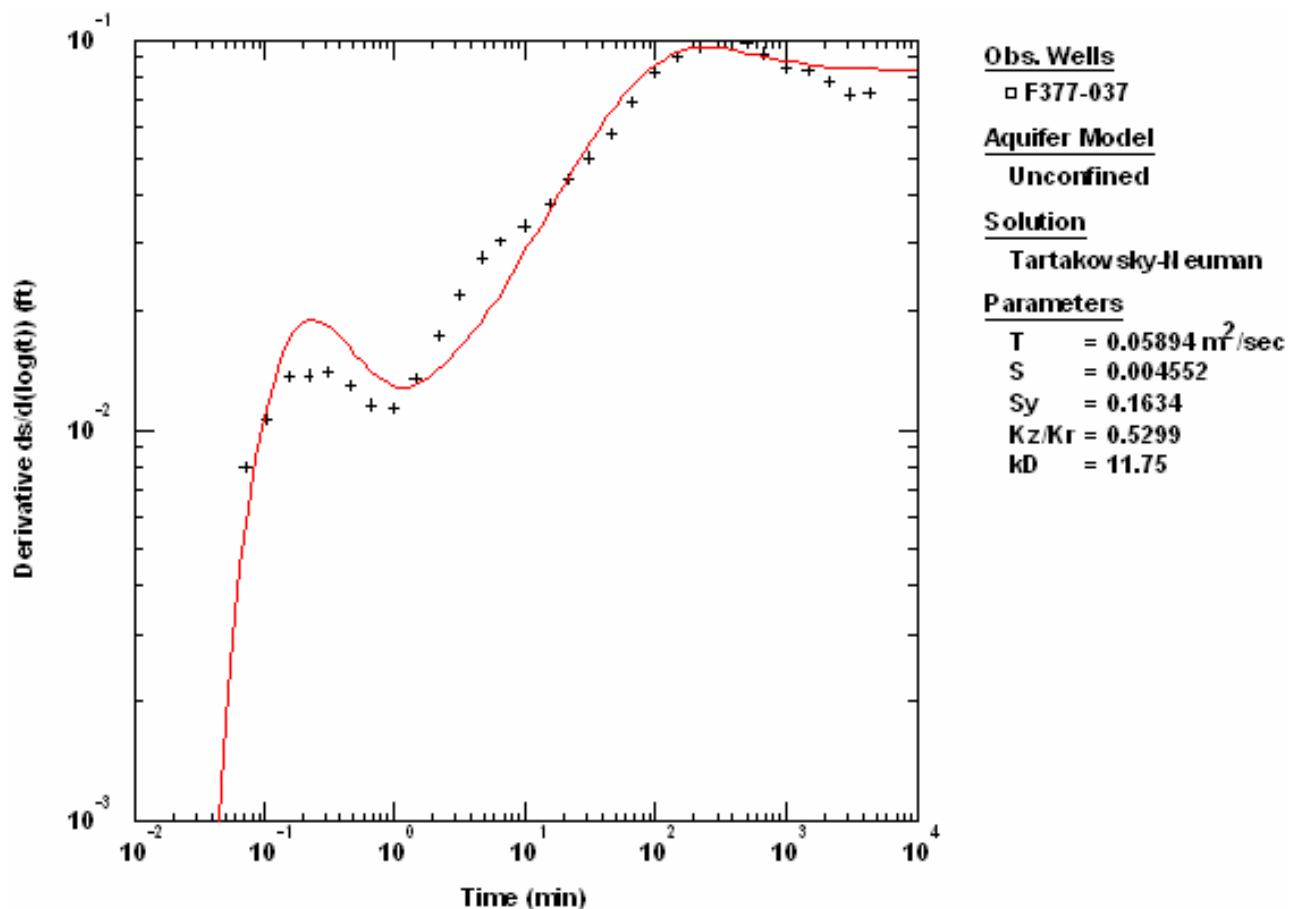
- A derivative-time plot allows you to view the derivative of displacement measurements from one or more observation wells.

- 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.

- Choose Options from the **View** menu to superimpose derivative data on displacement plots.

- Choose Options from the **View** menu to select a method for calculating derivatives from displacement data.

Related Topics

Discharge-Time Plot

(View > Discharge-Time)

Choose **Discharge-Time** from the **View** menu to view pumping well discharge rates from a variable-rate pumping test or constant-head test.

Example: Variable-Rate History for Pumping Test

Example: Constant-Head Test in a Confined Aquifer

Pumping Wells
▫ Well 28

Aquifer Model
Confined

Solution
Jacob-Lohman

Parameters
T = 11.08 ft^2/day
S = 3.229E-5
r(w) = 0.276 ft
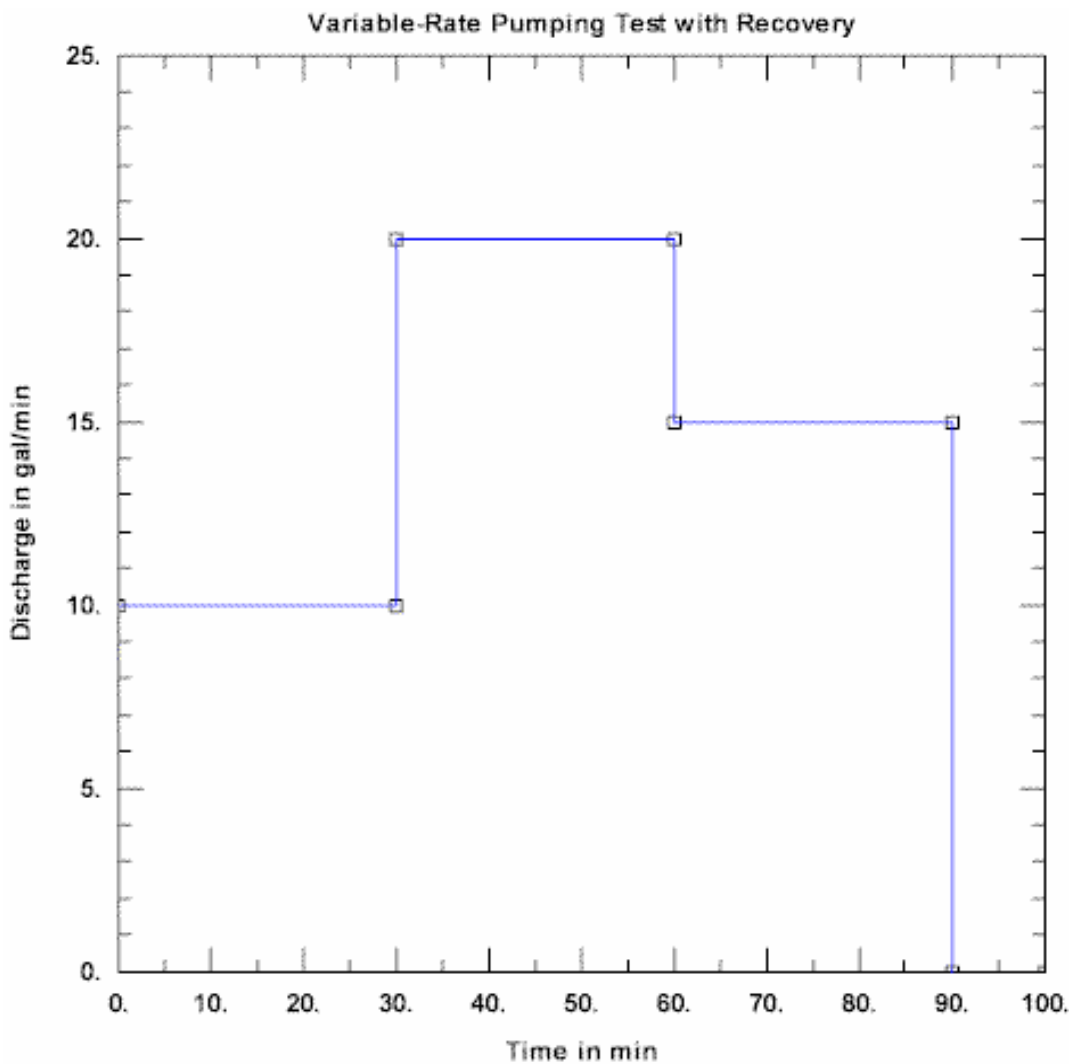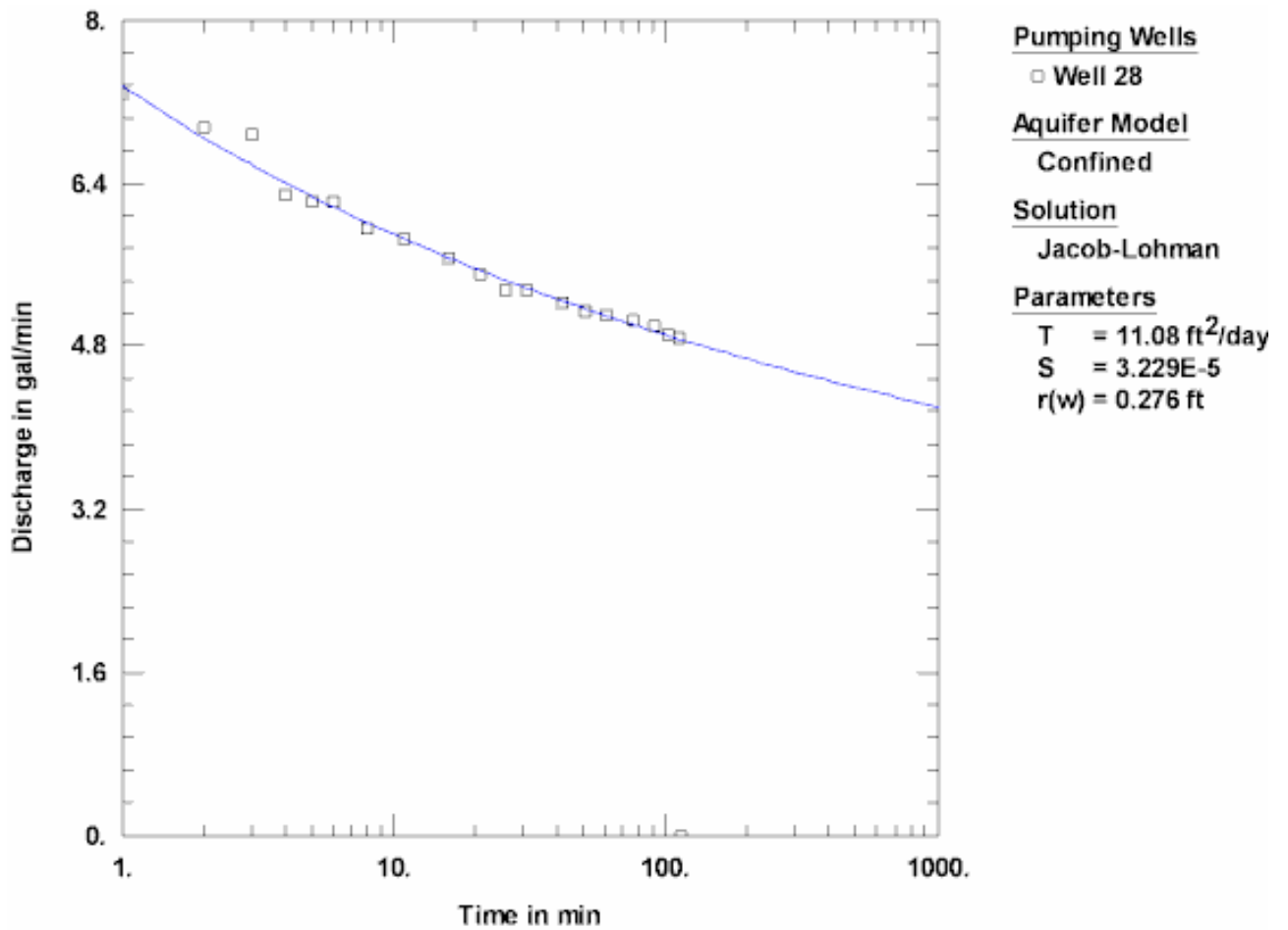
- The discharge-time view option allows you to view constant or variable pumping rates for one or more pumping wells.

- Discharge-time plots are active for pumping tests and constant-head tests.

Related Topics

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Diagnostic Flow Plots

Radial Flow Plot

(View > Radial Flow)

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

➡ Radial Flow Schematic in Plan View
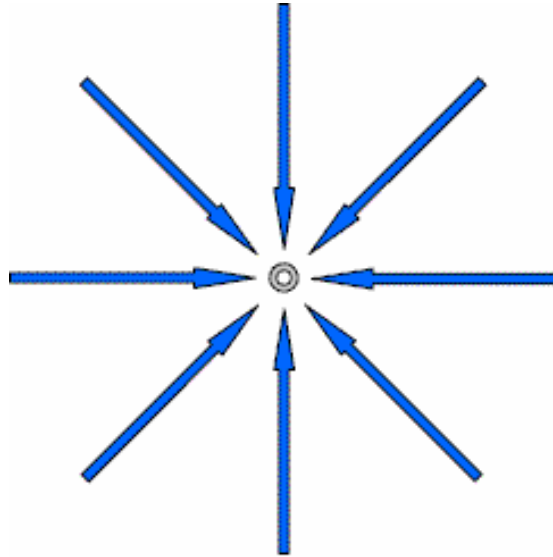
Radial flow to a discharging well.

- 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.

- On log-log axes, **early-time data** exhibiting a unit slope on a radial flow plot are indicative of **wellbore storage**.

- View one or more observation wells on radial flow plots.

➡ Example: Wellbore Storage
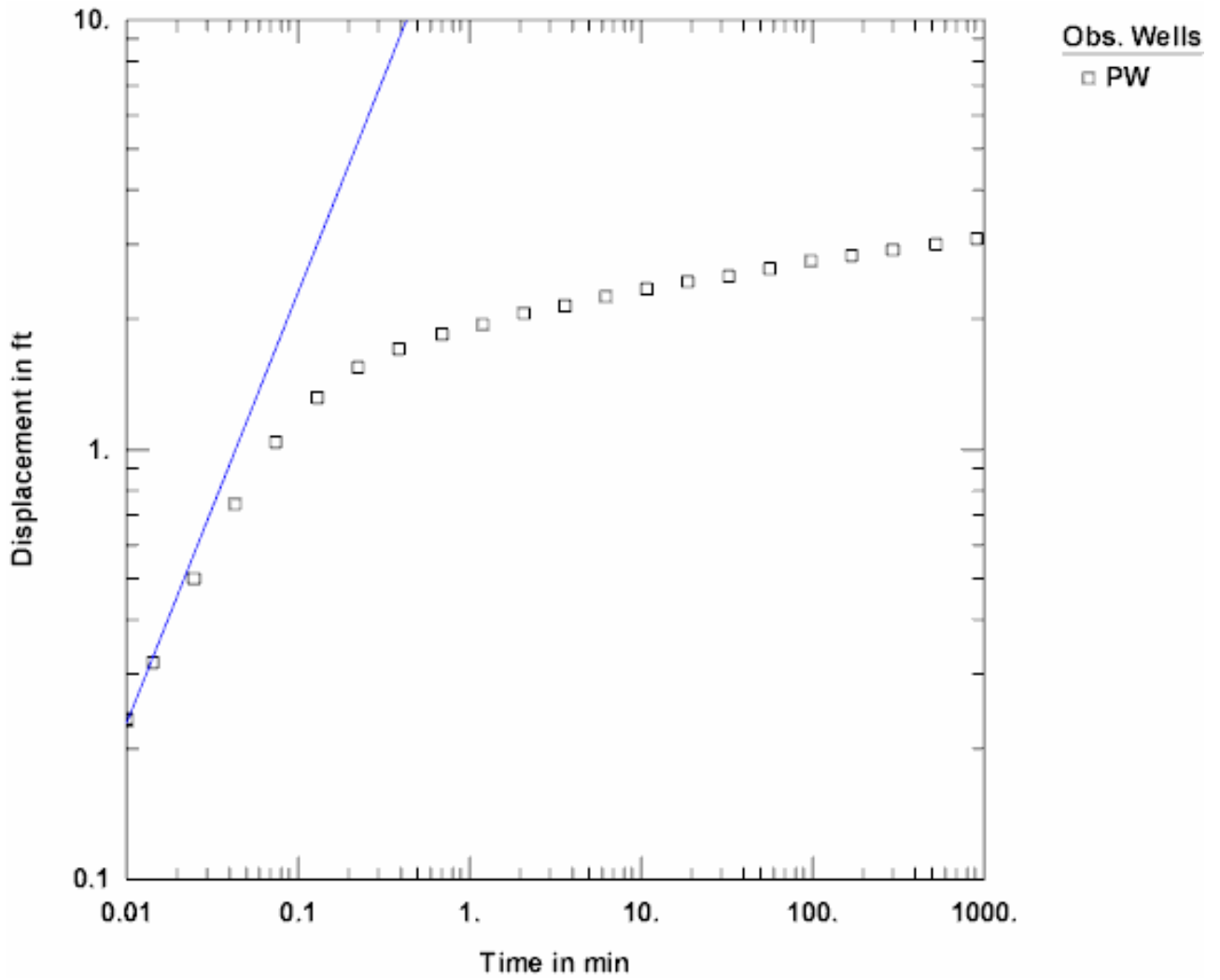
Example: Infinite-Acting Aquifer
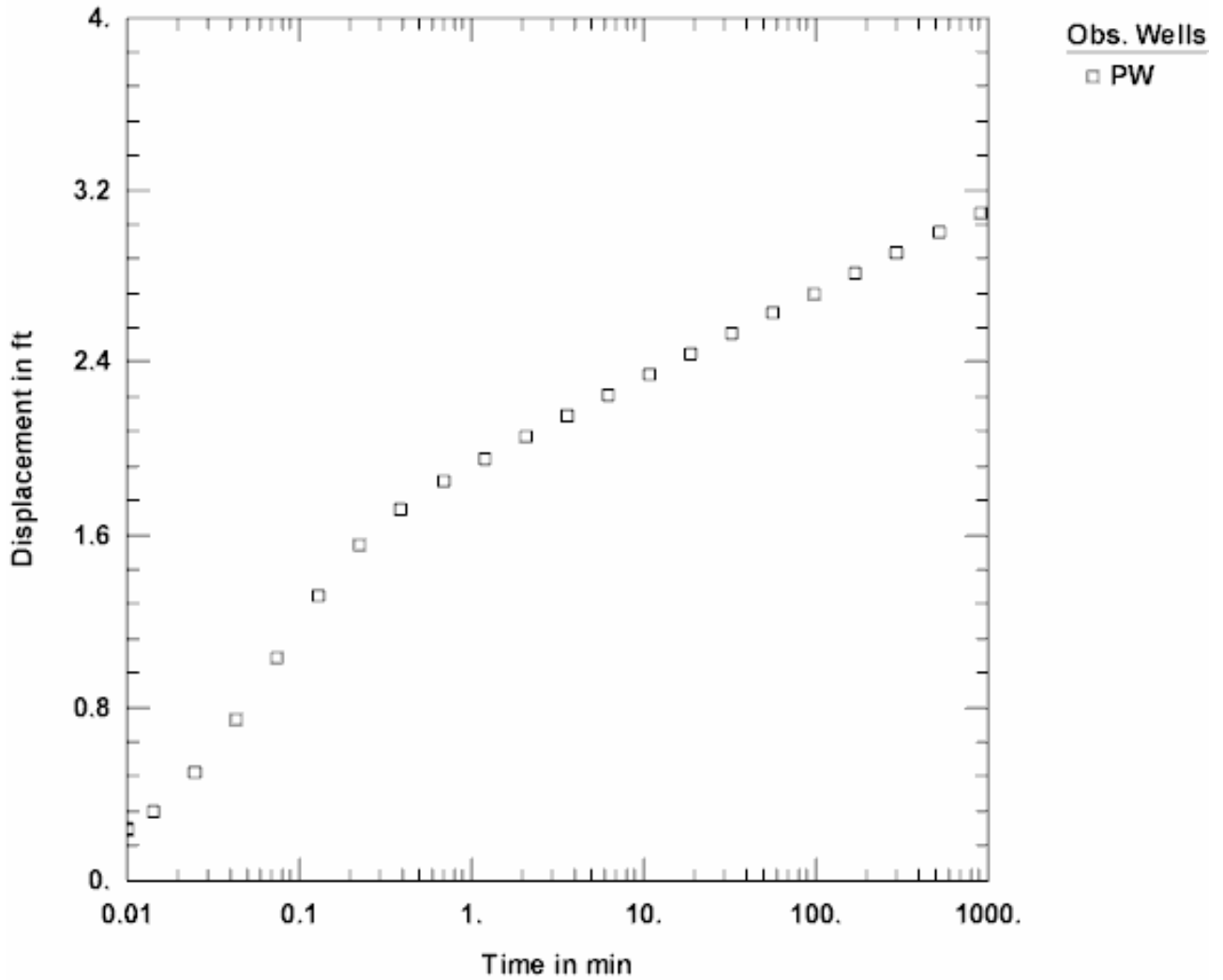
- Choose Visual from the **Match** menu to match a line with unit slope to data plotted on a radial flow plot with log-log axes.
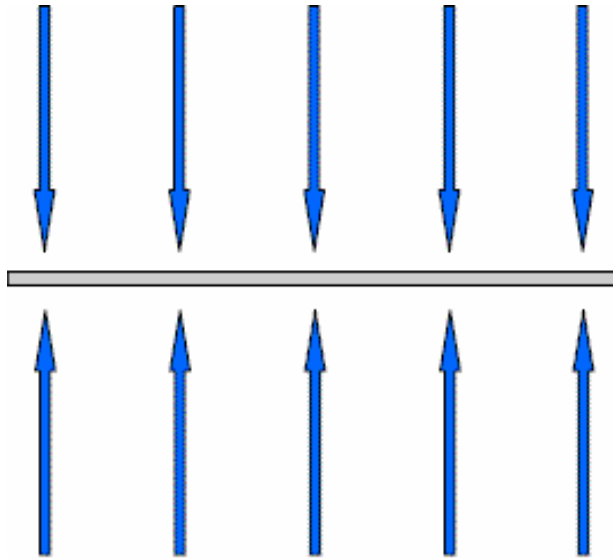
Related Topics

Linear Flow Plot

(View > Linear Flow)

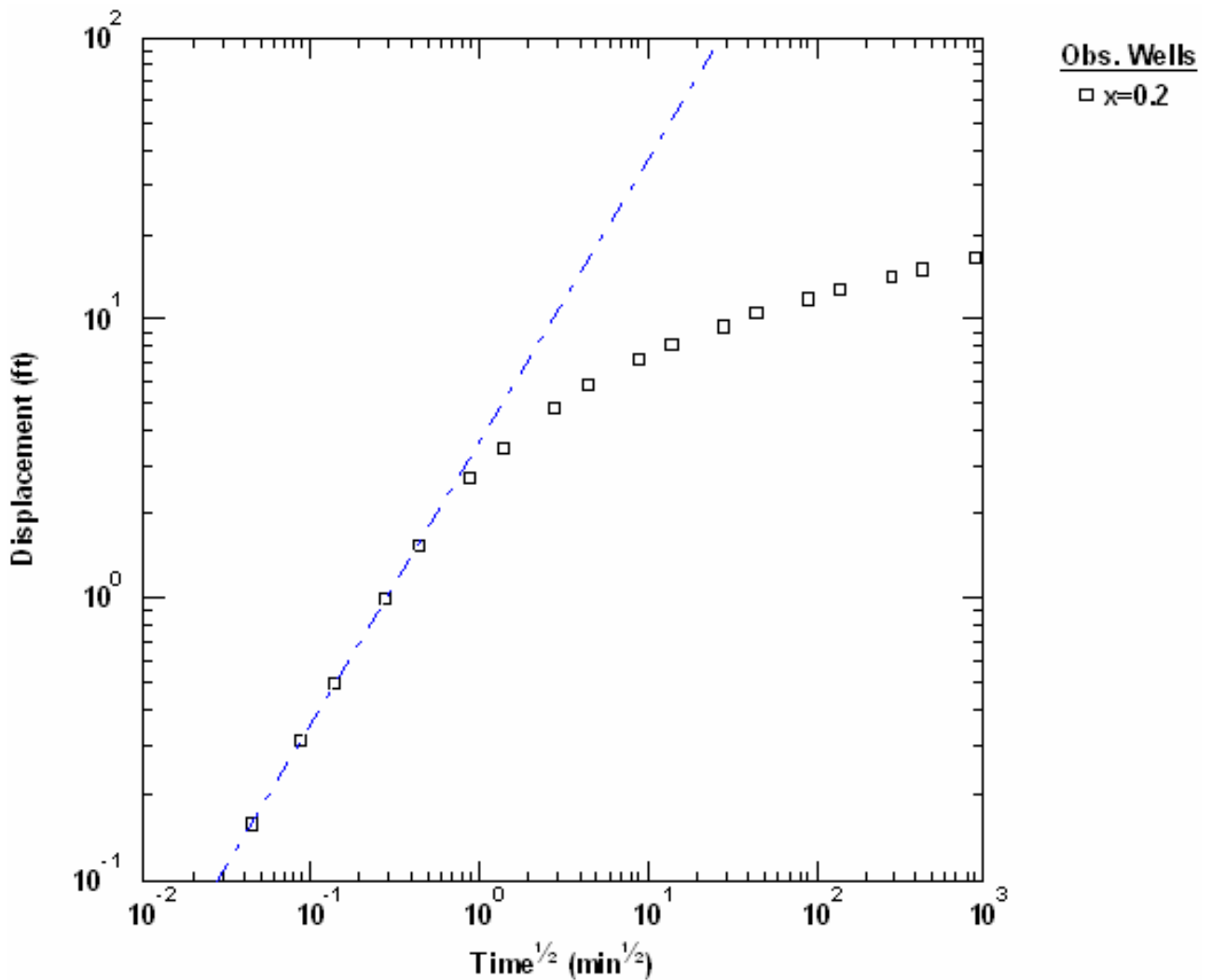Choose **Linear Flow** from the **View** menu to plot displacement as a function of the square root of time.

➡ Linear Flow to a Vertical Fracture in Plan View

Linear flow to an infinite-conductivity vertical fracture.

- Linear flow plots are useful diagnostic tools for identifying fracture flow behavior.

- On log-log 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.

- On log-log axes, late-time data exhibiting a unit slope on a linear flow plot are indicative of linear flow conditions to a well in a strip aquifer (e.g., a buried valley setting).

- View one or more observation wells on linear flow plots.

➡ Example: Uniform-Flux Vertical Fracture

- 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.

Related Topics

Bilinear Flow Plot

(View > Bilinear Flow)

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 log-log 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.

- View one or more observation wells on bilinear flow plots.

- 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.

Spherical Flow Plot

(View > Spherical Flow)

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 log-log axes, data exhibiting a unit slope on a spherical flow plot are indicative of spherical flow conditions.

- View one or more observation wells on spherical flow plots.

- 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.
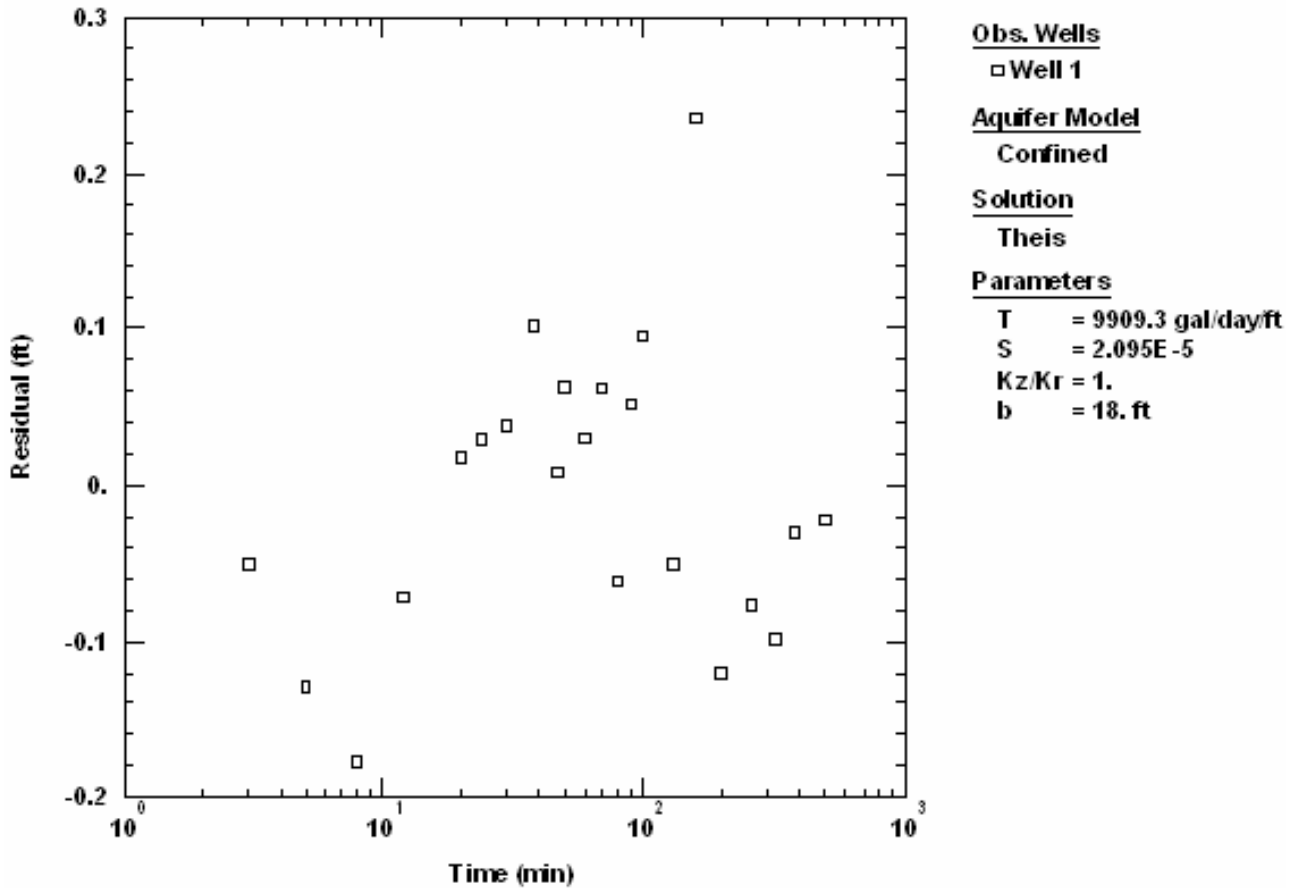
Residual Plots

Residual-Time Plot

(View > Residual-Time)

Choose **Residual-Time** from the **View** menu to plot residuals as a function of time.

➡️ Example: Pumping Test in Confined Aquifer

- Ideally, the residual values should not exhibit correlation with time.

- When residual-time data are plotted linear axes, AQTESOLV fits a straight line to the data indicating the degree to which the residuals are biased with respect to time.

- Residuals are computed for the current (visual or automatic) curve fit.

Related Topics

Residual-Simulated Plot

(View > Residual-Simulated)

Choose **Residual-Simulated** from the **View** menu to plot residuals as a function of simulated displacement.

➡ Example: Pumping Test in Confined Aquifer
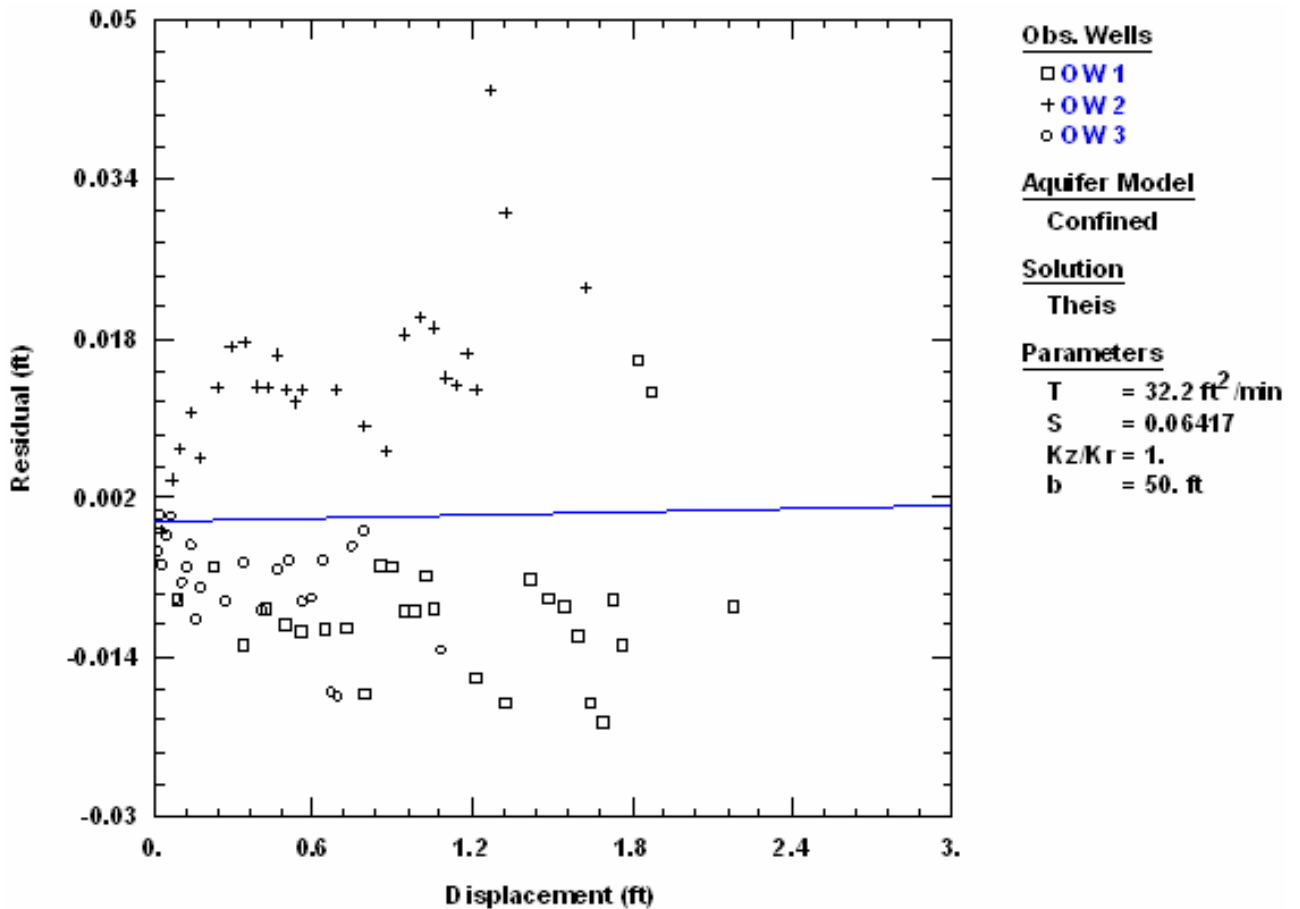
- Ideally, the residual values should not exhibit correlation with the values of simulated displacement.

- When residual-simulated data are plotted on linear axes, AQTESOLV fits a straight line to the data indicating the degree to which the residuals are biased with respect to simulated displacement.

- Residuals are computed for the current (visual or automatic) curve fit.

Related Topics

Normal Probability Plot

(View > Normal Probability)

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

➡️ Example: Pumping Test in Confined Aquifer
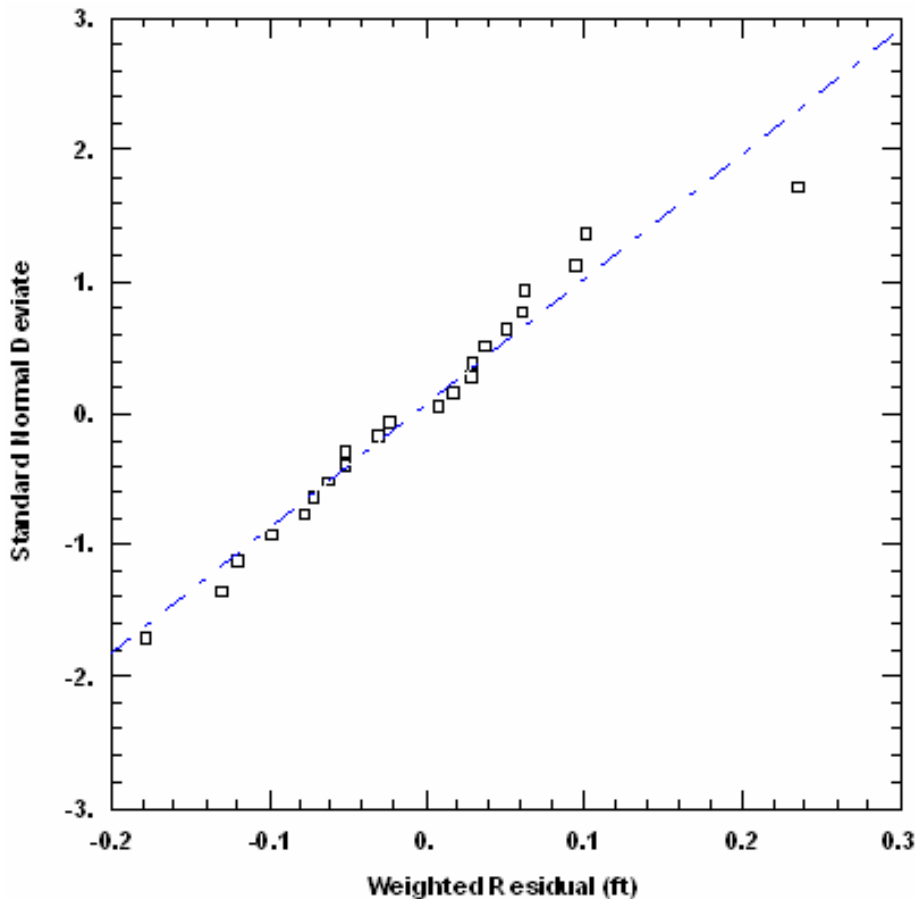
- A normal probability plot displays the standard normal deviates of the ranked residuals (residuals sorted from smallest to largest) as a function of the residual values.

- If the residuals are normally distributed, they will fall on a straight line when plotted on normal probability axes. AQTESOLV 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 plots the standard normal deviates using the plot symbol for the first observation well.

- Residuals are computed for the current (visual or automatic) curve fit.

Related Topics

Customizing Plots

Select options from the **View** menu to customize a plot in the active window.

- Choose Linear Axes, Log-Linear Axes, Linear-Log Axes or Log Axes to change the scales of the x and y axes.

- Choose Format to customize axes, labels, legends, styles for curve families and other plot features.

- Choose Options to select items to display on plots such as type curve families, derivative curves and recommended head ranges.
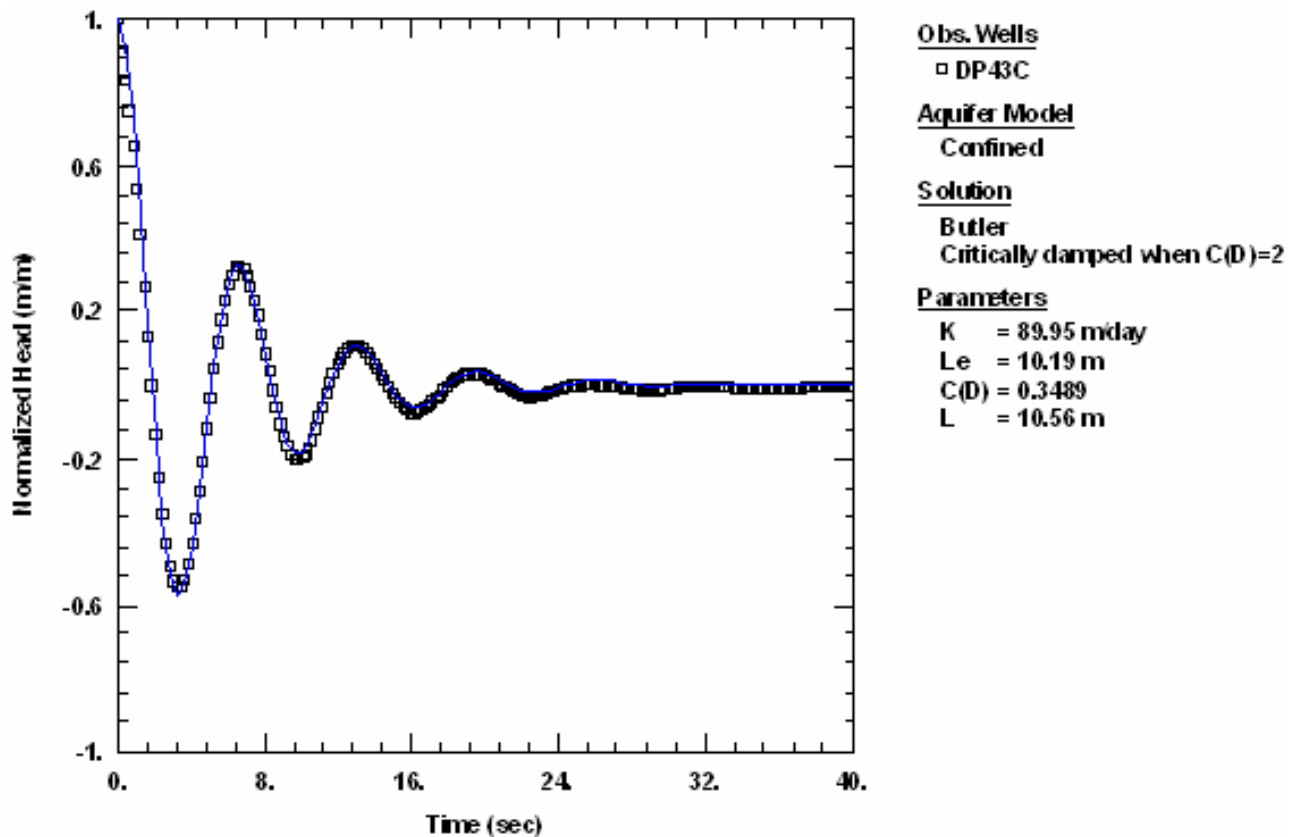
Related Topics

Linear Axes

(View > Linear Axes)

Choose **Linear Axes** from the **View** menu or click ⌐ on the toolbar to display a plot with linear x and y axes.
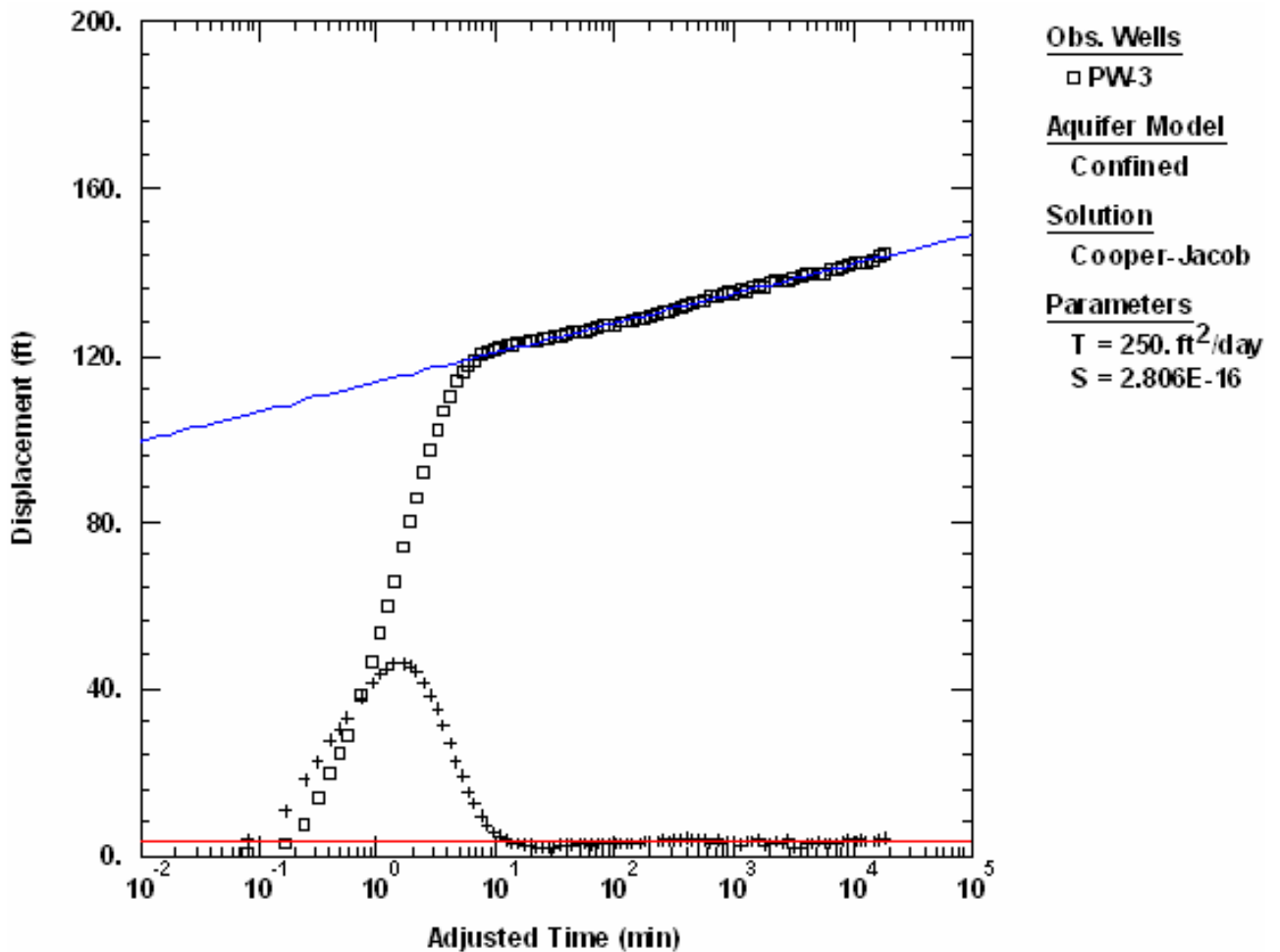
➡ Example: Slug Test
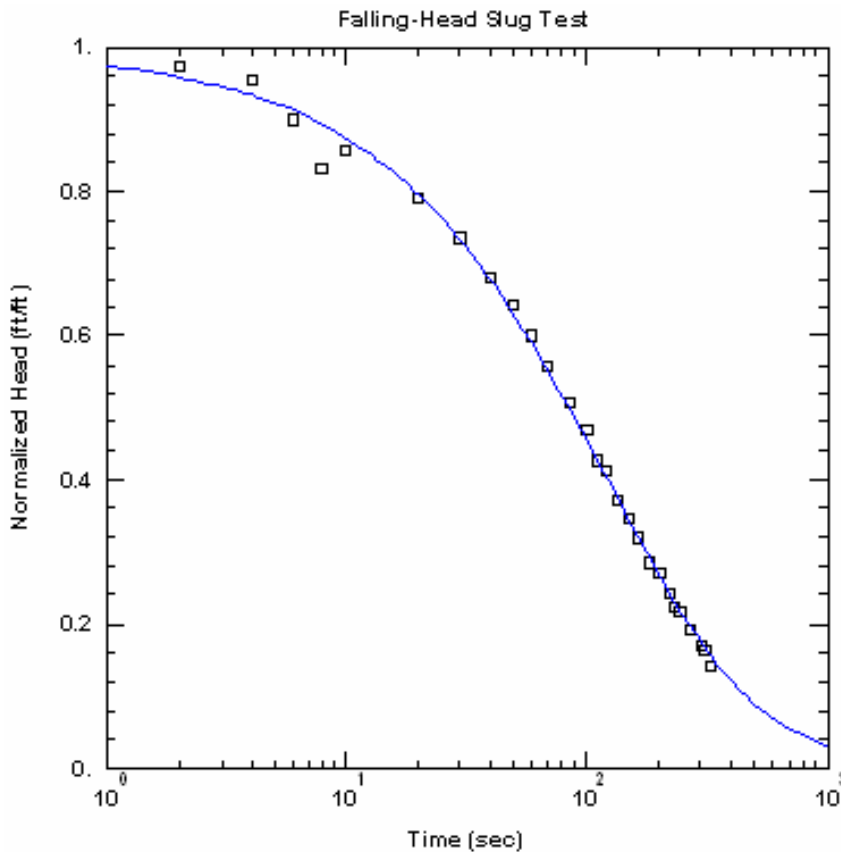
Log-Linear Axes

(View > Log-Linear Axes)

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

Example: Single-Well Pumping Test (with Derivative)

Example: Slug Test

Falling-Head Slug Test

Obs. Wells
□ Well 1

Aquifer Model
Confined

Solution
Cooper-Bredehoeft-Papadopulos

Parameters
$T = 0.3028 \, cm^2/sec$
$S = 0.0007837$

- Right-click over a plot to select **Log-Linear** axes.
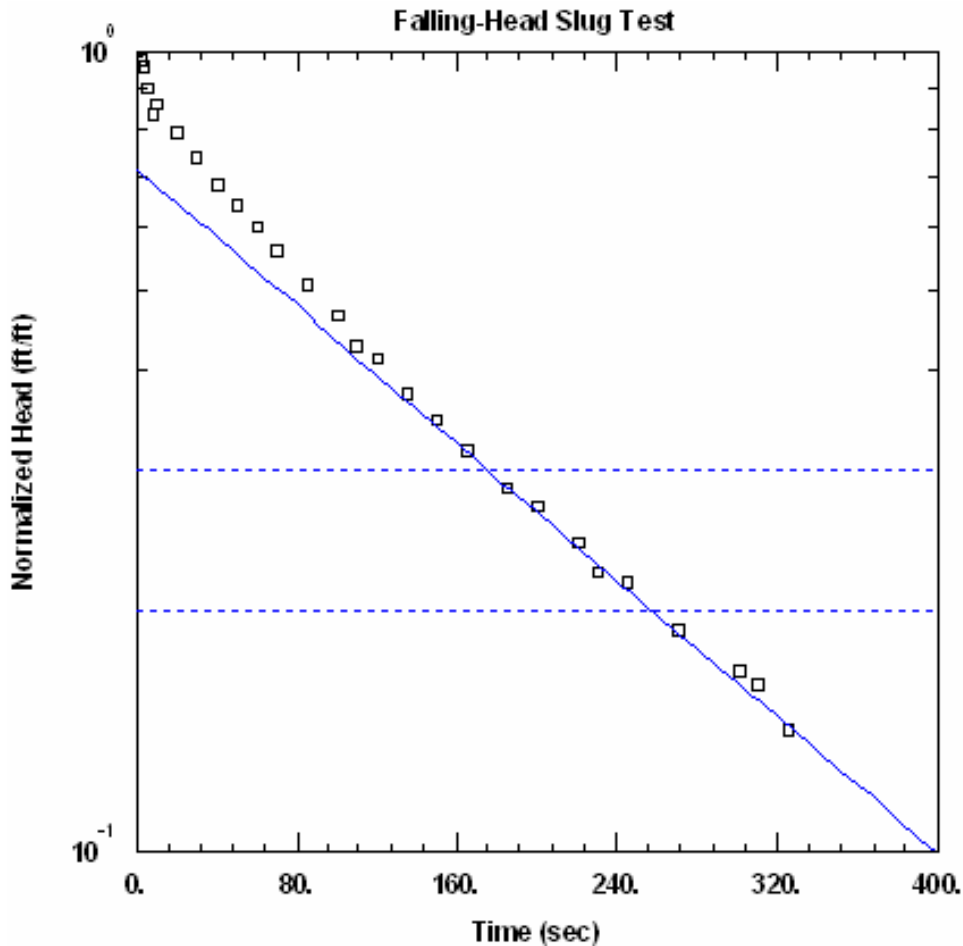
Related Topics

Linear-Log Axes

(View > Linear-Log Axes)

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

➡ Example: Slug Test

Falling-Head Slug Test

Obs. Wells
□ Well 1

Aquifer Model
Unconfined

Solution
Bouwer-Rice

Parameters
K = 0.000348 cm/sec
y0 = 1.052 ft

- Right-click over a plot to select **Linear-Log** axes.

Related Topics

Log Axes

(View > Log Axes)

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

Example: Pumping Test (with Derivative)
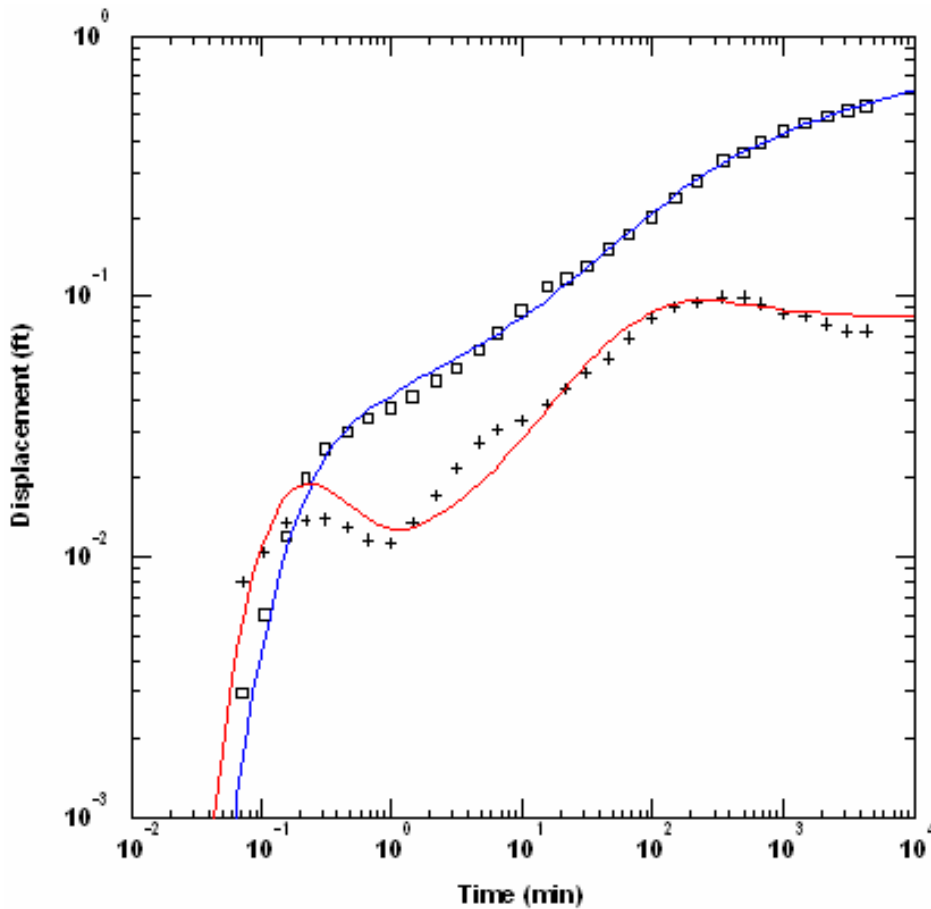
Obs. Wells
□ F377-037

Aquifer Model
Unconfined

Solution
Tartakovsky-Neuman

Parameters
T   = 0.05892 m^2/sec
S   = 0.004546
Sy   = 0.1634
Kz/Kr = 0.5303
kD   = 11.74

TIPS

- Right-click over a plot to select **Log** axes.

Related Topics

Format

(View > Format)

Choose **Format** from the **View** menu to select options for formatting a plot or report.

How to Format Plots

o   Graph Tab
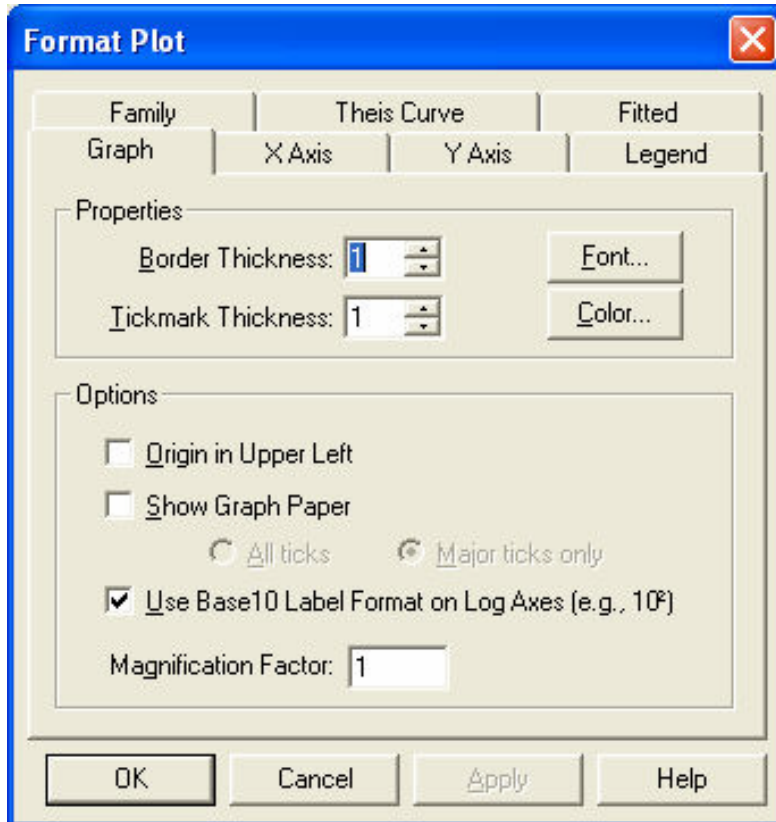
Properties

- Enter values controlling the **Border** thickness and **Tickmark** thickness of the plot.

- Click **Font** to change the font used to display axis labels.

- Click **Color** to change the color used for drawing the axis labels.

Options

- Check **Upper Left Origin** to place the origin of the plot axes in the upper left corner of the plot (i.e., flip the y axis).

- Check **Show Graph Paper** to display horizontal and vertical lines at the major tickmarks of the graph.

- Enter a value between 0.5 and 1.5 for the **Magnification Factor** to adjust the length of the plot axes.

o X and Y Axis Tabs
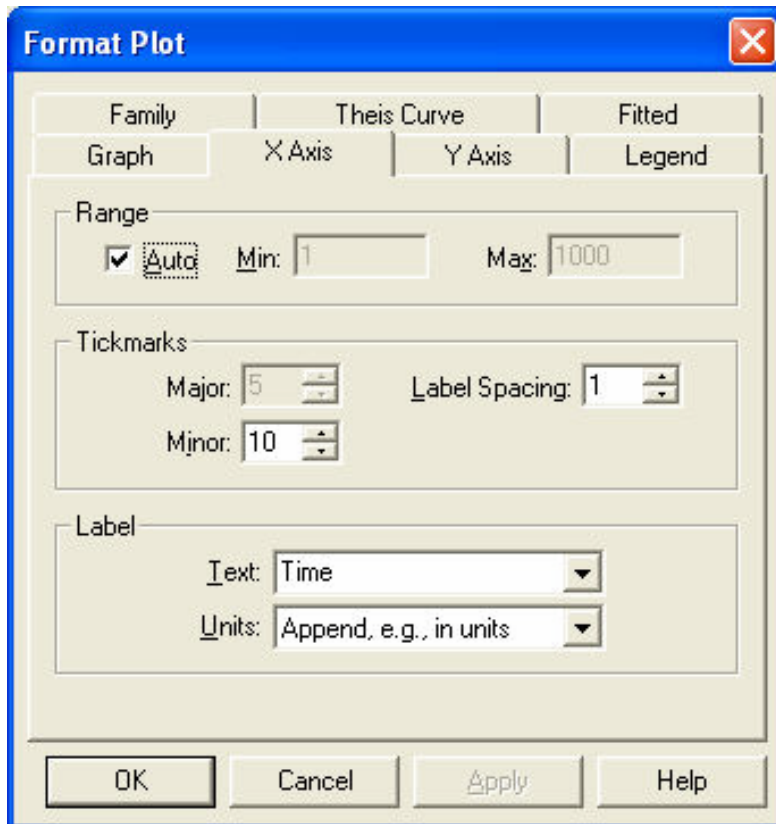
Range

- Check **Auto** to use **minimum** and **maximum** axis values selected automatically by the program for your data.

- Remove the **Auto** check to edit **minimum** and **maximum** axis values.

Tickmarks

- Edit values controlling **major** and **minor tickmark intervals**.

- Edit the **label spacing** for labels placed on the major tickmarks.

Labels

- Edit **Text** for the axis label. Choose one of the predefined axis labels or enter a new label.

- Choose a format for appending **Units** to the axis label.

  For example, if the time units in your data set are days, you may label a time axis as **Time (days)** or **Time in days** or **Time**. If the length units are meters, you may label a drawdown axis as **Drawdown (m)** or **Drawdown in m** or **Drawdown**.

  Choose Edit>Units to select the units that appear in axis labels.

  o Legend Tab
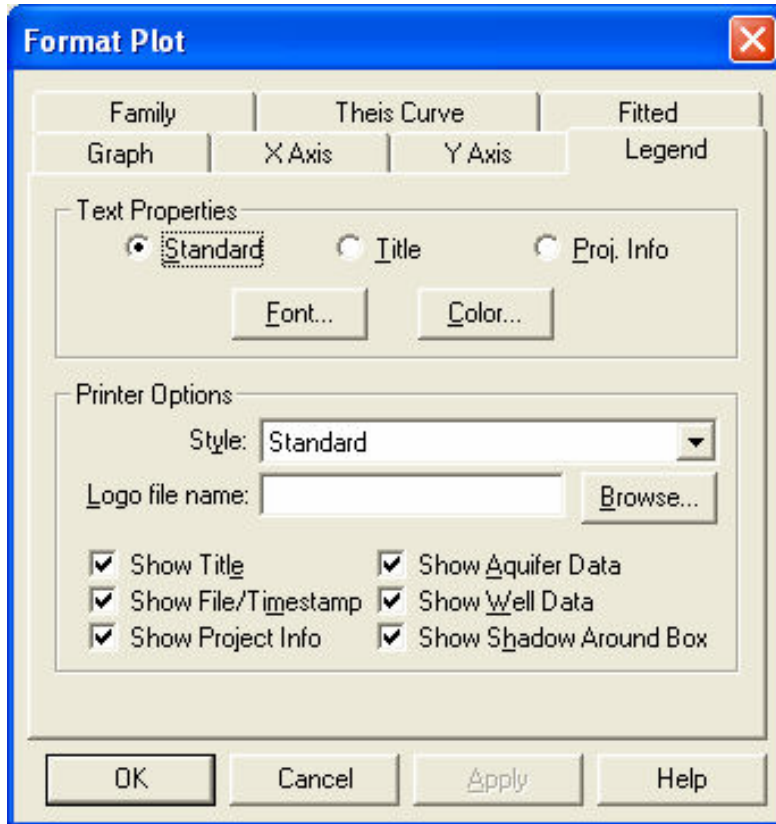
Text Properties

- Select the **text** to edit (Standard, Title, Proj. Info).

- Click **Font** to change the font used to display the selected text.

  Decrease the font size if the legend does not fit on one printed page.

- Click **Color** to change the color used for the selected text.

Printer Options

- Choose a **Style** from the list to format the appearance of printed output.

- 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).

- Check the items that you would like display in the printed legend (e.g., title, project info, aquifer data, well data, etc.).

o Family Tab
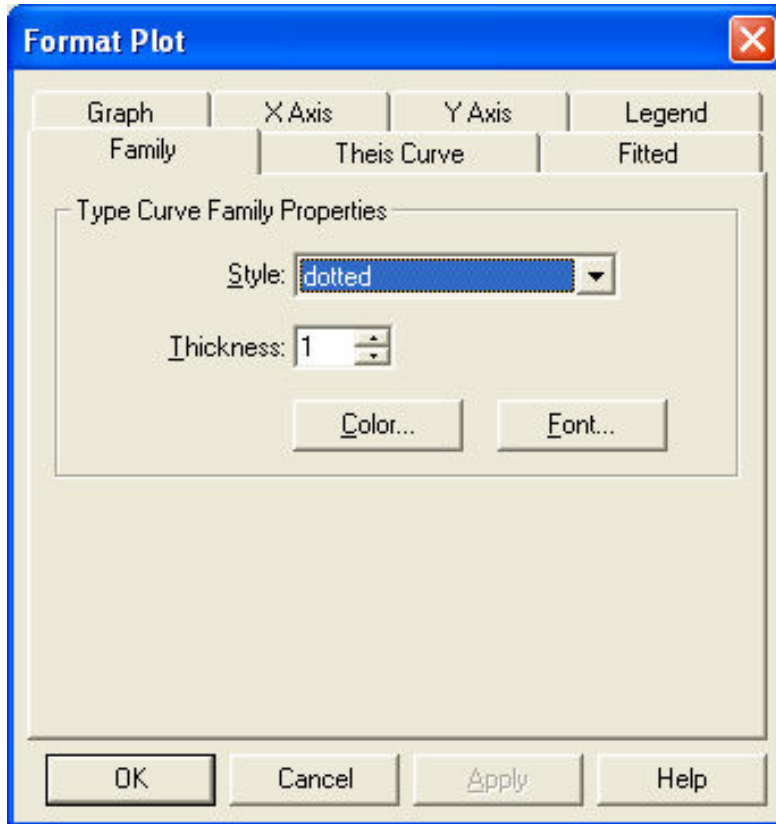
Style

- 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.

o Theis Curve Tab
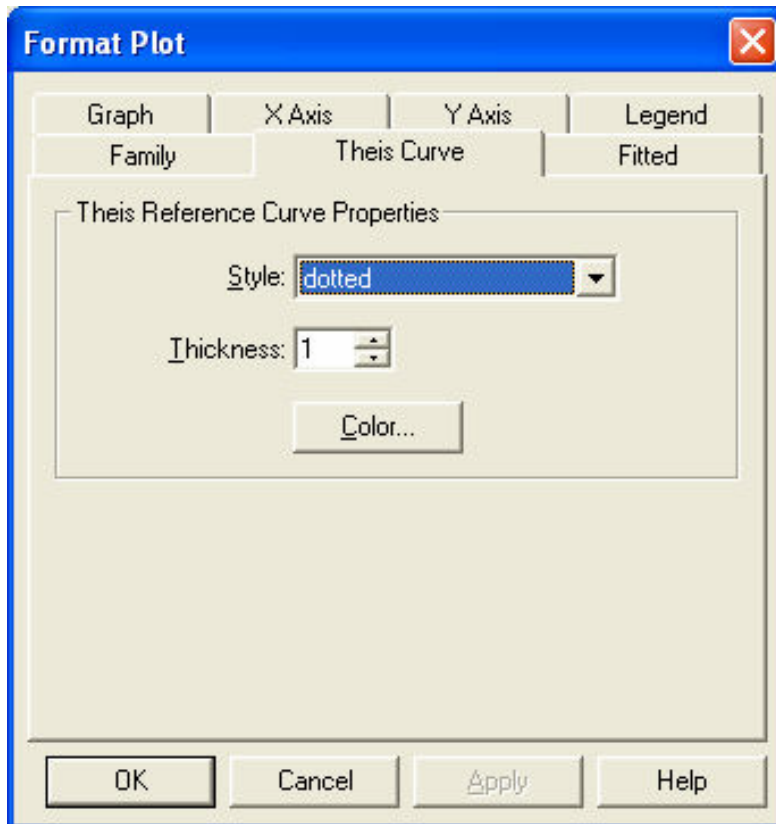
Style

- 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.

o Fitted Tab
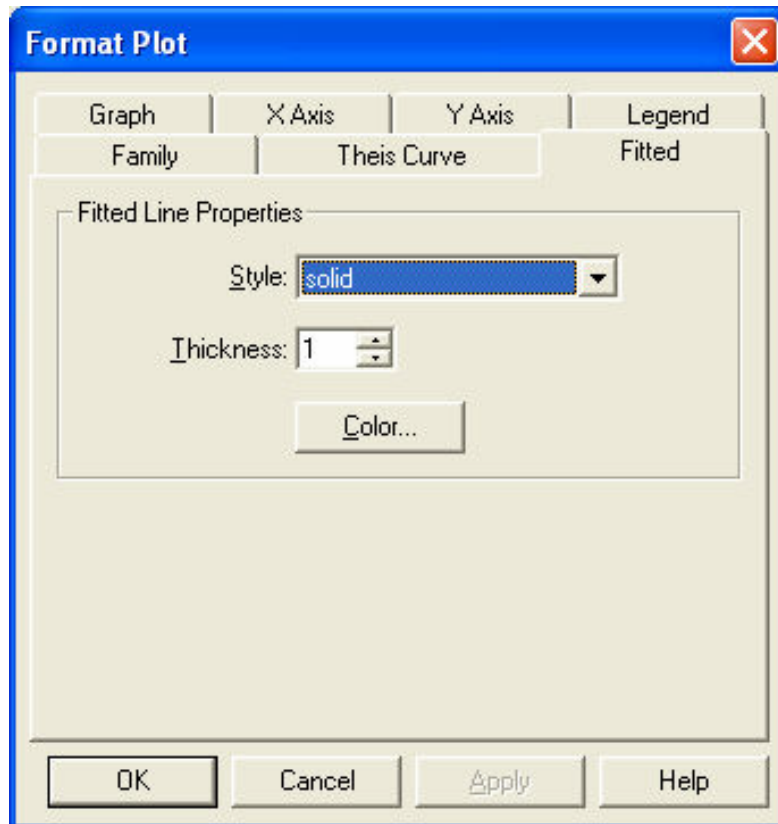
Style

- Choose a **Style** for the optional fitted line on residual plots.

Thickness

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

Color

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

How to Format Reports

- o Text Tab
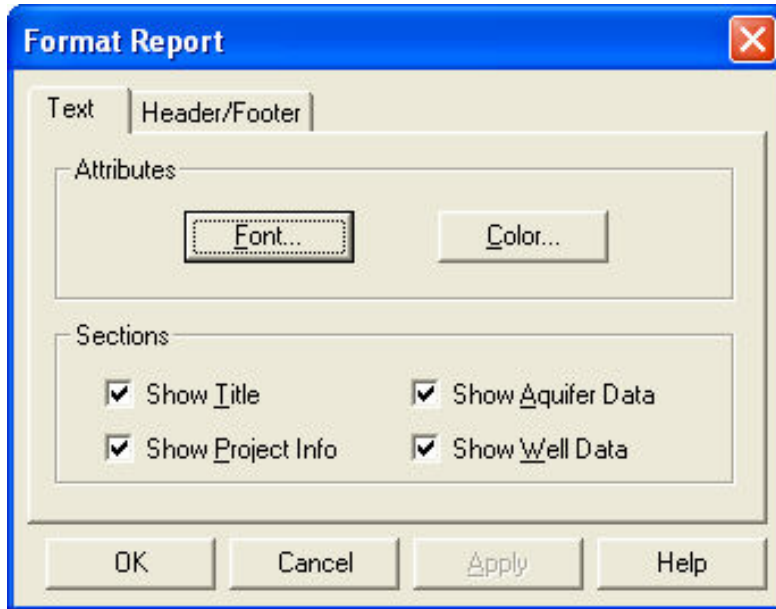
Text Properties

- Click **Font** to change the font used to display the report text.

- Click **Color** to change the color used for the report text.

Sections

- Check items to display in the report.

o Header/Footer Tab
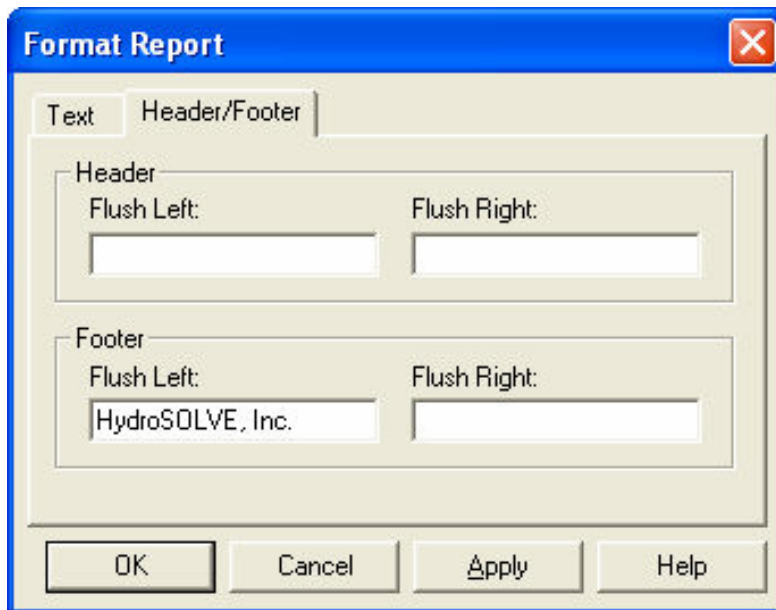
- Enter text for the headers and footers of a report.

- Click **Apply** to make changes immediately.

- Click **Cancel** to undo any changes.

- Right-click over a plot or report to select **Format**.

- Double-click over a report or outside the graph area of a plot to open the **Format** dialog.

- If a plot does not fit on one printed page, decrease the font size in the **Legend** tab.

Related Topics

Options

(View > Options)

Choose **Options** from the **View** menu to select optional plot items and enter parameters controlling the display of type curve families, derivatives, validity criteria, step-test parameters, distance-drawdown data and settings for rendering curves.

- o Plots Tab
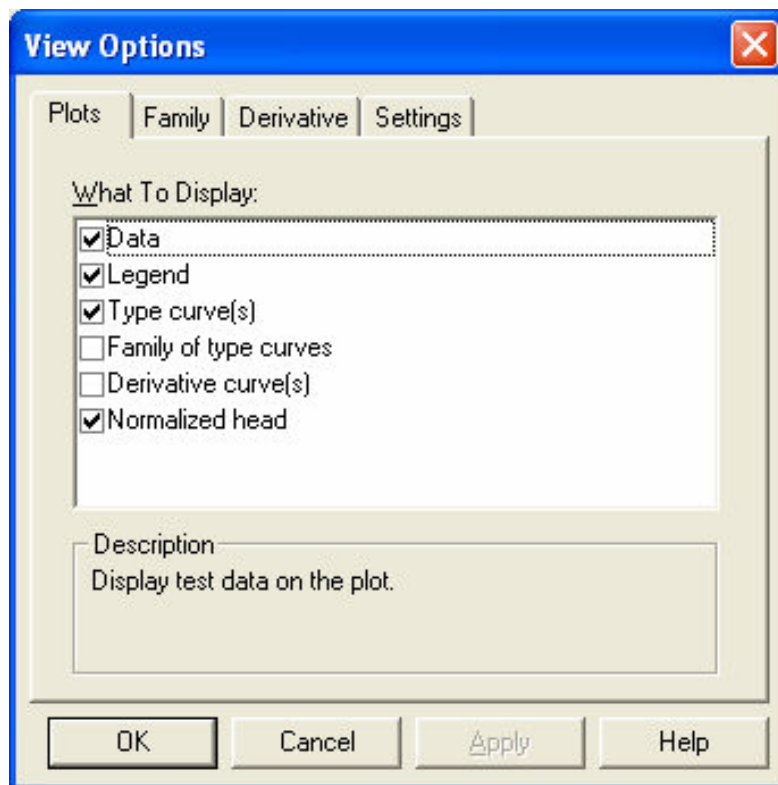
<u>**What To Display**</u>

- Check options to display on plots (Data, Legend, Type Curve, Curve Family, Theis Curve, Derivative Curve, Valid Time, Normalized Head and Recommended Head Range).

- You can toggle the **Type Curves** option from the keyboard by pressing **Ctrl-T**.

- The **Curve Family** option only applies to certain solutions having three or more parameters. Click the **Family Tab** to set more options for type curve families.

- The **Theis Curves** option applies to selected solutions. Select this option to superimpose a Theis reference curve on your plot.

  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 Sy.

- Choose **Derivative Curves** to superimpose derivative curves on a 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.

- 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. Click the **Valid Time Tab** to set the critical value of u used to compute the valid time.

- The option to display **Normalized Head** applies to slug test solutions.

- The **Recommended Head Range** option displays the head ranges recommended by Butler (1998) for matching certain slug test solutions.

- **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) and Springer-Gelhar (1991).

○ Family Tab
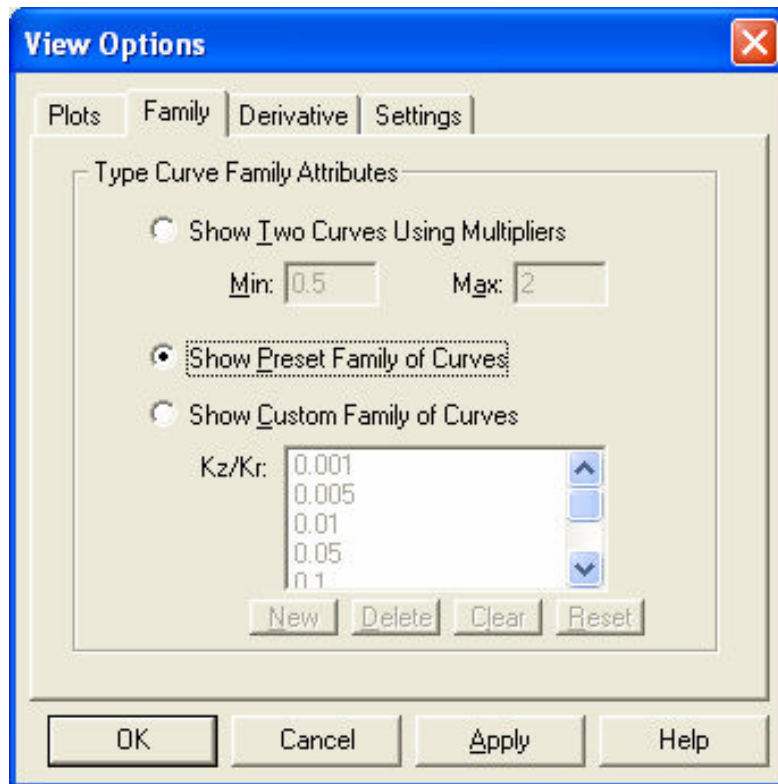
Type Curve Family Attributes

- 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.

- For a complete set of type curves, choose the option to **Show Preset Family of Curves**.

- Select **Show Custom Family of Curves** to display type curves from the values shown in the list box. Use **New** and **Delete** to add or remove curve values. Click **Clear** to remove all curves from the list. **Reset** restores curve values.

- Choose the **Show Family** option in the **Plots** tab to enable the display of type curve families.

- Select View>Format to edit formatting options for type curve families.

o   Derivative Tab
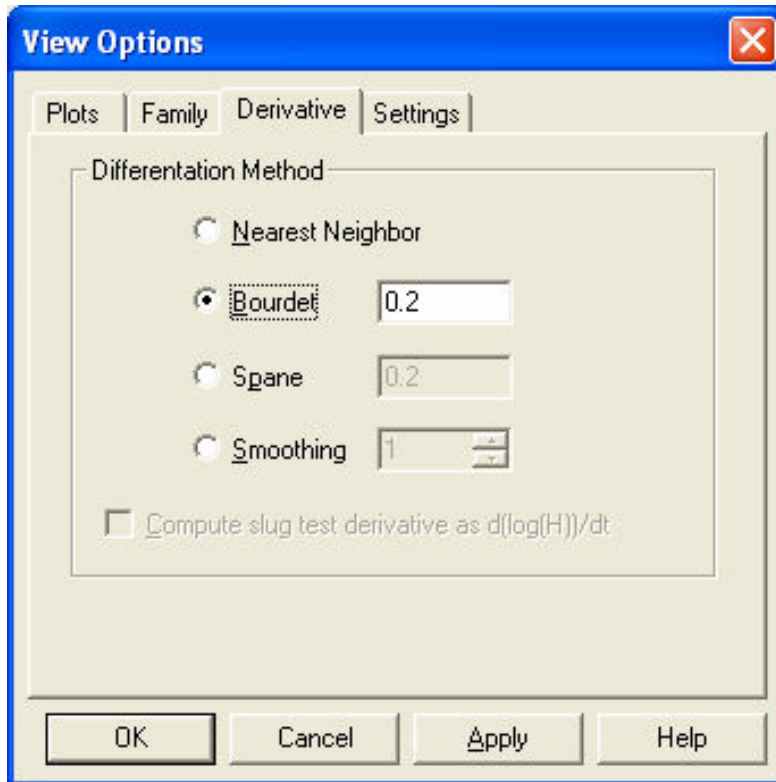
<u>Differentiation Method</u>

- Choose a **method** for calculating derivatives from time-displacement data (differentiation methods include **nearest neighbor**, **Bourdet**, **Spane** and **smoothing**).

- The **nearest neighbor** option provides the least amount of smoothing and works well for displacement data that show ideal response.

- The **Bourdet**, **Spane** and **smoothing** methods allow you to "smooth" the calculation of derivatives with "noisy" data. Enter the smallest differentiation interval or smoothing factor to discern the derivative pattern from the data.

- 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 **Compute slug test derivative as d(log(H))/dt** to show the deviation of the derivative from the steady-state model of slug-induced flow.

- Choose Edit>Wells to edit derivative symbol and curve properties.
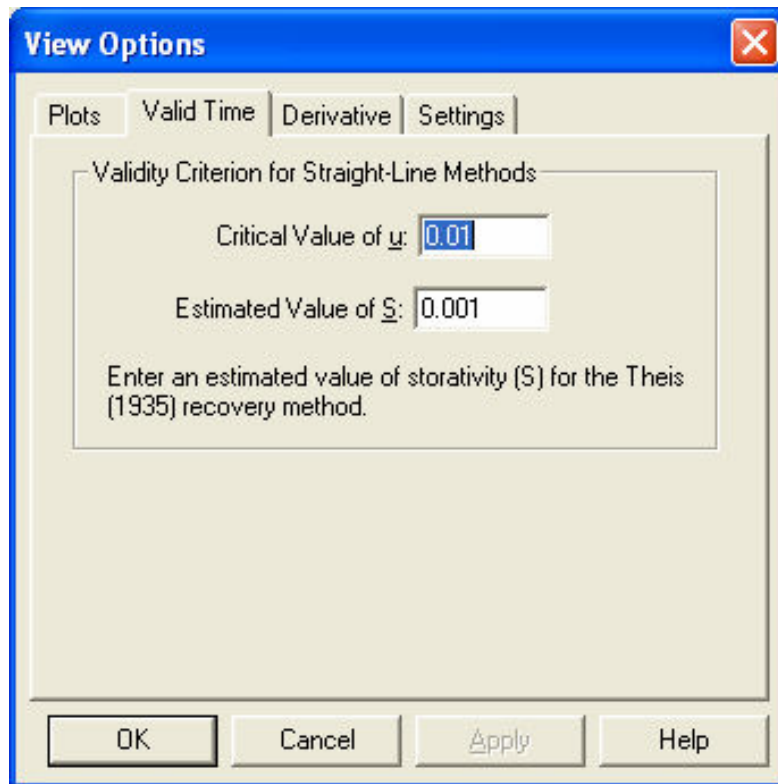
o Valid Time Tab

<u>Validity Criterion for Straight-Line Methods</u>

- Set the **Critical Value of u** used to compute the valid time displayed for the Cooper-Jacob (1946) solution when you enable **Show Valid Time** in the **Plots** tab.

  A conservative critical value of u is 0.01.

- Enter the **Estimated Value of S** (storativity) to compute the valid time displayed with the Theis (1935) residual drawdown method for recovery tests.

o   Step Test Tab
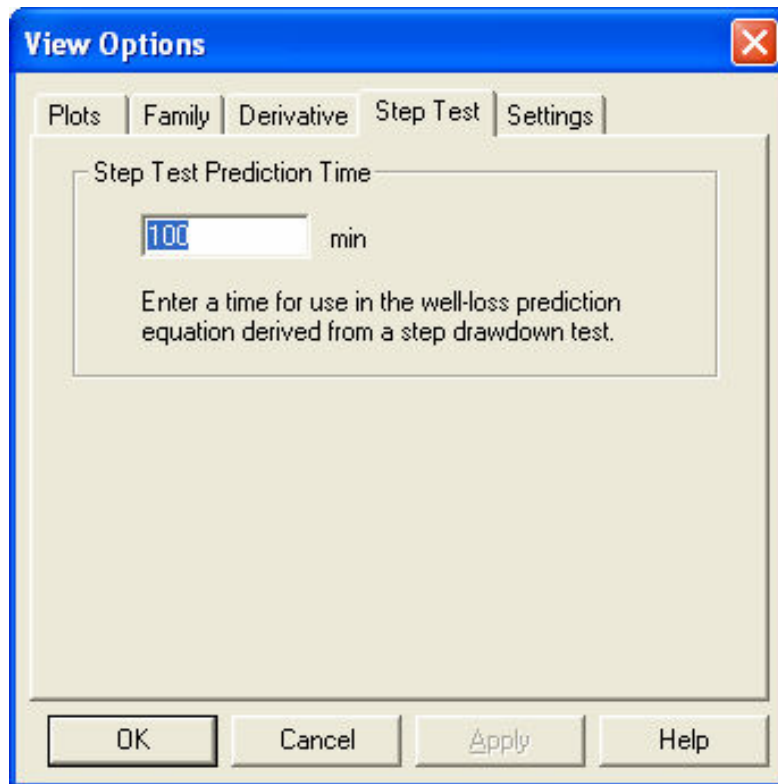
<u>Step Test Prediction Time</u>

- Set the **Step Test Prediction Time** used in the well loss prediction equation.
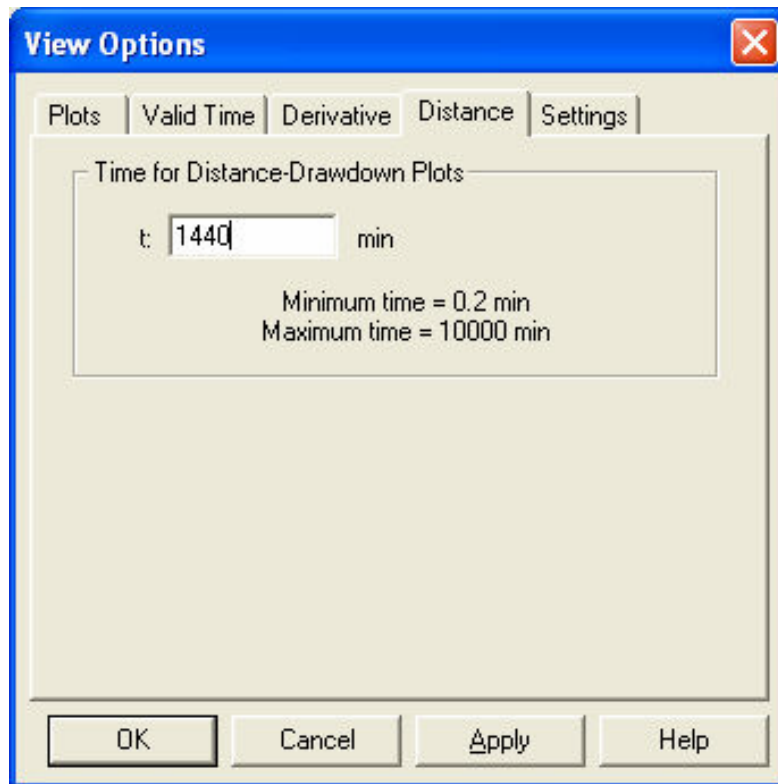
o Distance Tab

Time for Distance-Drawdown Plots

- Enter the **Time** used to display distance-drawdown plots.

- AQTESOLV automatically interpolates or extrapolates a value of drawdown when a well does not contain an observation at the time specified for distance-drawdown analysis.

- The **Distance** tab only appears when the active view is a distance-drawdown plot.

o Settings Tab
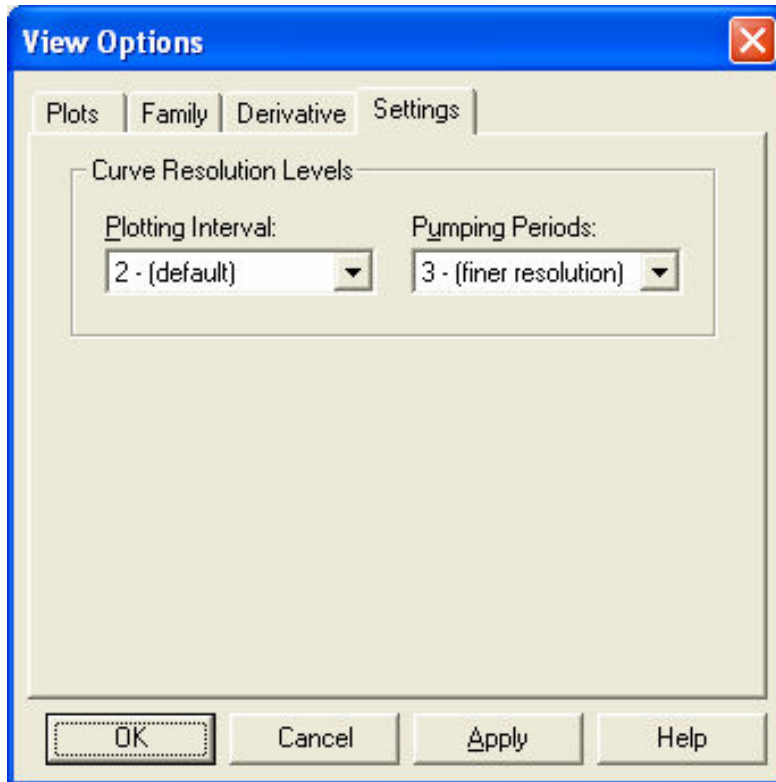
Curve Resolution Levels

- 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.

- 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 pumping tests or slug tests.

- The **Curve Resolution Levels** only affect the appearance (smoothness) of plotted type curves not the accuracy of the underlying solution methods (well functions).

- Click **Apply** to make changes immediately.

- Click **Cancel** to undo any changes.

- Right-click over a plot or report to select **Options**.

Related Topics

Reports

Overview (Reports)

The **View** menu provides options for viewing data, solutions and estimation results in several report formats.

➡ Report Options

- The report option gives a complete summary of the data set with the solution and estimation results.

- Use the diagnostics report with its summary of residual statistics and other diagnostics to help assess the fit of a model.

- Refer to the error log for a list of errors (if any) detected in the active data set.

➡ Customizing Reports

- Customize the appearance of reports using formatting options.

Related Topics

Diagnostics

(View > Diagnostics)

Choose **Diagnostics** from the **View** menu to display a report containing estimation statistics for parameters (hydraulic properties) and residuals. Inspect the diagnostics report after performing automatic curve matching.

- Parameter statistics include standard errors, confidence intervals and correlations.

- Residual summary statistics include number of residuals, mean, standard deviation, variance and sum of squares.

Related Topics

Report

(View > Report)

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

The **Report** also shows derived properties such as leakance coefficient (K'/b') and hydraulic conductivity (K') of aquitards.

- A printout of this report is a convenient summary of your aquifer test analysis that you can insert in your project report.

Error Log

(View > Error Log)

Choose **Error Log** from the **View** menu to display a report identifying errors (if any) detected in the active data set.

- The **Error Log** is the default view when create a new data set.

- Correct errors detected in the test data by choosing options from the Edit menu.

- When the **Error Log** shows no errors, choose options from the View menu to display data.

- Select this report if the **Check Errors** message appears on the status bar.

Customizing Reports

(View > Format)

Choose **Format** from the **View** menu to customize a report.

- Select Format to customize report text, color, headers and footers.

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Matching Data

Solutions

Overview (Solutions)

After entering data for an aquifer test and performing diagnostics, choose Solution from the **Match** menu to select a solution method for curve matching.

- Use diagnostic flow plots and derivative analysis to help identify appropriate solution methods before choosing a solution.

- Find solution methods that meet specific criteria with the Solution Expert.

Related Topics

Pumping Tests

Overview (Pumping Test Solutions)

AQTESOLV provides the following solutions for pumping tests in confined, leaky, unconfined and fractured aquifers.

Confined	Theis (1935)/Hantush (1961)
Confined	Theis (1935) residual drawdown/recovery
Confined	Theis (1935) step-drawdown test
Confined	Cooper-Jacob (1946)
Confined	Moench-Prickett (1972) unconfined conversion
Confined	Butler (1988) nonuniform aquifer
Confined	Papadopulos-Cooper (1967)
Confined	Dougherty-Babu (1984)
Confined	Dougherty-Babu (1984) step-drawdown test
Confined	Hantush (1962) wedge-shaped aquifer
Confined	Murdoch (1994) trench
Confined	Daviau et al. (1985) uniform-flux horizontal well
Confined	Daviau et al. (1985) infinite-conductivity horizontal well
Confined	Barker (1988)
Leaky	Hantush-Jacob (1955)/Hantush (1964) without aquitard storage
Leaky	Hantush-Jacob (1955) step-drawdown test
Leaky	Hantush (1960) with aquitard storage
Leaky	Hantush (1960) early-time solution
Leaky	Cooley-Case (1973) water-table aquitard
Leaky	Neuman-Witherspoon (1969) confined two-aquifer system
Leaky	Moench (1985) Case 1: constant head
Leaky	Moench (1985) Case 2: no-flow
Leaky	Moench (1985) Case 3: both
Unconfined	Theis (1935)
Unconfined	Cooper-Jacob (1946)
Unconfined	Neuman (1974)
Unconfined	Moench (1997)
Unconfined	Tartakovsky-Neuman (2007)
Fractured	Moench (1984) slab-shaped blocks
Fractured	Moench (1984) spherical blocks
Fractured	Barker (1988) slab-shaped blocks
Fractured	Barker (1988) spherical blocks
Fractured	Gringarten-Witherspoon (1972) uniform-flux vertical fracture
Fractured	Gringarten et al. (1974) infinite-conductivity vertical fracture

Fractured	Gringarten-Ramey (1974) uniform-flux horizontal fracture

- Choose Match>Solution to select a pumping test solution.

Related Topics

Constant-Rate Solutions

All of the pumping test solutions in AQTESOLV let you simulate constant-rate pumping tests.

Example: Constant-Rate Test in Confined Aquifer
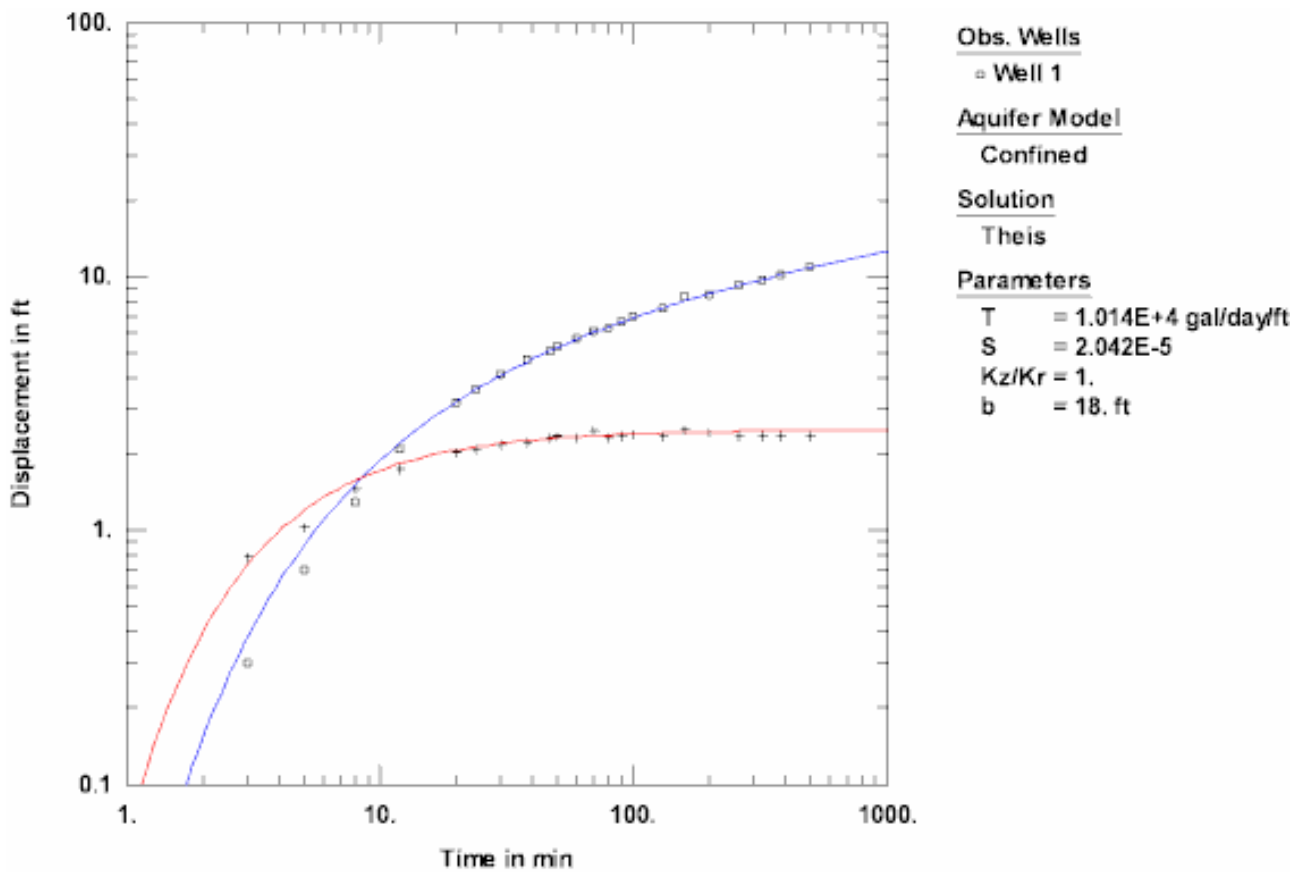
- Choose Match>Solution to select a pumping test solution.

Related Topics

Variable-Rate Solutions

All of the pumping test solutions in AQTESOLV let you simulate variable pumping rates using the principle of superposition in time which treats variable discharge as a sequence of steps with a constant rate in each step. The sequence of steps may include one or more periods of recovery in which the pumping rate is zero (e.g., recovery tests or intermittent pumping).

➡ Example: Variable Discharge History

Variable-Rate Pumping Test with Recovery

TIPS
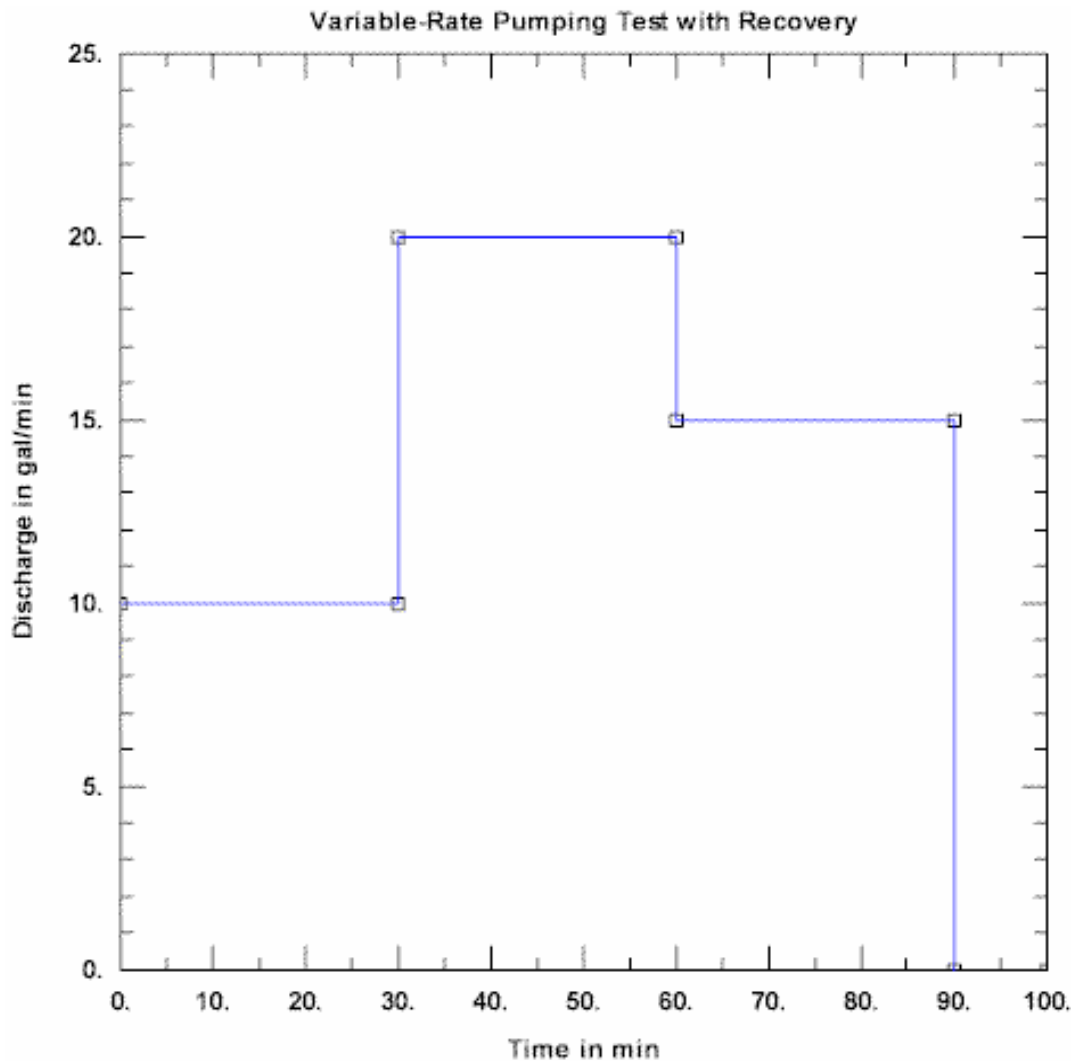
- Choose Match>Solution to select a pumping test solution.

- Enter variable rates as a sequence of pumping periods.

Related Topics

Recovery Solutions (Pumping Tests)

You may use any of the pumping test solutions in AQTESOLV to analyze data from a recovery test.

AQTESOLV applies the principle of superposition in time to simulate pumping tests with recovery.

➡ Example: Recovery Test in Confined Aquifer
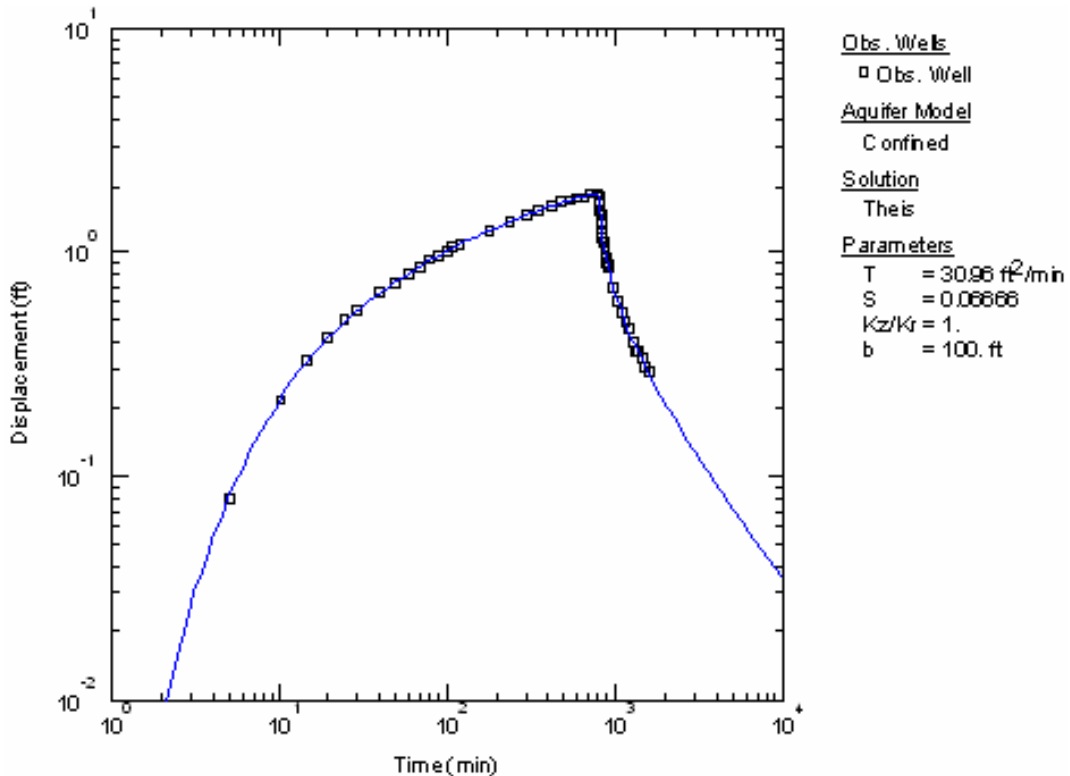
- Choose Match>Solution to select a pumping test solution.

- Use displacement-time, composite, residual drawdown and Agarwal plots to analyze recovery tests.

Single-Well Solutions

You may use any of the pumping test solutions in AQTESOLV for the analysis of single-well tests; however, when response data are only available from the pumped well, the effects of wellbore storage, wellbore skin, and partial penetration are often important. You can use the Solution Expert to identify pumping test solutions that include these and other special conditions that may affect your test.

For example, let's suppose that you are analyzing a pumping test in a confined aquifer with drawdown data from the pumping well. You could choose either the

Theis (1935) or Cooper-Jacob (1946) solution to analyze the single-well test data; however, because these line-source solutions ignore wellbore storage, it may be difficult to match early-time data. To account for wellbore storage, you could try to match the Papadopulos-Cooper (1967) solution for fully penetrating wells, or, for greater generality, the Dougherty-Babu (1984) solution which also includes wellbore skin for fully or partially penetrating wells.

Related Topics

Wellbore Storage Solutions

The following pumping test solutions account for the wellbore storage effect in confined, leaky, unconfined and fractured aquifers.

➡ Example: Pumping Test in Confined Aquifer
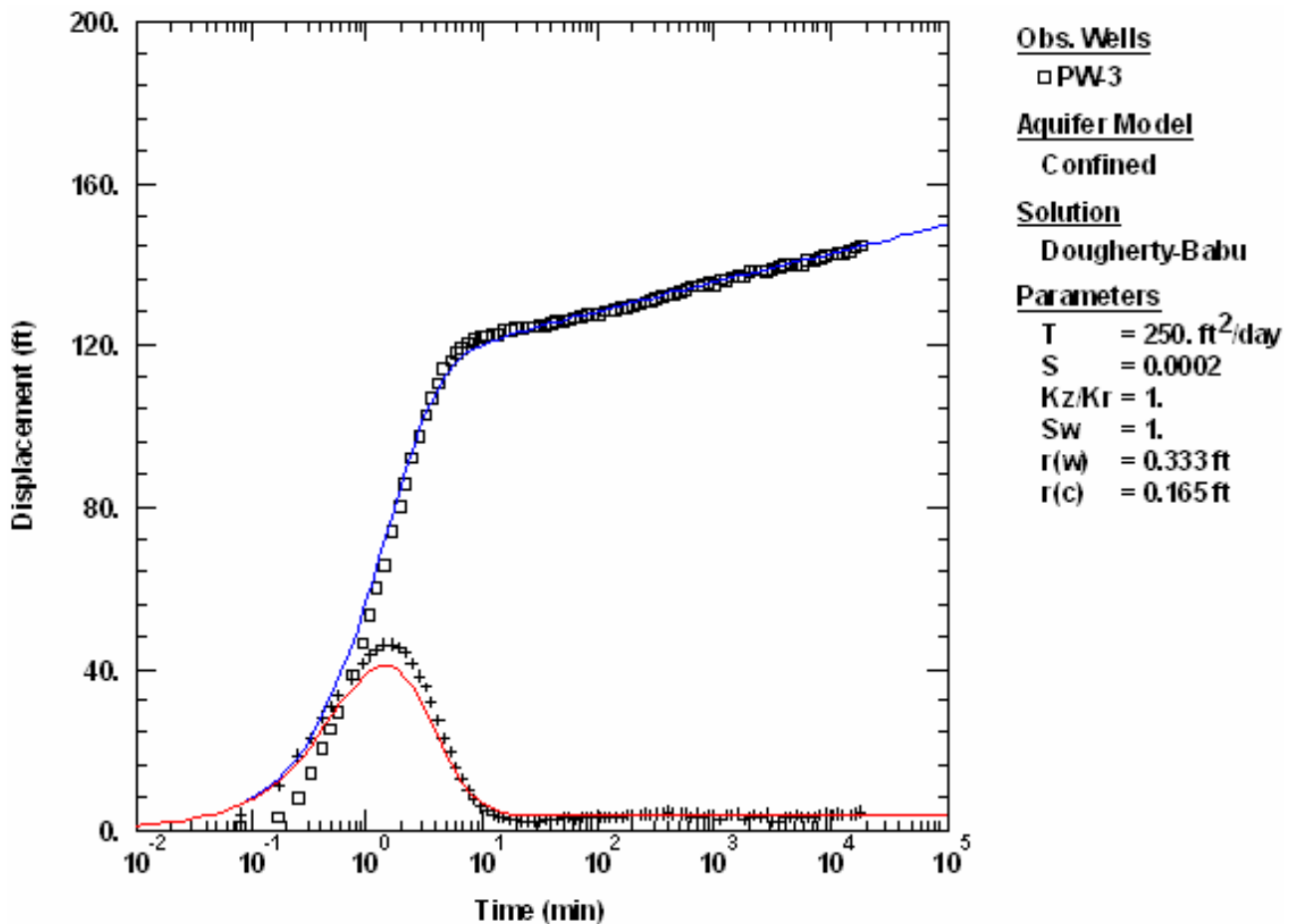
Confined	Papadopulos-Cooper (1967)
Confined	Dougherty-Babu (1984)
Confined	Dougherty-Babu (1984) step-drawdown test
Confined	Barker (1988)
Leaky	Moench (1985)
Unconfined	Moench (1997)

| Fractured | Moench (1984) |
| Fractured | Barker (1988) |

- Choose Match>Solution to select a pumping test solution. Check the **Wellbore storage** filter to find solutions that include wellbore storage.

- Wellbore storage often distorts early-time drawdown behavior in a pumped well. Use diagnostic flow plots to help identify response data affected by wellbore storage.

- All of the wellbore storage solutions allow you to estimate the value of casing radius for the pumped well. You may determine the effective casing radius for the pumped well by either (1) adjusting this parameter or (2) specifying values for nominal casing radius and downhole equipment radius and letting AQTESOLV compute the effective casing radius.

Related Topics

Single Fracture Solutions

Flow to a pumping well intersected by a single fracture may exhibit a period of linear flow at early time. Use diagnostic flow plots to help identify linear and bilinear flow.

The following pumping test solution methods simulate flow to a single fracture.

Vertical fracture	Gringarten-Witherspoon (1972) uniform flux
Vertical fracture	Gringarten et al. (1974) infinite conductivity
Horizontal fracture	Gringarten-Ramey (1974) uniform-flux

- Choose Match>Solution to select a pumping test solution.

- Select Edit>Aquifer Data to edit data for single-fracture solutions.

Related Topics

Double-Porosity Solutions

Double-porosity solutions represent a fractured aquifer by two overlapping media: fractures and matrix. Flow to a pumping well occurs in fractures while water stored in matrix blocks contributes flow to the fractures.

Slab and spherical models are commonly used to depict the geometry of fractures and matrix in double-porosity, fractured aquifers. In the slab model, the aquifer consists of horizontal slabs of matrix separated by horizontal fractures. In the spherical geometry, a three-dimensional, orthogonal fracture system breaks the

aquifer into cubic blocks of matrix.

The following pumping test solution methods simulate flow to a well in a double-porosity aquifer. The solutions differ by the geometry of the matrix blocks and fractures.

➡ Example: Pumping Test in a Fractured Aquifer
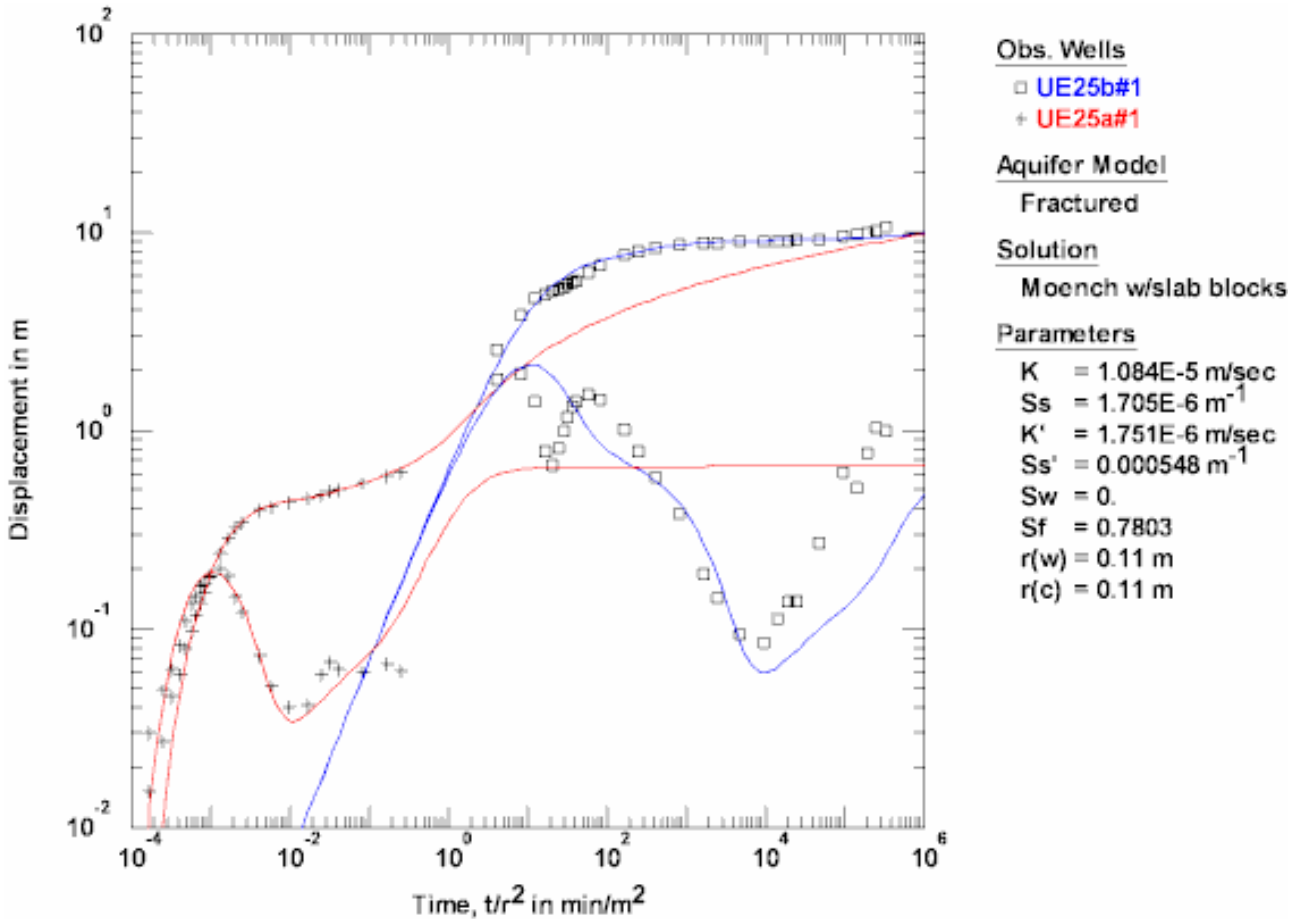
Slab-shaped blocks	Moench (1984)
Spherical blocks	Moench (1984)
Slab-shaped blocks	Barker (1988)
Spherical blocks	Barker (1988)

TIPS

- Choose Match>Solution to select a pumping test solution.

- Select Edit>Aquifer Data to edit data for double-porosity solutions.

Related Topics

Step-Drawdown Test Solutions

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 higher 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).
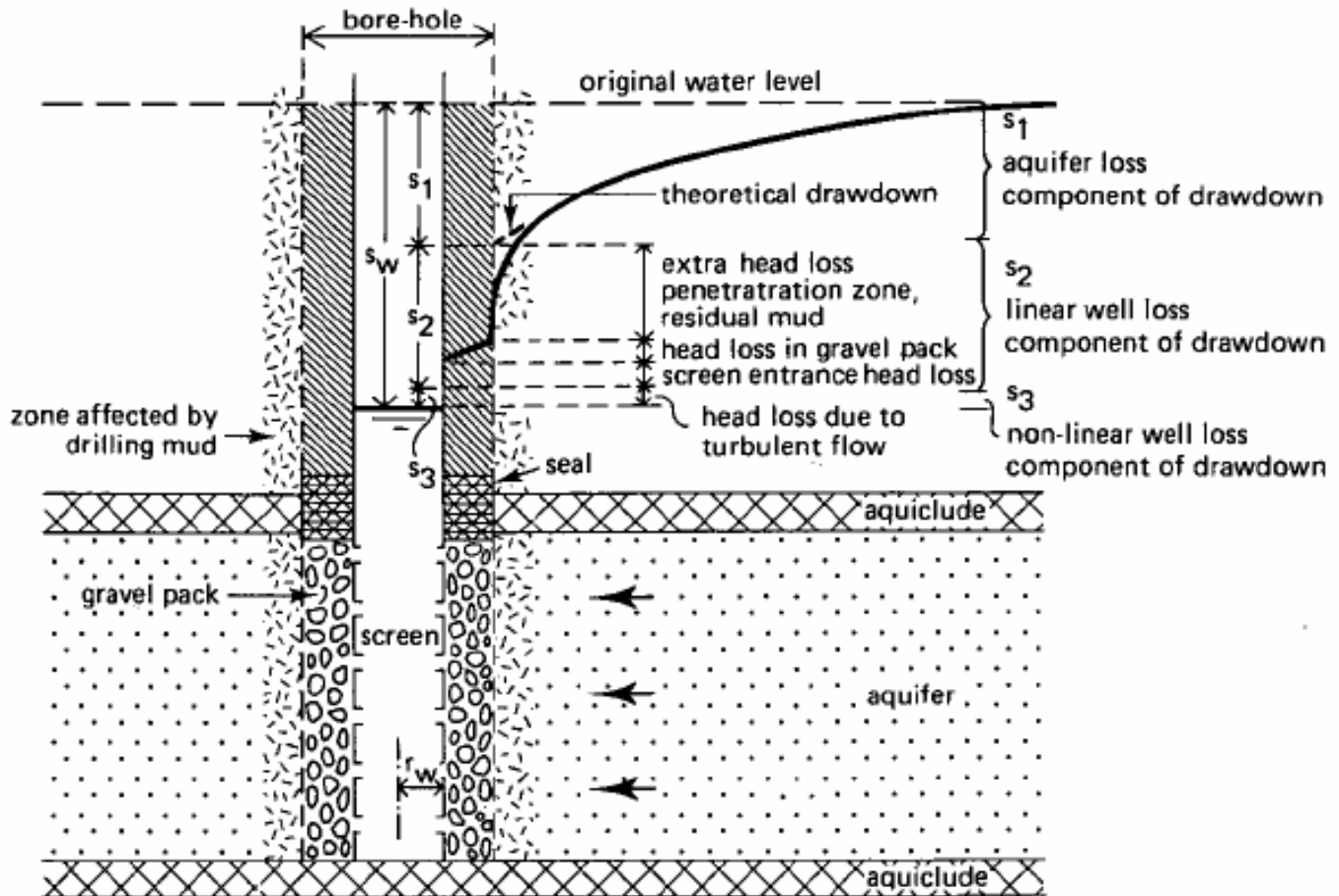
Illustration of aquifer loss and well loss components in a pumping well (Kruseman and de Ridder 1990).

Well Loss Equation

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

$$s_w = B(r_{we}, t)Q + CQ^2$$

where B is linear (laminar) head-loss coefficient and C is nonlinear (turbulent) well-loss coefficient. The first term in Jacob's drawdown equation represents linear head loss and consists of aquifer loss (s_1) and linear well loss (s_2). The second term in the

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equation is nonlinear well loss (s_3).

Linear Well Loss

The linear head-loss coefficient, B, is a function of the effective radius of the well and time. The effective well radius, r_{we}, is defined as the radial distance from the center of the well at which the theoretical drawdown in the aquifer (i.e., aquifer loss) is equal to the total linear head loss in the well (i.e., total drawdown in the well neglecting turbulent loss). The linear head-loss coefficient consists of two components:

$$B(r_{we}, t) = B_1(r_w, t) + B_2$$

where B_1 is linear aquifer-loss coefficient and B_2 is linear well-loss coefficient. The linear aquifer-loss coefficient is a function of the nominal radius of the well and time. The linear well-loss coefficient is assumed independent of time. When $B_2 > 0$, we find that $r_{we} < r_w$. When B_2 is < 0, $r_{we} > r_w$.

Ramey (1982) defines the linear well-loss coefficient in terms of a wellbore skin factor, S_w, as follows:

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

Assuming nonlinear (turbulent) well loss is negligible, the skin effect is the difference between the total drawdown in the well and the theoretical drawdown (aquifer loss) at the well screen. A positive skin ($B_2 > 0$) indicates permeability reduction at the wellbore (e.g., clogging). Negative skin ($B_2 < 0$) suggests permeability enhancement (e.g., stimulation).

Nonlinear Well Loss

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

$$s_w = B(r_{we}, t)Q + CQ^P$$

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).

Well Efficiency

The efficiency of a pumping well, which expresses the ratio of aquifer loss to total drawdown in the well, is computed as follows (Kruseman and de Ridder 1990):

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

When the linear and nonlinear well loss terms are zero, the well efficiency becomes 100%.

Solutions for Step Test Analysis

According to Bear (1979), any pumping test solution may be used to compute the linear aquifer-loss coefficient, B_1, in the well loss equation. For example, you can calculate aquifer loss using the Theis (1935) well function for confined aquifers or the Hantush-Jacob (1955) well function for leaky confined aquifers.

Choose from the following solutions for analyzing step-drawdown tests in confined and leaky aquifers.

➡ Example: Step-Drawdown Test in Confined Aquifer
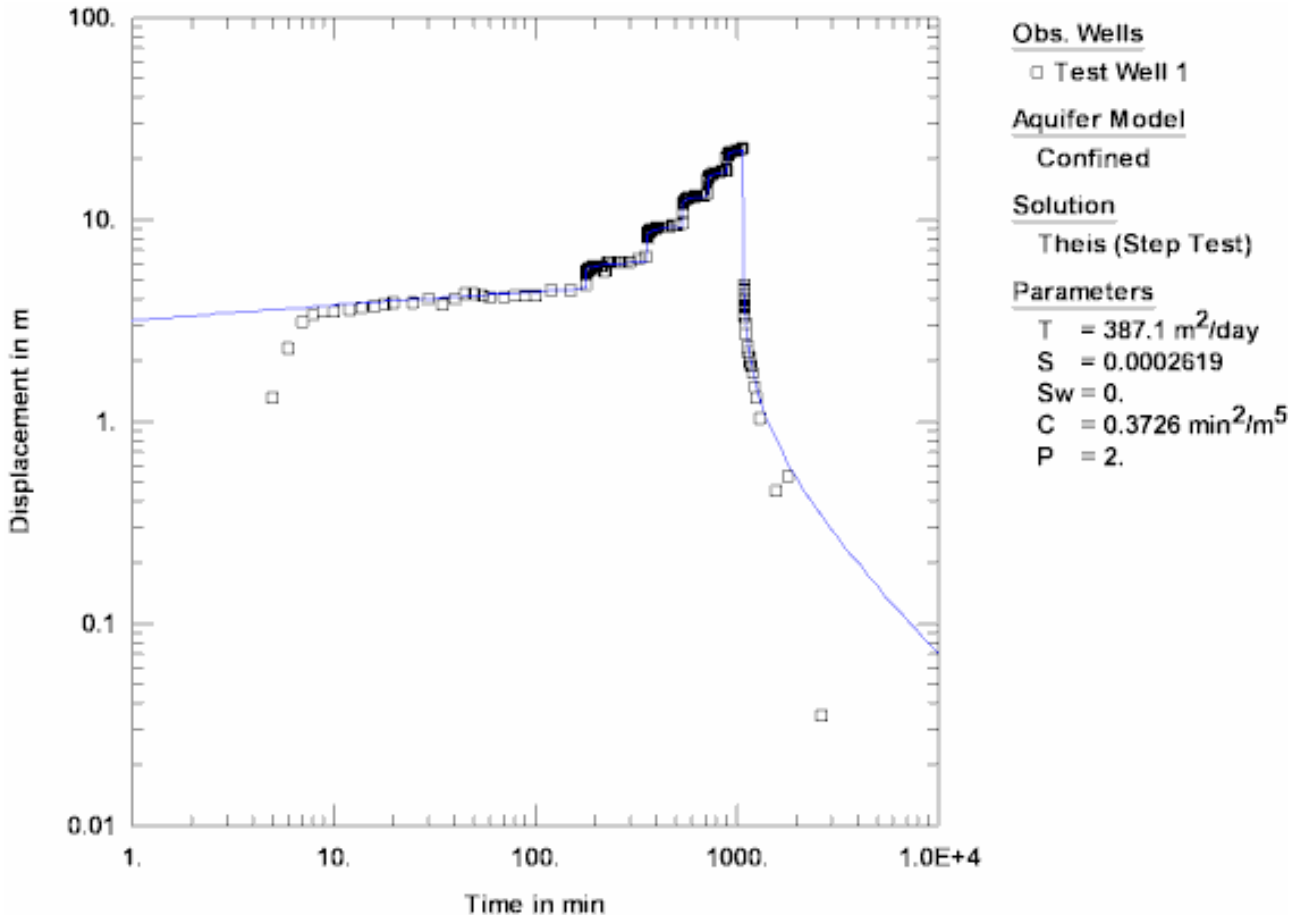
Confined	Theis (1935) step-drawdown test
Confined	Dougherty-Babu (1984) step-drawdown test
Leaky	Hantush-Jacob (1955) step-drawdown test

TIPS

- Choose Match>Solution to select a pumping test solution. Check the **Step-drawdown tests** filter to find solutions for analyzing a step-drawdown test.

Horizontal Well Solutions

AQTESOLV includes the Daviau et al. (1985) method for a pumping test in a uniform-flux or infinite-conductivity horizontal well in a confined aquifer.

- Choose Match>Solution to select a pumping test solution.

Multiaquifer Solutions

The following pumping test solution methods simulate flow in a multiaquifer system.

Confined Two-Aquifer System	Neuman-Witherspoon (1969)

- Choose Match>Solution to select a pumping test solution.

- Select Edit>Aquifer Data to edit aquifer and aquitard data.

Related Topics

Bounded Aquifer Solutions

Many of the pumping test solutions in AQTESOLV support aquifer boundaries. When you enable boundaries, AQTESOLV automatically generates images wells to simulate a number of configurations for no-flow and constant-head boundaries. Use the Solution Expert to identify which solutions support bounded aquifers.

- To apply the Vandenberg (1977) solution for a leaky strip aquifer, use the Hantush-Jacob (1955) solution with aquifer boundaries.

Nonuniform Aquifer Solutions

The following pumping test solution methods simulate flow in a nonuniform aquifer.

Confined	Moench-Prickett (1972) unconfined conversion
Confined	Butler (1988) nonuniform aquifer

- Choose Match>Solution to select a pumping test solution.

Delayed OW Response Solutions

The following pumping test solutions account for the delayed observation well response in confined, unconfined and fractured aquifers.

➡️ Example: Pumping Test in Unconfined Aquifer

Obs. Wells
- SA 1072 (Delayed)
- SA 1072

Aquifer Model
Unconfined

Solution
Moench

Parameters
T = 1.276E+4 gal/day/ft
S = 0.008449
Sy = 0.2374
Kz/Kr = 0.1208
Sw = 0.
r(w) = 0.5 ft
r(c) = 0.333 ft
alpha = 1.0E+30 day^{-1}
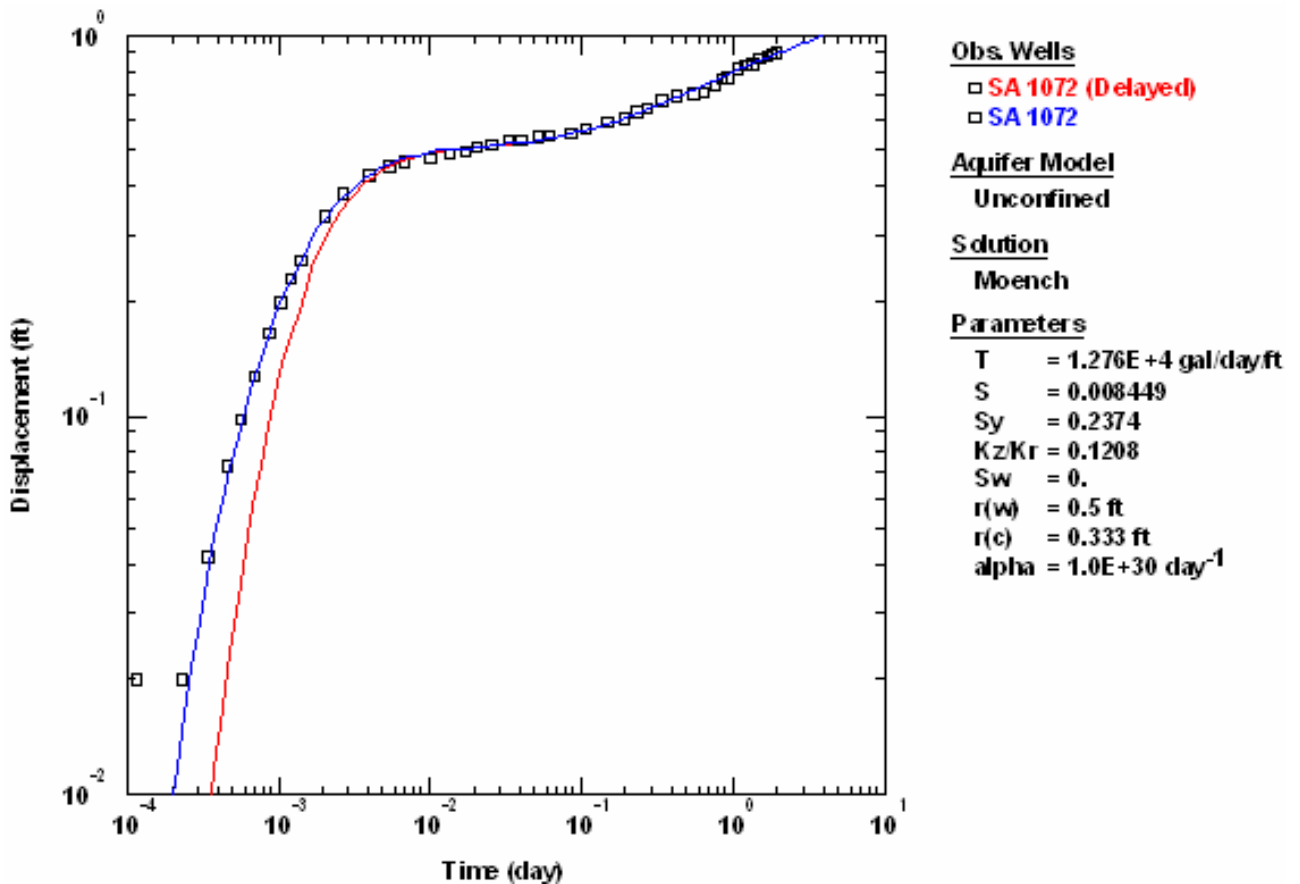
Confined	Dougherty-Babu (1984)
Unconfined	Moench (1997)
Fractured	Moench (1984)

TIPS

- Choose Match>Solution to select a pumping test solution. Check the **Delayed OW response** filter to find solutions that include the correction for delayed response in an observation well.

- Delayed observation well response may affect early-time drawdown.

- To eliminate the correction for delayed response in an observation well, enter a small casing radius value (e.g., 1.e-5).

Diagnostic Flow Plots

Use diagnostic flow plots (radial flow, linear flow, bilinear flow and spherical flow) to improve the interpretation of pumping test data.

Use diagnostic flow plots to help identify the following conditions:

- o Wellbore Storage Effects

  1. Use a radial flow plot with log-log axes to help identify wellbore storage effect in the pumped well. Early-time data exhibiting a unit slope on this plot are indicative of wellbore storage.

  2. AQTESOLV includes wellbore storage solutions for pumping tests in confined, leaky, unconfined and fractured aquifers.

- o Radial Flow in an Infinite-Acting Aquifer

  1. Use a radial flow plot with log-linear axes to help identify radial flow in an infinite-acting aquifer, i.e., late-time data plotting as a straight line. This late-time behavior on a semi-log plot is the basis for the Cooper-Jacob straight-line method of analysis.

- o Fracture Flow Conditions

  1. Use a linear flow plot with log-log axes to help identify linear flow conditions to a fracture. Early-time data exhibiting a unit slope on this plot are indicative of linear flow to a single fracture with infinite conductivity or uniform flux along the fracture.

  2. Use a bilinear flow plot with log-log axes to diagnose bilinear flow conditions to a fracture. Early-time data exhibiting a unit slope on this plot are indicative of bilinear flow to a single fracture with finite conductivity.

  3. AQTESOLV includes single fracture and double porosity solutions for pumping tests in fractured aquifers.

- o Spherical Flow Conditions

  1. Use a spherical flow plot with log-log axes to help identify spherical flow conditions. Early-time data exhibiting a unit slope on this plot are indicative of spherical flow.

Confined Aquifers

Theis (1935)/Hantush (1961) Solution for a Pumping Test in a Confined Aquifer

(Match > Solution)

Theis (1935) derived a solution for unsteady flow to a fully penetrating well in a confined aquifer. The solution assumes a line source for the pumped well and therefore neglects wellbore storage.

Hantush (1961a, b) extended the Theis method to correct for partially penetrating wells. When you choose the Theis solution in AQTESOLV, you may analyze data for fully or partially penetrating wells.

AQTESOLV uses the principle of superposition in time to simulate variable-rate tests including recovery with the Theis solution. Use this solution to analyze both pumping and recovery data from constant- or variable-rate pumping tests.

You can use the Theis (1935) solution for residual drawdown to analyze a recovery test using a straight-line matching procedure. For a well performance test, you may choose the Theis (1935) solution for a step-drawdown test.

    o   Illustration

$$s = h_o - h$$

$$\frac{\partial^2 s}{\partial r^2} + \frac{1}{r}\frac{\partial s}{\partial r} + \frac{K_z}{K_r}\frac{\partial^2 s}{\partial z^2} = \frac{S}{T}\frac{\partial s}{\partial t}$$
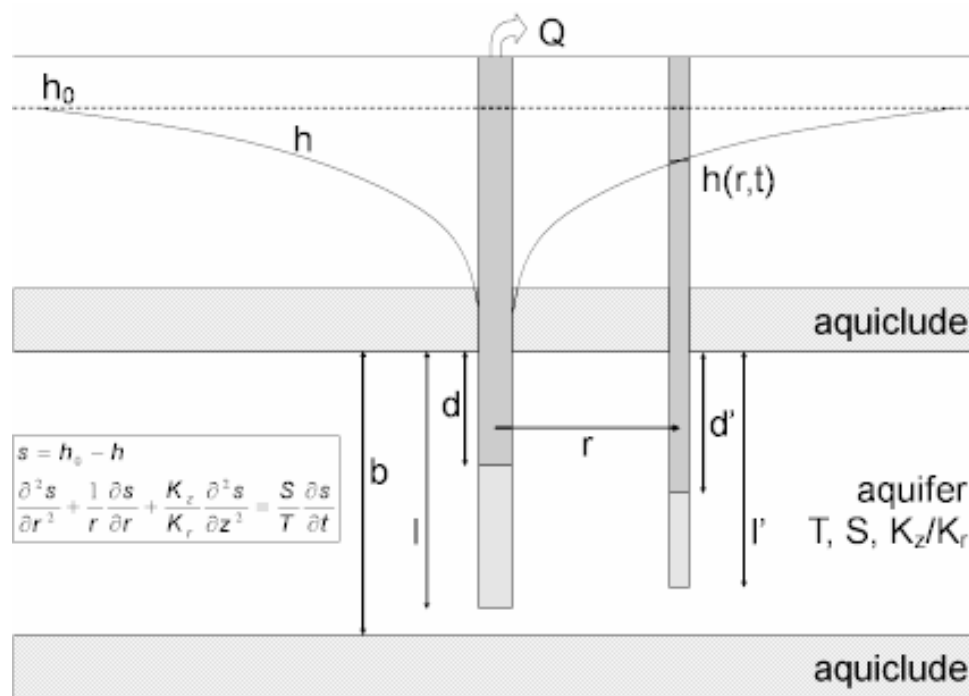
    o   Equations

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

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

$$s_D = \frac{4\pi T}{Q} s$$

$$t_D = \frac{Tt}{r^2 S}$$

where

- Q is pumping rate $[L^3/T]$
- r is radial distance $[L]$
- s is drawdown $[L]$
- S is storativity [dimensionless]
- t is time $[T]$
- T is transmissivity $[L^2/T]$

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:

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

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:

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

For an observation well, the following partial penetration correction applies:

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

where

- b is aquifer thickness $[L]$
- d is depth to top of pumping well screen $[L]$
- d' is depth to top of observation well screen $[L]$

- l is depth to bottom of pumping well screen [L]

- l' is depth to bottom of observation well screen [L]

- K_z/K_r is vertical to horizontal hydraulic conductivity anisotropy [dimensionless]

- $w(u,\beta)$ is the Hantush-Jacob well function for leaky confined aquifers

- z is depth to piezometer opening [L]

At large distances, the effect of partial penetration becomes negligible when

$$r > 1.5 b / \sqrt{K_z / K_r}$$

- o Assumptions

  - aquifer has infinite areal extent

  - aquifer is homogeneous 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

- o 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)

- o Solution Options

  - constant or variable pumping rate including recovery

  - multiple pumping wells

  - multiple observation wells

- partially penetrating wells

- boundaries

o Estimated Parameters

- T (transmissivity)

- S (storativity)

- Kz/Kr (hydraulic conductivity anisotropy ratio)

- b (saturated thickness)

Partially penetrating wells are required to estimate Kz/Kr and b.

o Curve Matching Tips

- Use the Cooper-Jacob (1946) solution to obtain preliminary estimates of aquifer properties.

- Choose Match>Visual to perform visual curve matching using the procedure for type curve solutions.

- Use active type curves for more effective visual matching with variable-rate pumping tests.

- For partially penetrating wells, select values of Kz/Kr from the **Family** and **Curve** drop-down lists on the toolbar.

- Use parameter tweaking to perform visual curve matching and sensitivity analysis.

- Perform visual curve matching prior to automatic estimation to obtain reasonable starting values for the aquifer properties.

o References

- 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.

- 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.

Related Topics

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

(Match > Solution)

Applying the principle of superposition in time, Theis (1935) proposed a straight-line solution for determining transmissivity and storativity from residual drawdown (i.e., the drawdown in a well after pumping stops) data collected during the recovery phase of a pumping test. The solution assumes a line source for the pumped well and therefore neglects wellbore storage.

If your observation data contain both pumping and recovery measurements, you may use the Theis recovery method to analyze only the recovery data recorded after the cessation of pumping.

- o   Illustration

$$s = h_0 - h$$
$$\frac{\partial^2 s}{\partial r^2} + \frac{1}{r}\frac{\partial s}{\partial r} = \frac{S}{T}\frac{\partial s}{\partial t}$$
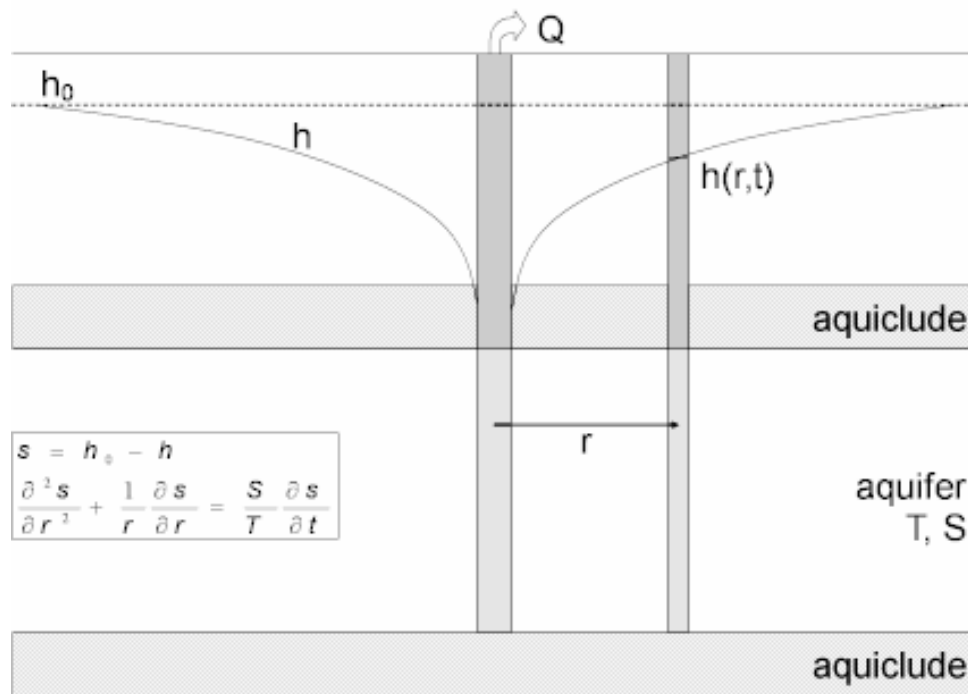
- o   Equations

Theis (1935) proposed the following equation for analyzing recovery data:

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

where

- •   Q is pumping rate [L^3/T]
- •   s' is residual drawdown [L]

- S is storativity during pumping [dimensionless]

- S' is storativity during recovery [dimensionless]

- t is time since pumping began [T]

- t' is time since pumping stopped [T]

- T is transmissivity[L^2/T]

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 recharge during the test. Conversely, a value of S/S' < 1.0 suggests the presence of a barrier or no-flow boundary.

- o 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 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)

- o Data Requirements

  - pumping and observation well locations

  - pumping rate(s)

  - observation well measurements (time and displacement)

- o Solution Options

  - constant or variable pumping rates

- o Estimated Parameters

  - T (transmissivity)

  - S/S' (ratio of storativity during pumping to storativity during recovery)

- Curve Matching Tips

  - Choose Match>Visual to perform visual curve matching using the procedure for straight-line solutions.

  - Use parameter tweaking to perform visual curve matching and sensitivity analysis.

  - Perform visual curve matching prior to automatic estimation to obtain reasonable starting values for the aquifer properties.

- 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.
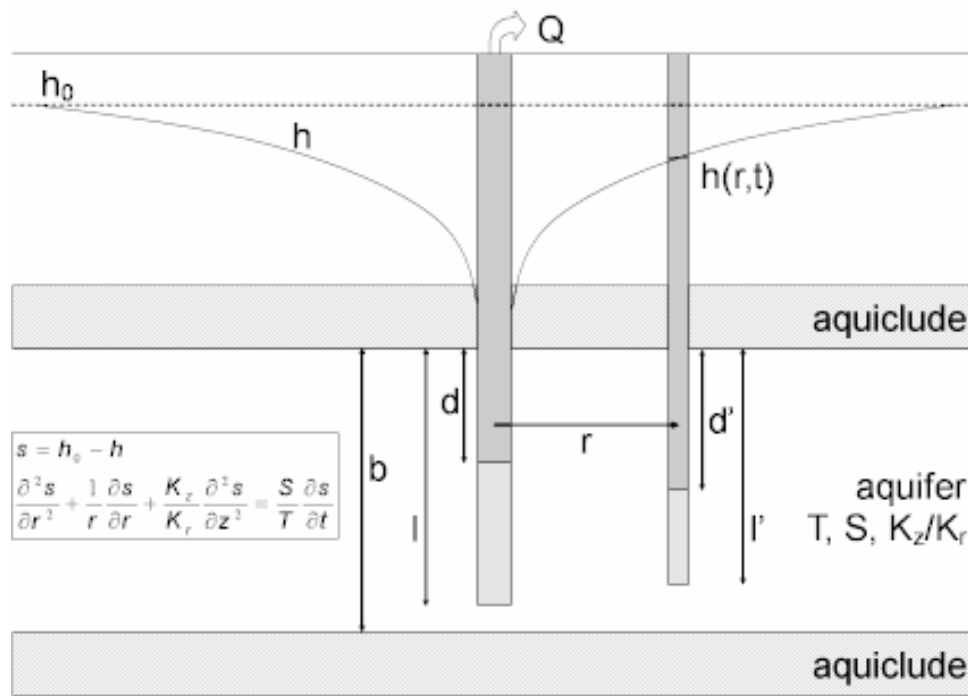
Related Topics

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

(Match > Solution)

We modify the Theis (1935) solution for unsteady flow to a well in a confined aquifer to simulate linear and nonlinear well losses using a general procedure for step-drawdown tests.

- Illustration

o Equations

The Theis (1935) solution for a fully penetrating pumping well in a confined aquifer, modified to include linear and nonlinear well losses in a step-drawdown test, is expressed as follows:

$$s_w = \frac{Q}{4\pi T}\left[W(u) + 2S_w\right] + CQ^P$$

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

$$s_D = \frac{4\pi T}{Q} s$$

$$t_D = \frac{Tt}{r^2 S}$$

where

- CQ^P is nonlinear well loss [L]

- Q is pumping rate [L^3/T]

- r is radial distance [L]

- s_w is drawdown in the pumped well [L]

- S is storativity [dimensionless]

- S_w is wellbore skin factor [dimensionless]

- t is time [T]

- T is transmissivity [L^2/T]

AQTESOLV also lets you simulate partially penetrating wells with this solution.

The effective well radius employed in this solution to incorporate wellbore skin (linear well loss) leads to correlation in the equations between S (storativity) and Sw (wellbore skin factor). Therefore, you should estimate either S or Sw for a single-well test.

o Assumptions

- aquifer has infinite areal extent

- aquifer is homogeneous 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

o 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)

o Solution Options

- variable pumping rate including recovery

- multiple pumping wells

- multiple observation wells

- partially penetrating wells

o Estimated Parameters

- T (transmissivity)

- S (storativity)

- Sw (wellbore skin factor)

- C (nonlinear well loss coefficient)

- P (nonlinear well loss exponent)

o Curve Matching Tips

- Use the Cooper-Jacob (1946) solution to obtain preliminary estimates of aquifer properties.

- Choose Match>Visual to perform visual curve matching using the procedure for type curve solutions.

- Use active type curves for more effective visual matching with variable-rate pumping tests.

- Use parameter tweaking to perform visual curve matching and sensitivity analysis.

- Perform visual curve matching prior to automatic estimation to obtain reasonable starting values for the aquifer properties.

- Due to correlation in the equations between S (storativity) and Sw (wellbore skin factor), estimate either S or Sw for a single-well test.

  o References

- 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.

- 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.

Related Topics

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

(Match > Solution)

Cooper and Jacob (1946) developed a method of analyzing pumping tests based on a straight-line approximation of the Theis (1935) equation for unsteady flow to a fully penetrating well in a confined aquifer. The solution assumes a line source for the pumped well and therefore neglects wellbore storage.

Using the principle of superposition in time, the Cooper-Jacob solution can simulate variable-rate tests. The Cooper-Jacob solution as implemented in AQTESOLV encompasses the method of Birsoy and Summers (1980) for variable pumping.

If your observation data contain **recovery measurements**, you may use the Cooper-Jacob method to analyze drawdown data up to the first recovery period. You also may use this solution to analyze data from the first recovery period on an Agarwal plot. For intermittent pumping (i.e., where the pump cycles on and off), choose the Theis (1935) solution (or any other pumping test solution in AQTESOLV) to analyze the entire set of observations (i.e., all drawdown and recovery data).

The Cooper-Jacob solution is not applicable to more than one pumping well; therefore, if your data set contains multiple pumping wells, the Cooper-Jacob solution uses only the **first** pumping well in the analysis of observation data.

o   Illustration

$$s = h_o - h$$

$$\frac{\partial^2 s}{\partial r^2} + \frac{1}{r}\frac{\partial s}{\partial r} = \frac{S}{T}\frac{\partial s}{\partial t}$$
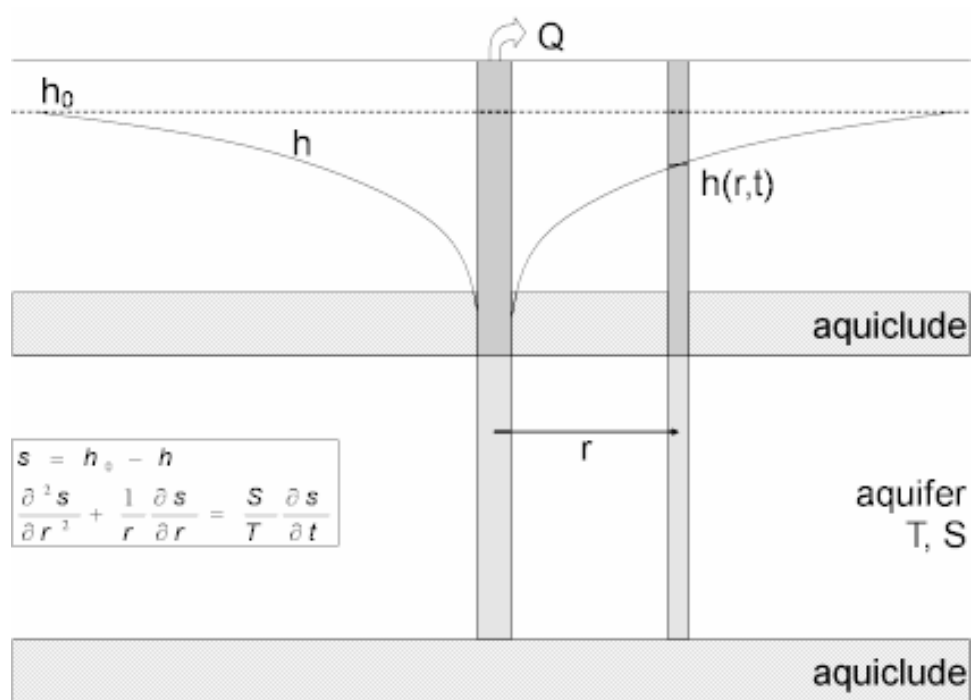
o   Equations

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

$$s = \frac{2.303Q}{4\pi T}\log\left(\frac{2.25Tt}{r^2 S}\right)$$

$$s_D = \frac{4\pi T}{Q}s$$

$$t_D = \frac{Tt}{r^2 S}$$

where

- Q is pumping rate [L^3/T]

- r is radial distance [L]

- t is time [T]

- s is drawdown [L]

- S is storativity [dimensionless]

- T is transmissivity [L^2/T]

The Cooper-Jacob solution derives from the truncation of an infinite series expression for the Theis well function. The following expression computes the value of the Theis well function, abbreviated as w(u):

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

For small values of u (e.g., u 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:

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

After rearranging and rewriting as decimal logarithms, the drawdown equation reduces to the following relationship:

$$s = \frac{2.303Q}{4\pi T}\log\left(\frac{2.25Tt}{r^2 S}\right)$$

By drawing a straight line through the data on a plot of s versus log t, we can determine T and S from the following equations:

$$T = \frac{2.303Q}{4\pi\Delta s}$$

$$S = \frac{2.25Tt_0}{r^2}$$

where Δs is change in drawdown per log cycle time and t_0 is the intercept of the fitted line on the time axis.

o 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 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)

o Data Requirements

- pumping and observation well locations

- pumping rate(s)

- observation well measurements (time and displacement)

o Solution Options

- constant or variable pumping rates

- multiple observation wells

o Estimated Parameters

- T (transmissivity)

- S (storativity)

o Curve Matching Tips

- Choose Match>Visual to perform visual curve matching using the procedure for straight-line solutions.

- Use parameter tweaking to perform visual curve matching and sensitivity analysis.

- Choose View>Options to display the critical value of u on the plot. Change the critical u value in the Valid Time tab.

- Perform visual curve matching prior to automatic estimation to obtain reasonable starting values for the aquifer properties.

- Use Agarwal plots to analyze recovery data.

- You may use the Cooper-Jacob solution to analyze drawdown data from the start of the test up to the first recovery period (a recovery period is any period with a rate equals zero).

- If your data set contains more than one recovery period, you may use the Cooper-Jacob solution to analyze recovery data in the first recovery period on an Agarwal plot.

- If your data set contains more than one pumping well, the Cooper-Jacob solution uses the **first** pumping well in the well data to analyze test data.

o   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.

- Birsoy, Y.K. and W.K. Summers, 1980. Determination of aquifer parameters from step tests and intermittent pumping, Ground Water, vol. 18, no. 2, pp. 137-146.

Related Topics

Moench-Prickett (1972) Solution for a Pumping Test in a Confined/Unconfined Aquifer

(Match > Solution)

Moench and Prickett (1972) derived a solution for unsteady flow to a fully penetrating well in a confined aquifer undergoing conversion to water-table conditions. The solution assumes a line source for the pumped well and therefore neglects wellbore storage.

o   Illustration
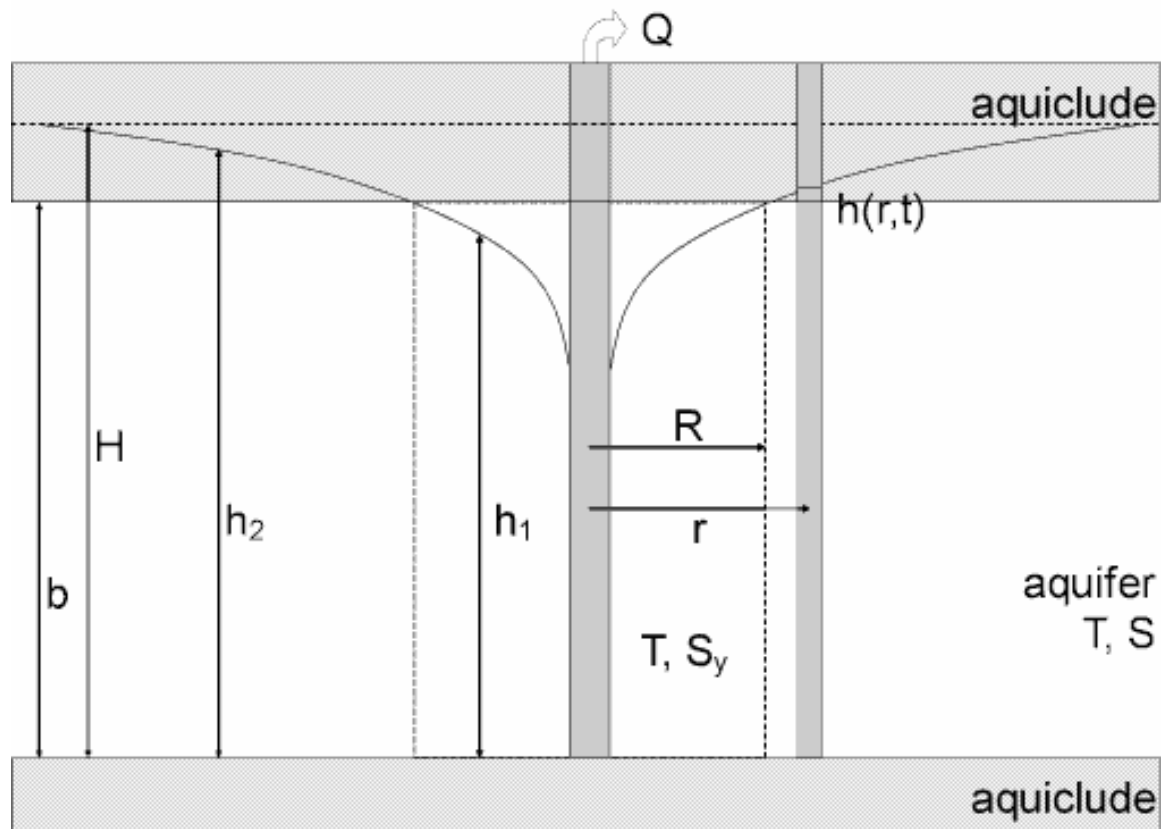
- Equations

  Moench and Prickett (1972) derived an analytical solution for unsteady flow to a fully penetrating well in a confined aquifer undergoing conversion to water-table conditions.

  when r < R,

  $$h_1 = b - \frac{Q}{4\pi T}\left(W(u_1) - W(v)\right)$$

  when r > R,

  $$h_2 = H - \frac{(H-b)W(u_2)}{W(vS/S_y)}$$

  when r = R, h = b

  $$W(x) = \int_x^\infty \frac{e^{-z}}{z}\,dz$$

  $$u_1 = \frac{r^2 S}{4Tt}$$

  $$u_2 = \frac{r^2 S_y}{4Tt}$$

  $$v = \frac{R^2 S}{4Tt}$$

  $$\frac{Q}{4\pi T(H-b)}e^{-v} - \frac{e^{-vS/S_y}}{W(vS/S_y)} = 0$$

  $$h_D = \frac{4\pi T}{Q}h$$

  $$t_D = \frac{Tt}{r^2 S}$$

  where

  - b is aquifer thickness [L]

  - h_1 is the elevation of the water table when r < R [L]

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- h_2 is the elevation of the potentiometric surface when r > R [L]

- H is the elevation of the initial potentiometric surface above the base of the aquifer [L]

- Q is pumping rate [L^3/T]

- r is radial distance [L]

- R is the radial distance to the point of conversion [L]

- S is storativity in the confined zone when r > R [dimensionless]

- Sy is the storativity in the unconfined zone when r < R [dimensionless]

- t is time [T]

- T is transmissivity [L^2/T]

Drawdown, s, is computed from the above equations as follows:

s_1 = H - h_1 (r < R)

s_2 = H - h_2 (r > R)

s_R = H - b (r = R)

When ν is greater than about 3, which implies H - b is small, the curve generated by the Moench-Prickett solution is essentially the same as the Theis solution using T and Sy. On the other hand when H - b is large and ν is small, the Moench-Prickett solution is virtually identical to the Theis solution using T and S.

- Assumptions

  - aquifer has infinite areal extent

  - aquifer is homogeneous, isotropic and of uniform thickness

  - pumping well is fully penetrating

  - pumping rate is constant

  - flow to pumping well is horizontal

  - aquifer is confined/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

- o Data Requirements

  - pumping and observation well locations

  - pumping rate

  - observation well measurements (time and displacement)

- o Solution Options

  - constant pumping rate

  - multiple observation wells

- o Estimated Parameters

  - T (transmissivity)

  - S (storativity)

  - Sy (specific yield)

  - H - b (initial head above top of aquifer)

- o Curve Matching Tips

  - Use the Cooper-Jacob (1946) solution to obtain preliminary estimates of aquifer properties.

  - Choose Match>Visual to perform visual curve matching using the procedure for type curve solutions.

  - Use active type curves for more effective visual matching.

  - Use parameter tweaking to perform visual curve matching and sensitivity analysis.

  - Perform visual curve matching prior to automatic estimation to obtain reasonable starting values for the aquifer properties.

- o References

  - Moench, A.F. and T.A. Prickett, 1972. Radial flow in an infinite aquifer undergoing conversion from artesian to water-table conditions, Water Resources Research, vol. 8, no. 2, pp. 494-499.

Related Topics

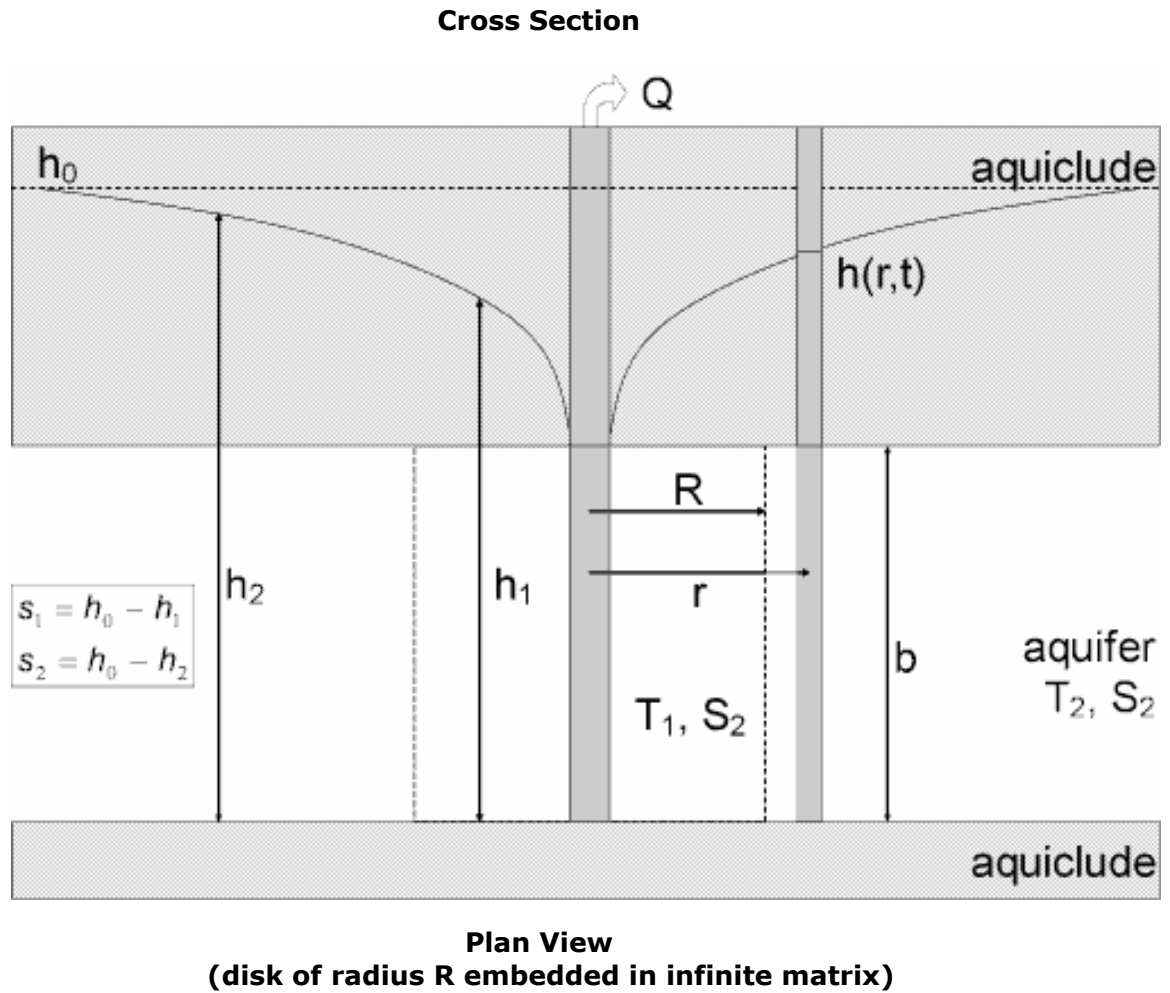# Butler (1988) Solution for a Pumping Test in a Confined Aquifer
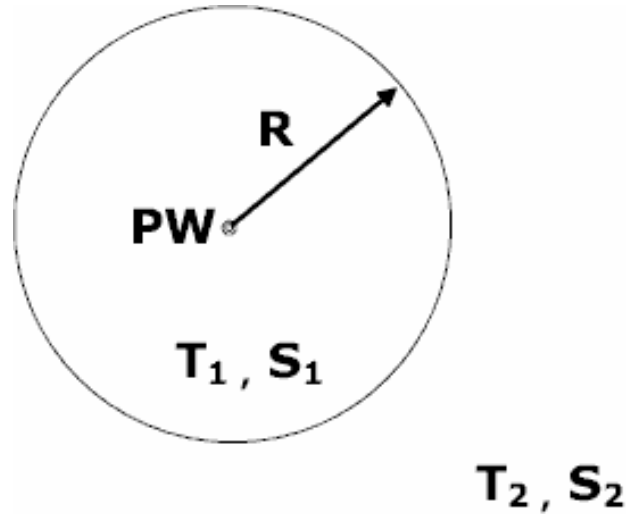
(Match > Solution)

Butler (1988) derived a solution for unsteady flow to a fully penetrating well in a heterogeneous, isotropic confined aquifer. The solution assumes the pumping well is

located at the center of a disk of radius R embedded within an infinite matrix. Hydraulic properties of the disk and matrix are assumed uniform, but may differ between the two zones. The solution assumes a line source for the pumped well and therefore neglects wellbore storage.

The Butler solution can simulate variable-rate tests including recovery using the principle of superposition in time. Use this solution to analyze both pumping and recovery data from constant- or variable-rate pumping tests.

o   Illustration

Cross Section

Plan View
(disk of radius R embedded in infinite matrix)

- o Equations

Butler (1988) derived a solution for unsteady flow to a fully penetrating well in a heterogeneous, isotropic confined aquifer. The solution assumes the pumping well is located at the center of a disk of radius R embedded within an infinite matrix. The Laplace transform solution is as follows:

$$\overline{s}_1 = \left(\frac{Q}{2\pi T_1}\right)\frac{K_0(Nr)}{p} + \left(\frac{Q}{2\pi T_1}\right)\frac{\left[K_1(NR)K_0(AR) - \frac{T_2}{T_1}\frac{A}{N}K_0(NR)K_1(AR)\right]I_0(Nr)}{p\left[\frac{T_2}{T_1}\frac{A}{N}I_0(NR)K_1(AR) + I_1(NR)K_0(AR)\right]}$$

$$\overline{s}_2 = \left(\frac{Q}{2\pi T_1}\right)\frac{\left[K_0(NR)I_1(NR) + K_1(NR)I_0(NR)\right]K_0(Ar)}{p\left[\frac{T_2}{T_1}\frac{A}{N}I_0(NR)K_1(AR) + I_1(NR)K_0(AR)\right]}$$

$$N = \sqrt{S_1 p / T_1}$$

$$A = \sqrt{S_2 p / T_2}$$

$$s_D = \frac{4\pi T}{Q}s$$

$$t_D = \frac{Tt}{r^2 S}$$

where

- I_i is modified Bessel function of first kind, order i

- K_i is modified Bessel function of second kind, order i
- p is Laplace transform variable
- Q is pumping rate $[L^3/T]$
- r is radial distance [L]
- R is radial distance to disk-matrix interface [L]
- s_1 is drawdown in the disk [L]
- s_2 is drawdown in the matrix [L]
- S_1 is storativity in the disk [dimensionless]
- S_2 is storativity in the matrix [dimensionless]
- t is time [T]
- T_1 is transmissivity in the disk $[L^2/T]$
- T_2 is transmissivity in the matrix $[L^2/T]$

o Assumptions
- aquifer has infinite areal extent
- aquifer is heterogeneous with a disk embedded in a matrix
- 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

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

o Solution Options
- constant or variable pumping rate including recovery
- multiple observation wells

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- Estimated Parameters

  - T1 (transmissivity in disk)

  - S2 (storativity in disk)

  - T2 (transmissivity in matrix)

  - S2 (storativity in matrix)

  - R (radial distance to disk-matrix interface)

- Curve Matching Tips

  - Use the Cooper-Jacob (1946) solution to obtain preliminary estimates of aquifer properties.

  - Choose Match>Visual to perform visual curve matching using the procedure for type curve solutions.

  - Use active type curves for more effective visual matching with variable-rate pumping tests.

  - Use parameter tweaking to perform visual curve matching and sensitivity analysis.

  - Perform visual curve matching prior to automatic estimation to obtain reasonable starting values for the aquifer properties.

- References

  - Butler, J.J., Jr., 1988. Pumping tests in nonuniform aquifers—the radially symmetric case, Journal of Hydrology, vol. 101, pp. 15-30.

Related Topics

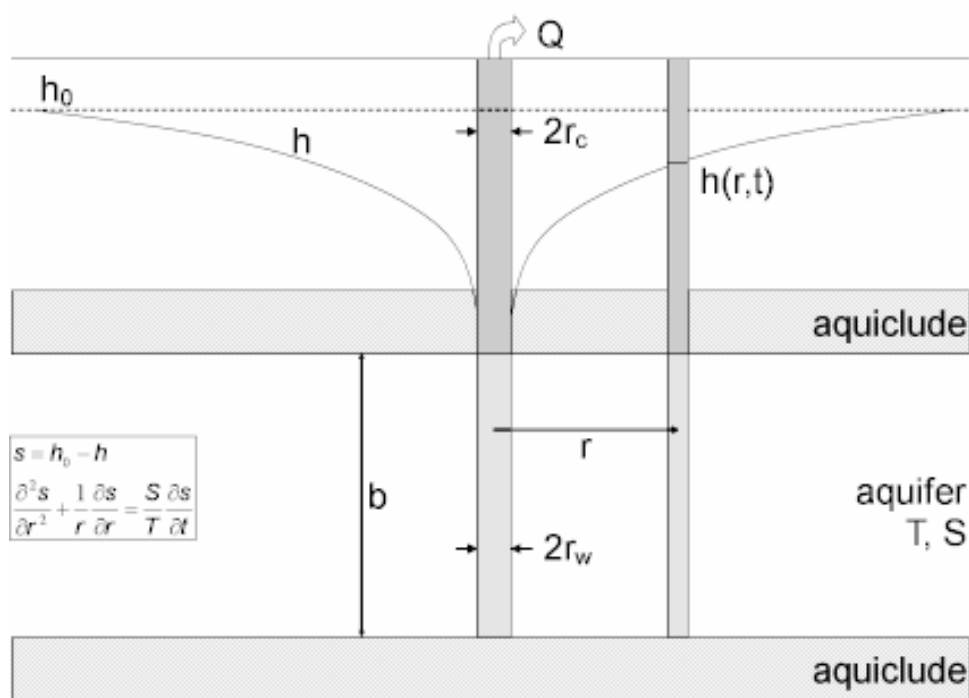# Papadopulos-Cooper (1967) Solution for a Pumping Test in a Confined Aquifer

(Match > Solution)

Papadopulos and Cooper (1967) derived a solution for unsteady flow to a fully penetrating, finite-diameter well with wellbore storage in a homogeneous, isotropic confined aquifer.

AQTESOLV uses the principle of superposition in time to simulate variable-rate tests including recovery with the Papadopulos-Cooper solution. Use this solution to analyze both pumping and recovery data from constant- or variable-rate pumping tests.

Wellbore storage has a distinct signature in the early-time response of a pumped well. Use the radial flow and derivative-time plots to detect the wellbore storage effect.

- o Illustration

- o Equations

Papadopulos and Cooper (1967) derived a solution for a finite-diameter pumping well with wellbore storage in a confined aquifer as follows:

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

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

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

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

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

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

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

$$s_D = \frac{4\pi T}{Q} s$$

$$t_D = \frac{Tt}{r_w^2 S}$$

where

- J_i is Bessel function of first kind, order i

- Q is pumping rate [L^3/T]

- r is radial distance [L]

- r_c is casing radius [L]

- r_w is well radius [L]

- s is drawdown [L]

- S is storativity [dimensionless]

- t is time [T]

- T is transmissivity [L^2/T]

- Y_i is Bessel function of second kind, order i

If you enter a radius for downhole equipment, AQTESOLV uses the effective casing radius instead of the nominal casing radius in the equations for this 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

  - 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)
- downhole equipment radius (optional)

o Solution Options

- constant or variable pumping rate including recovery
- multiple pumping wells
- multiple observation wells
- boundaries

o Estimated Parameters

- T (transmissivity)
- S (storativity)
- r(w) (well radius)
- r(c) (nominal casing radius)

o Curve Matching Tips

- Use radial flow plots to help diagnose wellbore storage.
- Match the Cooper-Jacob (1946) solution to late-time data to obtain preliminary estimates of aquifer properties.
- Match early-time data affected by wellbore storage by adjusting **r(c)** with parameter tweaking.
- If you estimate **r(c)** for the test well, the estimated value replaces the nominal casing radius and AQTESOLV still performs the correction for downhole equipment.
- Choose Match>Visual to perform visual curve matching using the procedure for type curve solutions.
- Use active type curves for more effective visual matching with variable-rate pumping tests.
- Select values of S, r(w) and r(c) from the **Family** and **Curve** drop-down lists on the toolbar.
- Use parameter tweaking to perform visual curve matching and sensitivity analysis.
- Perform visual curve matching prior to automatic estimation to obtain reasonable starting values for the aquifer properties.

- Papadopulos, I.S. and H.H. Cooper, 1967. Drawdown in a well of large diameter, Water Resources Research, vol. 3, no. 1, pp. 241-244.

Related Topics

Dougherty-Babu (1984) Solution for a Pumping Test in a Confined Aquifer
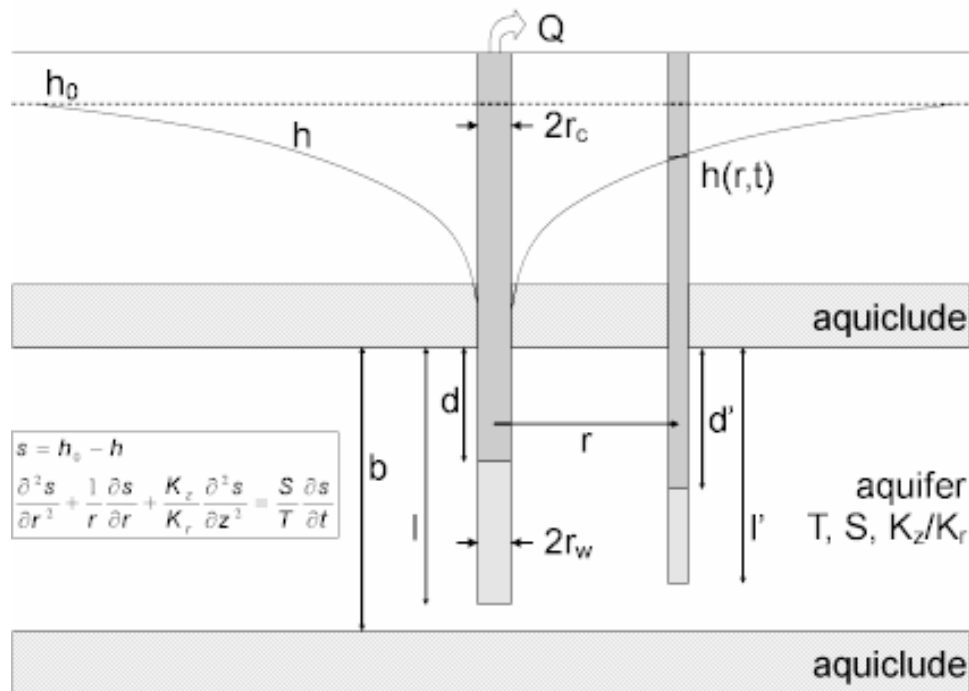
(Match > Solution)

Dougherty and Babu (1984) derived an analytical solution for unsteady flow to a fully or partially penetrating, finite-diameter well with wellbore storage and wellbore skin in a homogeneous, isotropic confined aquifer. Moench (1988) extended the method to include anisotropy. The Dougherty-Babu solution also includes delayed response in an observation well based on the work of Moench (1997).

AQTESOLV uses the principle of superposition in time to simulate variable-rate tests including recovery with the Dougherty-Babu solution. Use this solution to analyze both pumping and recovery data from constant- or variable-rate pumping tests.

Wellbore storage has a distinct signature in the early-time response of a pumped well. Use the radial flow and derivative-time plots to detect the wellbore storage effect.

o Illustration

$$s = h_o - h$$

$$\frac{\partial^2 s}{\partial r^2} + \frac{1}{r}\frac{\partial s}{\partial r} + \frac{K_z}{K_r}\frac{\partial^2 s}{\partial z^2} = \frac{S}{T}\frac{\partial s}{\partial t}$$

o Equations

Dougherty and Babu (1984) derived an analytical solution for predicting

drawdown in response to pumping in a confined aquifer assuming partially penetrating wells, wellbore storage and wellbore skin. The following equations include a modification by Moench (1988) to include anisotropy.

The Laplace transform solution for dimensionless drawdown in the pumped well is as follows:

$$\bar{h}_{wD} = \frac{2(A_0 + A + S_w)}{p(l_D - d_D)[1 + pW_D(A_0 + A + S_w)]}$$

The following equation is the Laplace transform solution for dimensionless drawdown in a piezometer:

$$\bar{h}_D = \frac{2(E_0 + E)}{p(l_D - d_D)[1 + pW_D(A_0 + A + S_w)]}$$

The equation for dimensionless drawdown in an observation well is:

$$\bar{h}_D' = \frac{2(E_0' + E')}{p(l_D - d_D)[1 + pW_D(A_0 + A + S_w)]}$$

$$A_0 = \frac{(l_D - d_D)K_0(q_0)}{q_0 K_1(q_0)}$$

$$A = \frac{2}{(l_D - d_D)} \sum_{n=1}^{\infty} \frac{K_0(q_n)[\sin(n\pi l_D) - \sin(n\pi d_D)]^2}{n^2\pi^2 q_n K_1(q_n)}$$

$$E_0 = E_0' = \frac{(l_D - d_D)K_0(q_0 r_D)}{q_0 K_1(q_0)}$$

$$E = 2\sum_{n=1}^{\infty} \frac{K_0(\bar{q}_n r_D)\cos(n\pi z_D)[\sin(n\pi l_D) - \sin(n\pi d_D)]}{n\pi \bar{q}_n K_1(\bar{q}_n)}$$

$$E' = 2\sum_{n=1}^{\infty} \frac{K_0(q_n r_D)[\sin(n\pi l_D') - \sin(n\pi d_D')][\sin(n\pi l_D) - \sin(n\pi d_D)]}{(l_D' - d_D')n^2\pi^2 q_n K_1(q_n)}$$

$$W_D = \frac{\pi r_c^2}{2\pi r_w^2 S_s(l - d)}$$

$$q_n = \sqrt{\frac{r_w^2 n^2 \pi^2}{b^2} \frac{K_z}{K_r} + p}$$

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

$$t_D = \frac{Kt}{S_s r_w^2}$$

$$h_D = \frac{4\pi Kb}{Q}(h_0 - h)$$

where

- b is aquifer thickness [L]

- d is distance from water table to top of pumping well screen [L]

- d_D is d/b

- K, K_r is radial hydraulic conductivity [L/T]

- K_z is vertical hydraulic conductivity [L/T]

- K_i is modified Bessel function of second kind, order i

- l is distance from water table to bottom of pumping well screen [L]

- l_D is l/b

- p is the Laplace transform variable

- Q is pumping rate [L^3/T]

- r is radial distance [L]

- r_c is casing radius [L]

- r_w is well radius [L]

- S_s is specific storage [1/L]

- S_w is wellbore skin factor [dimensionless]

- t is time [T]

- z is elevation of piezometer above base of aquifer [L]

- z_D is z/b

- z_1 is elevation of bottom of observation well screen above base of aquifer [L]

- z_{1D} is z_1/b

- z_2 is elevation of top of observation well screen above base of aquifer [L]

- z_{2D} is z_2/b

In the Laplace transform solution, S_w is limited to positive values; however, using the effective well radius concept, we also may simulate a negative skin (Hurst, Clark and Brauer 1969).

If you enter a radius for downhole equipment, AQTESOLV uses the effective casing radius instead of the nominal casing radius in the equations for this solution.

Refer to the Moench (1997) solution for the equations relating to delayed response in an observation well.

- o Assumptions

  - aquifer has infinite areal extent

  - aquifer is homogeneous and of uniform thickness

  - aquifer potentiometric surface is initially horizontal

  - pumping and observation wells are fully or partially penetrating

  - flow is unsteady

  - aquifer is confined

  - water is released instantaneously from storage with decline of hydraulic head

- o 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)

  - downhole equipment radius (optional)

  - partial penetration depths

  - saturated thickness

  - hydraulic conductivity anisotropy ratio

- o Solution Options

  - constant or variable pumping rate including recovery

  - multiple pumping wells

  - multiple observation wells
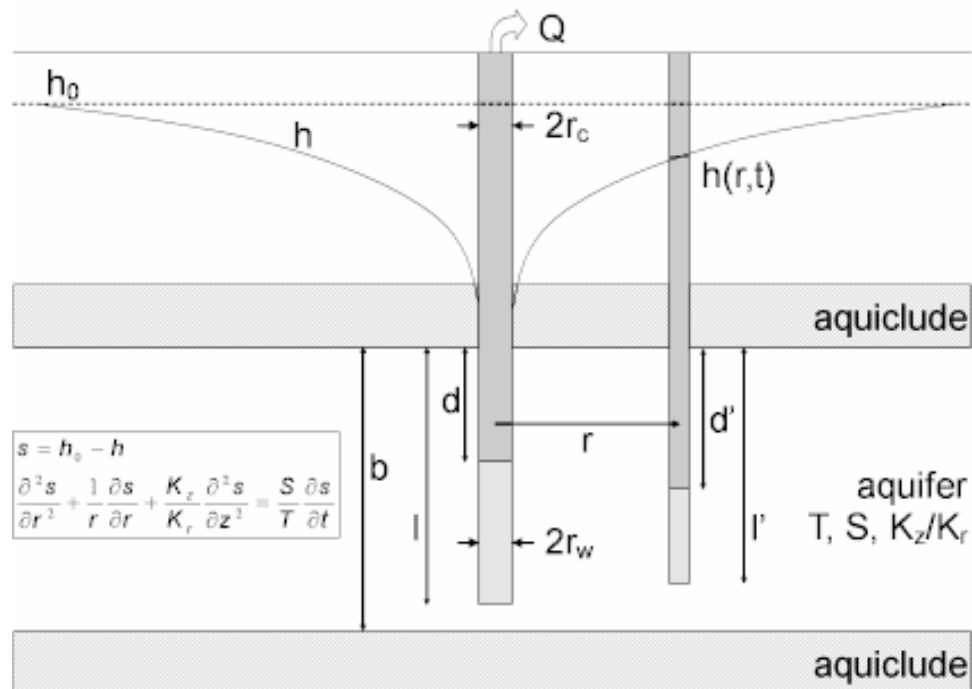
  - partially penetrating wells

- boundaries

  o Estimated Parameters

  - T (transmissivity)

  - S (storativity)

  - Kz/Kr (hydraulic conductivity anisotropy ratio)

  - Sw (dimensionless wellbore skin factor)

  - r(w) (well radius)

  - r(c) (nominal casing radius)

  o Curve Matching Tips

  - Use radial flow plots to help diagnose wellbore storage.

  - Match the Cooper-Jacob (1946) solution to late-time data to obtain preliminary estimates of aquifer properties.

  - Match early-time data affected by wellbore storage by adjusting **r(c)** with parameter tweaking.

  - If you estimate **r(c)** for the test well, the estimated value replaces the nominal casing radius and AQTESOLV still performs the correction for downhole equipment.

  - Choose Match>Visual to perform visual curve matching using the procedure for type curve solutions.

  - Use active type curves for more effective visual matching with variable-rate pumping tests.

  - Select values of Kz/Kr from the **Family** and **Curve** drop-down lists on the toolbar.

  - Use parameter tweaking to perform visual curve matching and sensitivity analysis.

  - Perform visual curve matching prior to automatic estimation to obtain reasonable starting values for the aquifer properties.

  o References

  - Dougherty, D.E and D.K. Babu, 1984. Flow to a partially penetrating well in a double-porosity reservoir, Water Resources Research, vol. 20, no. 8, pp. 1116-1122.

  - Moench, A.F., 1988. The response of partially penetrating wells to pumpage from double-porosity aquifers, Proceedings of the International Conference on Fluid Flow in Fractured Rocks, Atlanta, GA, May 16-18, 1988.

Dougherty-Babu (1984) Solution for a Step-Drawdown Test in a Confined Aquifer

(Match > Solution)

We modify the Dougherty-Babu (1984) solution for unsteady flow to a well in a confined aquifer to simulate linear and nonlinear well losses using a general procedure for step-drawdown tests.

- o Illustration

- o Equations

  Dougherty and Babu (1984) derived an analytical solution for predicting drawdown in response to pumping in a confined aquifer assuming partially penetrating wells, wellbore storage and wellbore skin.

  For a step-drawdown test, we modify the equations for drawdown in the pumped well in the Dougherty-Babu (1984) solution by adding a term for nonlinear well loss:

  CQ^P

  where

  - C is nonlinear well loss coefficient $[T^2/L^5]$

  - P is nonlinear well exponent [-]

- Q is pumping rate $[L^3/T]$

- Assumptions

  - aquifer has infinite areal extent

  - aquifer is homogeneous and of uniform thickness

  - aquifer potentiometric surface is initially horizontal

  - pumping and observation wells are fully or partially penetrating

  - flow is unsteady

  - aquifer is confined

  - 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)

  - downhole equipment radius (optional)

  - partial penetration depths

  - saturated thickness

  - hydraulic conductivity anisotropy ratio

- Solution Options

  - constant or variable pumping rate including recovery

  - multiple pumping wells

  - multiple observation wells

  - partially penetrating wells

  - boundaries

- Estimated Parameters

  - T (transmissivity)

  - S (storativity)

  - Kz/Kr (hydraulic conductivity anisotropy ratio)

  - Sw (dimensionless wellbore skin factor)

- r(w) (well radius)

- r(c) (nominal casing radius)

- C (nonlinear well loss coefficient)

- P (nonlinear well loss exponent)

o Curve Matching Tips

- Use radial flow plots to help diagnose wellbore storage.

- Match the Cooper-Jacob (1946) solution to late-time data to obtain preliminary estimates of aquifer properties.

- Match early-time data affected by wellbore storage by adjusting **r(c)** with parameter tweaking.

- If you estimate **r(c)** for the test well, the estimated value replaces the nominal casing radius and AQTESOLV still performs the correction for downhole equipment.

- Choose Match>Visual to perform visual curve matching using the procedure for type curve solutions.

- Use active type curves for more effective visual matching with variable-rate pumping tests.

- Select values of Kz/Kr from the **Family** and **Curve** drop-down lists on the toolbar.

- Use parameter tweaking to perform visual curve matching and sensitivity analysis.

- Perform visual curve matching prior to automatic estimation to obtain reasonable starting values for the aquifer properties.

o References

- Dougherty, D.E and D.K. Babu, 1984. Flow to a partially penetrating well in a double-porosity reservoir, Water Resources Research, vol. 20, no. 8, pp. 1116-1122.

- Moench, A.F., 1988. The response of partially penetrating wells to pumpage from double-porosity aquifers, Proceedings of the International Conference on Fluid Flow in Fractured Rocks, Atlanta, GA, May 16-18, 1988.

- Bear, J., 1979. Hydraulics of Groundwater, McGraw-Hill, New York, 569p.

Related Topics

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

(Match > Solution)

Hantush (1962) derived a solution for unsteady flow to a fully penetrating well in a wedge-shaped confined aquifer. The solution assumes a line source for the pumped well and therefore neglects wellbore storage.

AQTESOLV uses the principle of superposition in time to simulate variable-rate tests including recovery with the Hantush wedge aquifer solution. Use this solution to analyze both pumping and recovery data from constant- or variable-rate pumping tests.

- o Illustration
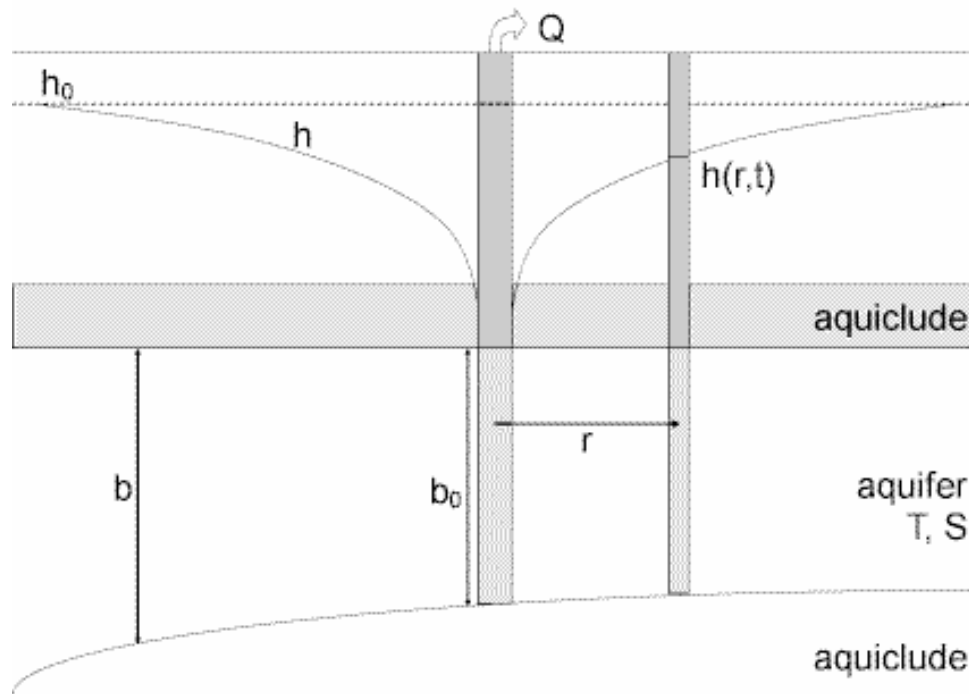
- o Equations

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

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

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

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

$$s_D = \frac{4\pi T}{Q} s$$

$$t_D = \frac{Tt}{r^2 S}$$

where

- b is aquifer thickness [L]

- Q is pumping rate [L^3/T]

- r is radial distance [L]

- s is drawdown [L]

- S is storativity [dimensionless]

- t is time [T]

- T is transmissivity [T^2/T]

- x is coordinate direction [L]

- x_0 is x-coordinate of pumped well [L]

Ordinarily, the slope on the base of the confined aquifer varies exponentially in the x direction and is constant in the y 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, b, 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:

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

Hydrogeologists commonly refer to the integral in the drawdown equation as the Hantush well function.

- o 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 leaky 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 does not extend 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

- o Data Requirements

  - pumping and observation well locations

  - pumping rate(s)

  - observation well measurements (time and displacement)

- o Solution Options

  - constant or variable pumping rate including recovery

  - multiple observation wells

- o Estimated Parameters

  - T (transmissivity)

  - S (storativity)

  - r/a (leakage parameter)

  - Kz/Kr (hydraulic conductivity anisotropy ratio)

  - b (saturated thickness)

- o Curve Matching Tips

    - Use the Cooper-Jacob (1946) solution to obtain preliminary estimates of aquifer properties.

    - Choose Match>Visual to perform visual curve matching using the procedure for type curve solutions.

    - Use active type curves for more effective visual matching with variable-rate pumping tests.

    - For partially penetrating wells, select values of r/a from the **Family** and **Curve** drop-down lists on the toolbar.

    - Use parameter tweaking to perform visual curve matching and sensitivity analysis.

    - Perform visual curve matching prior to automatic estimation to obtain reasonable starting values for the aquifer properties.

- o References

    - 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.

Related Topics

Murdoch (1994) Solution for a Pumping Test in a Confined Aquifer

(Match > Solution)

Murdoch (1994) presented an analytical solution for unsteady flow to an interceptor trench based on the Gringarten and Witherspoon (1972) solution for flow to a uniform-flux plane vertical fracture in an anisotropic confined aquifer. The trench is represented by a fully penetrating vertical plane source oriented parallel to the x axis. In the uniform-flux formulation of this solution, drawdown is variable and flux is uniformly distributed along the length of the trench.

AQTESOLV uses the principle of superposition in time to simulate variable-rate tests including recovery with the Murdoch solution. Use this solution to analyze both pumping and recovery data from constant- or variable-rate pumping tests.

The early-time response of a pumped well intersecting an interceptor trench has a distinct signature that you can diagnose with a linear flow plot.

o Illustration
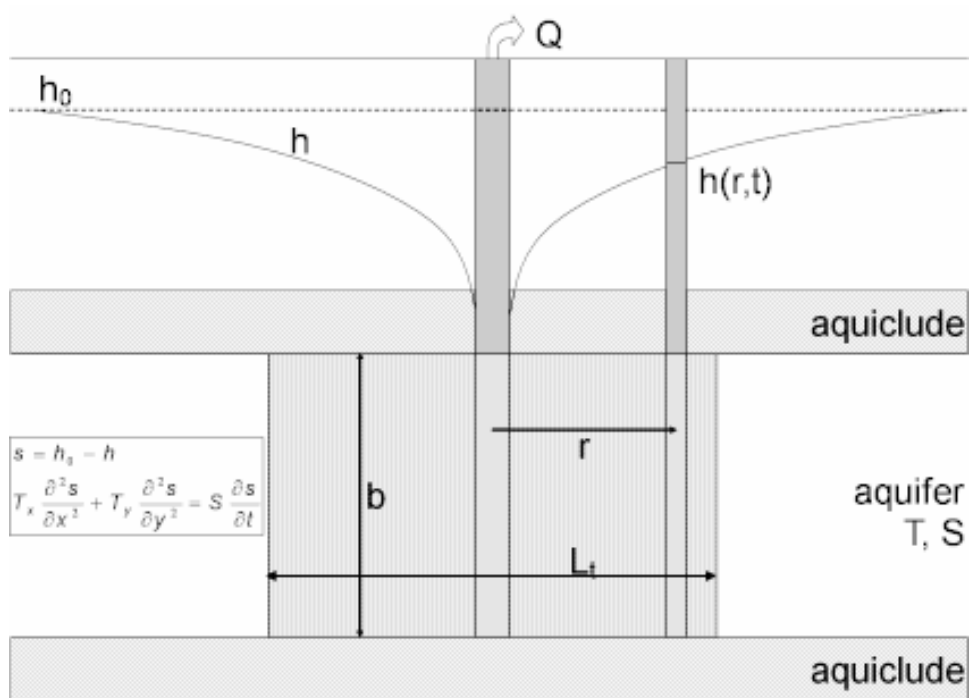
o Equations

In the Gringarten-Witherspon (1972) solution for a vertical fracture in a confined aquifer, the Murdoch (1994) solution for an interceptor trench replaces the length of the fracture (L_f) with the length of the trench (L_t).

o 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

o Data Requirements

- interceptor trench and observation well locations

- pumping rate(s)

- observation well measurements (time and displacement)

- saturated thickness

- length of trench

o Solution Options

- constant or variable pumping rate including recovery

- multiple pumping wells

- multiple observation wells

- boundaries

o Estimated Parameters

- Kx (hydraulic conductivity in x direction)

- Ss (specific storage)

- Ky/Kx (hydraulic conductivity anisotropy ratio)

- Lt (length of trench)

o Curve Matching Tips

- Use linear flow plots to help diagnose linear flow.

- Use the Cooper-Jacob (1946) solution to obtain preliminary estimates of aquifer properties.

- Choose Match>Visual to perform visual curve matching using the procedure for type curve solutions.

- Use active type curves for more effective visual matching with variable-rate pumping tests.

- Select values of Ky/Kx from the **Family** and **Curve** drop-down lists on the toolbar.

- Use parameter tweaking to perform visual curve matching and sensitivity analysis.

- Perform visual curve matching prior to automatic estimation to obtain reasonable starting values for the aquifer properties.

o References

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

- 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.

Related Topics

Daviau et al. (1985) Solution for a Pumping Test in a Confined Aquifer

(Match > Solution)

In the petroleum industry literature, Daviau et al. (1985) and Clonts and Ramey (1986) appear to have developed independently an analytical solution for a uniform-flux or infinite-conductivity horizontal well in an anisotropic confined aquifer. The horizontal well is represented in the solution by a line source oriented parallel to the x axis.

AQTESOLV uses the principle of superposition in time to simulate variable-rate tests including recovery with the Daviau et al. solution. Use this solution to analyze both pumping and recovery data from constant- or variable-rate pumping tests.

When you choose a solution, AQTESOLV provides two options for the Daviau et al. solution: uniform-flux and infinite-conductivity horizontal wells.

- o Illustration

$$s = h_0 - h$$

$$\frac{\partial^2 s}{\partial r^2} + \frac{1}{r}\frac{\partial s}{\partial r} + \frac{K_z}{K_r}\frac{\partial^2 s}{\partial z^2} = S_s \frac{\partial s}{\partial t}$$
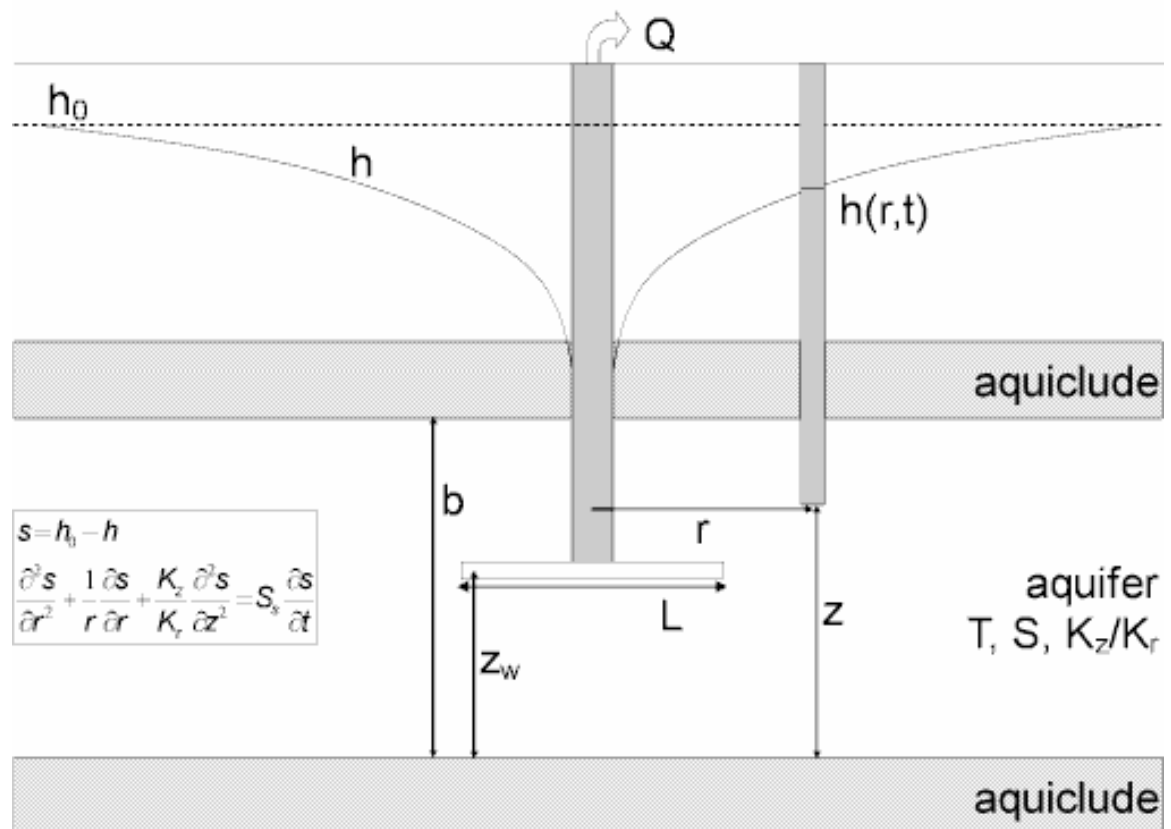
- o Equations

  The following equation by Daviau et al. (1985) and Clonts and Ramey (1986) predicts drawdown in a point (piezometer) in a confined aquifer with a uniform-flux horizontal well:

$$s = \frac{Q}{4\pi T} \frac{\sqrt{\pi}}{2} \int\limits_0^{t_D} \left[\text{erf} \frac{1-x_D}{2\sqrt{\tau}} + \text{erf} \frac{1+x_D}{2\sqrt{\tau}} \right] \exp(-y_D^2/4\tau)$$

$$\times \left[1 + 2\sum_{n=1}^{\infty} \exp(-n^2\pi^2 L_D^2 \tau) \cos(n\pi z_D) \cos(n\pi z_{wD}) \right] \frac{d\tau}{\sqrt{\tau}}$$

$$t_D = \frac{4Tt}{SL^2}$$

$$x_D = \frac{2x}{L}$$

$$y_D = \frac{2y}{L}$$

$$z_D = \frac{z}{b}$$

$$L_D = \frac{L}{2b}\sqrt{K_z/K_r}$$

$$r_{wD} = \frac{2r_w}{L}\sqrt{K_z/K_r}$$

$$s_D = \frac{4\pi T}{Q}s$$

where

- b is aquifer thickness [L]
- K_r is radial hydraulic conductivity [L/T]
- K_z is vertical hydraulic conductivity [L/T]
- L is length of the well [L]
- Q is pumping rate [L^3/T]
- r_w is well radius [L]
- s is drawdown [L]
- S is storativity [dimensionless]
- t is time [T]

- T is transmissivity $[L^2/T]$

- x, y and z are coordinate distances $[L]$

Drawdown in an observation well may be found by integrating the preceding equations with respect to z.

Following the work of Daviau et al. (1985), Clonts and Ramey (1986) and Ozkan et al. (1989), the wellbore pressure is computed with $y_D = r_{wD}$.

Clonts and Ramey (1986) and Ozkan et al. (1989), citing the work of Gringarten, Ramey and Raghavan (1974), modify the uniform-flux solution to predict the drawdown in an infinite-conductivity fracture by simply setting $x_D = 0.732$ to compute head in the horizontal well.

- o Assumptions

  - aquifer has infinite areal extent

  - aquifer has uniform thickness

  - aquifer potentiometric surface is initially horizontal

  - pumping well is horizontal

  - observation wells are fully or partially penetrating

  - 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

- o Data Requirements

  - pumping and observation well locations

  - pumping rate(s)

  - observation well measurements (time and displacement)

  - saturated thickness

  - length of horizontal well

- o Solution Options

  - constant or variable pumping rate including recovery

  - multiple pumping wells

  - multiple observation wells

- o Estimated Parameters

  - T (transmissivity)

  - S (storativity)

  - Kz/Kr (hydraulic conductivity anisotropy ratio)

- o Curve Matching Tips

  - Use the Cooper-Jacob (1946) solution to obtain preliminary estimates of aquifer properties.

  - Choose Match>Visual to perform visual curve matching using the procedure for type curve solutions.

  - Use active type curves for more effective visual matching with variable-rate pumping tests.

  - Select values of Kz/Kr from the **Family** and **Curve** drop-down lists on the toolbar.

  - Use parameter tweaking to perform visual curve matching and sensitivity analysis.

  - Perform visual curve matching prior to automatic estimation to obtain reasonable starting values for the aquifer properties.

- o References

  - Daviau, F., Mouronval, G., Bourdarot, G. and P. Curutchet, 1985. Pressure analysis for horizontal wells, SPE Paper 14251, presented at the 60th Annual Technical Conference and Exhibition in Las Vegas, NV, Sept. 22-25, 1985.

  - Clonts, M.D. and H.J. Ramey, Jr., 1986. Pressure transient analysis for well with horizontal drainholes, SPE Paper 15116, presented at the 56th California Regional Meeting, Oakland, CA, April 2-4, 1986.

  - Ozkan, E., Raghavan, R. and S.D. Joshi, 1989. Horizontal-well pressure analysis, SPE Formation Evaluation (December 1989), pp. 567-575.

Related Topics

Barker (1988) Solution for a Pumping Test in a Confined Aquifer

(Match > Solution)

Barker (1988) derived a generalized radial flow model for unsteady, n-dimensional flow to a fully penetrating source in an isotropic, single- or double-porosity fractured aquifer. The single-porosity form of the model describes flow in a confined aquifer. For details, refer to the Barker (1998) solution for a fractured aquifer.

Related Topics

Hantush-Jacob (1955)/Hantush (1964) Solution for a Pumping Test in a Leaky Aquifer

(Match > Solution)

Hantush and Jacob (1955) derived a solution for unsteady flow to a fully penetrating well in a homogeneous, isotropic leaky confined aquifer. The solution assumes a line source for the pumped well and therefore neglects wellbore storage.

Hantush (1964) extended the method to correct for partially penetrating wells and anisotropy. When you choose the Hantush-Jacob solution in AQTESOLV, you may analyze data for fully or partially penetrating wells.

The Hantush-Jacob solution can simulate variable-rate tests including recovery through the application of the principle of superposition in time. Use this solution to analyze both pumping and recovery data from constant- or variable-rate pumping tests.

Walton (1962) developed a manual curve-fitting procedure based on the Hantush-Jacob solution. To apply Walton's method in AQTESOLV, choose the Hantush-Jacob solution.

For a well performance test, you may choose the Hantush-Jacob (1955) solution for a step-drawdown test in a leaky confined aquifer.

Vandenberg (1977) presented a solution for evaluating drawdown a leaky confined aquifer bounded by two parallel no-flow boundaries (i.e., a leaky strip aquifer). In AQTESOLV, you may use the Hantush-Jacob solution in conjunction with aquifer boundaries to evaluate the same leaky strip aquifer problem as the Vandenberg method. Unlike Vandenberg's method, however, you may use AQTESOLV to evaluate partially penetrating wells and observation wells may be located at any radial distance from the pumped well.

- Illustration
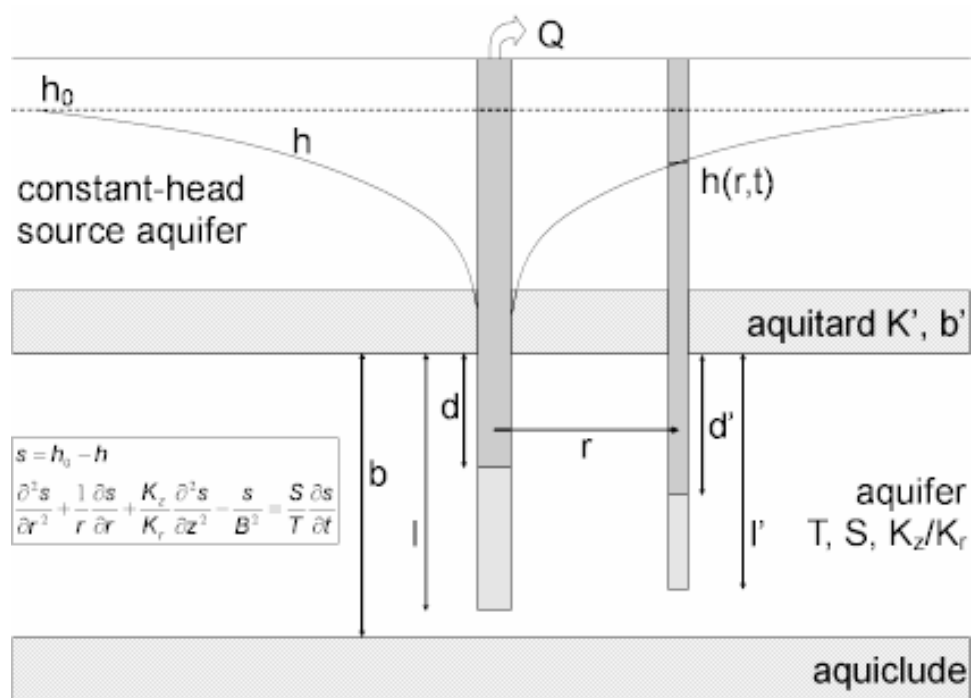
- Equations

  Hantush and Jacob (1955) derived an analytical solution for predicting water-level changes in response to pumping in a homogeneous, isotropic leaky confined aquifer assuming steady flow (no storage) in the aquitard(s):

  $$s = \frac{Q}{4\pi T} \int_{u}^{\infty} e^{-y - r^2/4B^2 y} \frac{dy}{y}$$

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

  $$B = \sqrt{\frac{Tb'}{K'}}$$

  $$s_D = \frac{4\pi T}{Q} s$$

  $$t_D = \frac{Tt}{r^2 S}$$

  where

  - b' is aquitard thickness [L]

- K' is vertical hydraulic conductivity in the aquitard [L/T]

- Q is pumping rate [L^3/T]

- r is radial distance [L]

- s is drawdown [L]

- S is storativity [dimensionless]

- t is time [T]

- T is transmissivity [L^2/T]

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:

$$s = \frac{Q}{4\pi T} w(u, r/B)$$

Hantush (1964) derived equations for the effects of partial penetration and anisotropy in a leaky aquifer. The partial penetration correction for a piezometer is as follows:

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

For an observation well, the following partial penetration correction applies:

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

where

- b is aquifer thickness [L]

- d is depth to top of pumping well screen [L]

- d' is depth to top of observation well screen [L]

- l is depth to bottom of pumping well screen [L]

- l' is depth to bottom of observation well screen [L]

- K_r is radial hydraulic conductivity [L/T]

- K_z is vertical hydraulic conductivity [L/T]

- z is depth to piezometer opening [L]

At large distances, the effect of partial penetration becomes negligible when

$$r > 1.5 b / \sqrt{K_z / K_r}$$

- o Assumptions
  - aquifer has infinite areal extent
  - aquifer is homogeneous 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 leaky 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
  - 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 is vertical in the aquitard(s)
- o 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)
- o Solution Options
  - constant or variable pumping rate including recovery
  - multiple pumping wells
  - multiple observation wells
  - partially penetrating wells
  - boundaries

- o Estimated Parameters

  - T (transmissivity)

  - S (storativity)

  - r/B (leakage parameter)

  - Kz/Kr (hydraulic conductivity anisotropy ratio)

  - b (saturated thickness)

  Partially penetrating wells are required to estimate Kz/Kr and b.

  The Report also shows aquitard properties (K'/b' and K') computed from the leakage parameter (r/B).

- o Curve Matching Tips

  - Use the Cooper-Jacob (1946) solution to obtain preliminary estimates of aquifer properties.

  - Choose Match>Visual to perform visual curve matching using the procedure for type curve solutions.

  - Use active type curves for more effective visual matching with variable-rate pumping tests.

  - For partially penetrating wells, select values of r/B and Kz/Kr from the **Family** and **Curve** drop-down lists on the toolbar.

  - Use parameter tweaking to perform visual curve matching and sensitivity analysis.

  - Perform visual curve matching prior to automatic estimation to obtain reasonable starting values for the aquifer properties.

- o References

  - 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.

  - Hantush, M.S., 1964. Hydraulics of wells, in: <u>Advances in Hydroscience</u>, V.T. Chow (editor), Academic Press, New York, pp. 281-442.

Related Topics

Hantush-Jacob (1955) Solution for a Step-Drawdown Test in a Leaky Aquifer

(Match > Solution)

We modify the Hantush-Jacob (1955) solution for unsteady flow to a well in a leaky confined aquifer to simulate linear and nonlinear well losses using a general procedure for step-drawdown tests.

    o   Illustration
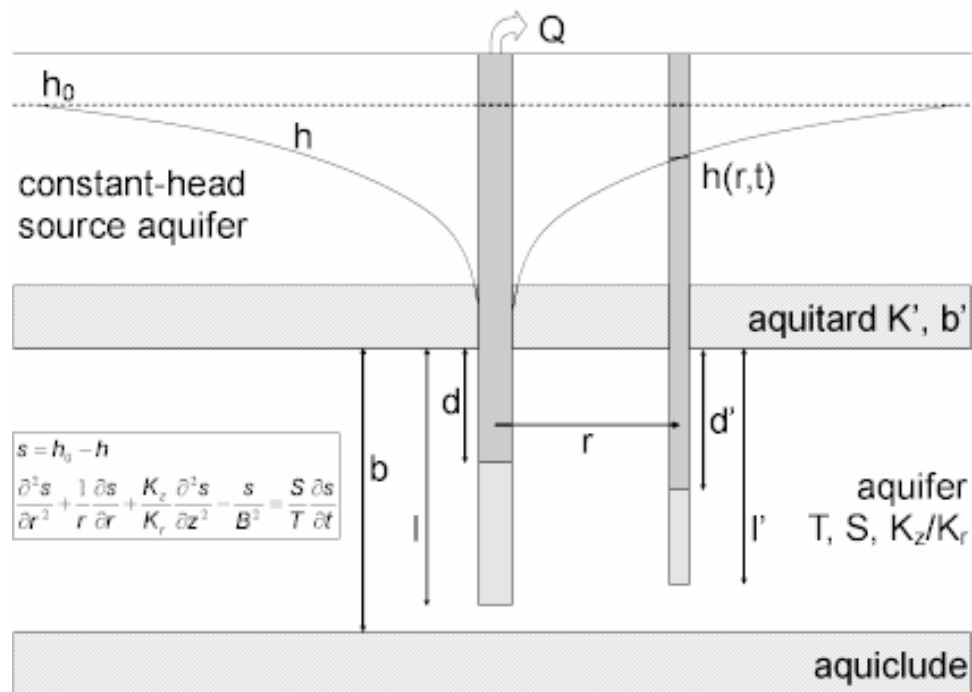
    o   Equations

The Hantush-Jacob (1955) solution for a fully penetrating pumping well in a leaky confined aquifer, modified to include linear and nonlinear well losses in a step-drawdown test, is expressed as follows:

$$s_w = \frac{Q}{4\pi T}\left[W(u, r/B) + 2S_w\right] + CQ^P$$

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

$$s_D = \frac{4\pi T}{Q}s$$

$$t_D = \frac{Tt}{r^2 S}$$

where

- CQ^P is nonlinear well loss

- Q is pumping rate [L^3/T]

- r is radial distance [L]

- r/B is leakage factor [dimensionless]

- s_w is drawdown in the pumped well [L]

- S is storativity [dimensionless]

- S_w is wellbore skin factor [dimensionless]

- T is transmissivity [T^2/T]

- t is time [T]

AQTESOLV also lets you simulate partially penetrating wells with this solution.

The effective well radius employed in this solution to incorporate wellbore skin (linear well loss) leads to correlation in the equations between S (storativity) and Sw (wellbore skin factor). Therefore, you should estimate either S or Sw for a single-well test.

o Assumptions

- aquifer has infinite areal extent

- aquifer is homogeneous 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 leaky 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

- 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 rate including recovery

  - multiple pumping wells

  - multiple observation wells

  - partially penetrating wells

- Estimated Parameters

  - T (transmissivity)

  - S (storativity)

  - r/B (leakage parameter)

  - Sw (wellbore skin factor)

  - C (nonlinear well loss coefficient)

  - P (nonlinear well loss exponent)

  The Report also shows aquitard properties (K'/b' and K') computed from the leakage parameter (r/B).

- Curve Matching Tips

  - Use the Cooper-Jacob (1946) solution to obtain preliminary estimates of aquifer properties.

  - Choose Match>Visual to perform visual curve matching using the procedure for type curve solutions.

  - Use active type curves for more effective visual matching with variable-rate pumping tests.

  - Select values of **r/B** from the **Family** and **Curve** drop-down lists on the toolbar.

- Use parameter tweaking to perform visual curve matching and sensitivity analysis.

- Perform visual curve matching prior to automatic estimation to obtain reasonable starting values for the aquifer properties.

- Due to correlation in the equations between S (storativity) and Sw (wellbore skin factor), estimate either S or Sw for a single-well test.

o References

- 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.

- Hantush, M.S., 1964. Hydraulics of wells, in: Advances in Hydroscience, V.T. Chow (editor), Academic Press, New York, pp. 281-442.

- Bear, J., 1979. Hydraulics of Groundwater, McGraw-Hill, New York, 569p.

Related Topics

Hantush (1960) Solution for a Pumping Test in a Leaky Aquifer

(Match > Solution)

Hantush (1960) derived a solution for unsteady flow to a fully penetrating well in a homogeneous, isotropic leaky confined aquifer. The solution assumes a line source for the pumped well and therefore neglects wellbore storage.

Hantush (1960) also derived an approximate solution for drawdown at early time in the pumped aquifer. Using the work by Hantush (1961a, b; Hantush 1964), AQTESOLV extends the early-time solution to correct for partially penetrating wells and anisotropy. When you choose the early-time form of the Hantush solution, you may analyze data for fully or partially penetrating wells.

The Hantush solution can simulate variable-rate tests including recovery using the principle of superposition in time. Use this solution to analyze both pumping and recovery data from constant- or variable-rate pumping tests.

> When you choose a solution, AQTESOLV provides two configurations for simulating a leaky confined aquifer with aquitard storage using the Hantush (1960) solution.

- *Pro* The **complete solution** models fully penetrating wells for any value

of time.

- The **early-time solution** simulates fully or partially penetrating wells for small values of time (see equations for time restrictions).

Both solution options assume constant-head source aquifers supply leakage across overlying and underlying aquitards (Hantush Case 1). The solution by Moench (1985) lets you simulate Hantush Cases 2 and 3.

- o Illustration
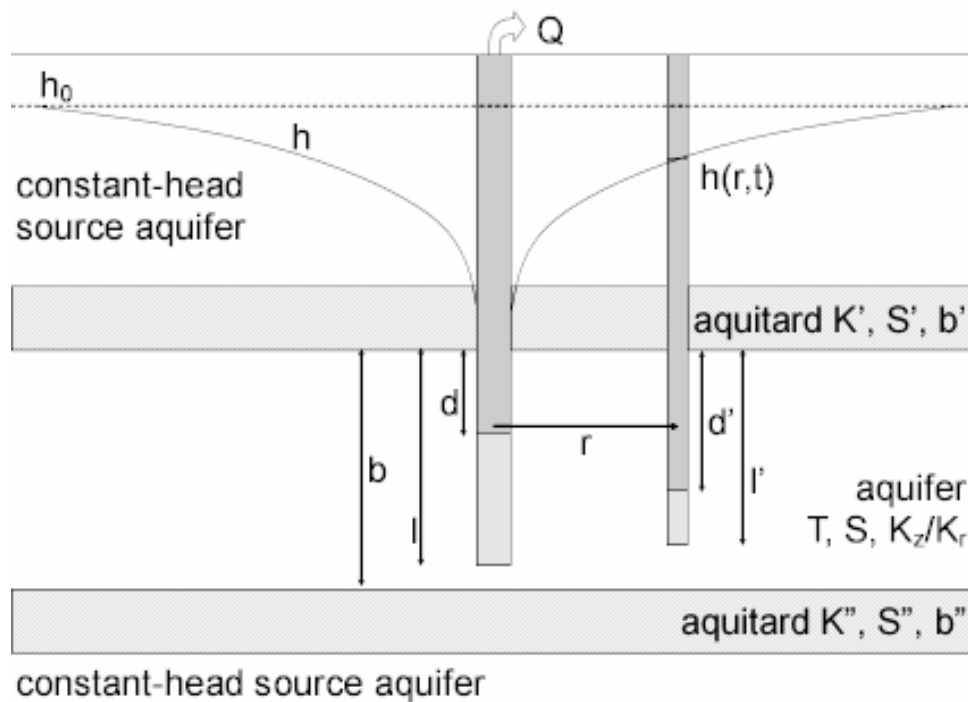
- o Equations

Hantush (1960) derived a solution for unsteady flow to a fully penetrating well in a homogeneous, isotropic leaky confined aquifer assuming aquitard storage. The Laplace transform solution is as follows:

$$\overline{s}_D = \frac{2K_0(x)}{p}$$

$$x = (p + \overline{q}_D)^{1/2}$$

$$\overline{q}_D = 4\sqrt{p}\,\beta' \coth\left(\frac{4\sqrt{p}\,\beta'}{(r/B')^2}\right) + 4\sqrt{p}\,\beta'' \coth\left(\frac{4\sqrt{p}\,\beta''}{(r/B'')^2}\right)$$

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$$B' = \sqrt{\frac{Tb'}{K'}}$$

$$B'' = \sqrt{\frac{Tb''}{K''}}$$

$$\beta' = \frac{r}{4}\sqrt{\frac{K'S'}{b'TS}}$$

$$\beta'' = \frac{r}{4}\sqrt{\frac{K''S''}{b''TS}}$$

$$t_D = \frac{Tt}{Sr^2}$$

$$s_D = \frac{4\pi T}{Q}s$$

where

- b' is thickness of first aquitard [L]

- b" is thickness of second aquitard [L]

- K' is vertical hydraulic conductivity of first aquitard [L/T]

- K" is vertical hydraulic conductivity of second aquitard [L/T]

- K_i is modified Bessel function of second kind, order i

- p is Laplace transform variable

- Q is pumping rate [L^3/T]

- r is radial distance [L]

- s is drawdown [L]

- S is storativity [dimensionless]

- S' is storativity of first aquitard [dimensionless]

- S" is storativity of second aquitard [dimensionless]

- t is time [T]

- T is transmissivity [L^2/T]

Hantush (1960) also presented an asymptotic solution for drawdown in the pumped aquifer at short values of time:

$$s = \frac{Q}{4\pi T} \int_u^\infty \frac{e^{-y}}{y} \, erfc \, \frac{\beta\sqrt{u}}{\sqrt{y(y-u)}} \, dy$$

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

$$\beta = \frac{r}{4}\sqrt{\frac{K'S'}{b'TS}}$$

or

$$\beta = \frac{r}{4}\left[\sqrt{\frac{K'S'}{b'TS}} + \sqrt{\frac{K''S''}{b''TS}}\right]$$

The solution assumes small values of time, i.e., when t < b'S'/10K' and t < b"S"/10K".

The early-time approximate solution can be corrected for partial penetrating wells and anisotropy using the approach of Hantush (1961a, b).

At large distances, the effect of partial penetration becomes negligible when

$$r > 1.5\, b\big/\sqrt{K_z/K_r}$$

- o Assumptions

  - aquifer has infinite areal extent

  - aquifer is homogeneous 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 leaky 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

  - confining bed(s) has infinite areal extent, uniform vertical hydraulic conductivity, storage coefficient and thickness

  - confining bed(s) is overlain or underlain by an infinite constant-head plane source

- flow is vertical in the aquitard(s)
  - o 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)
  - o Solution Options
    - constant or variable pumping rate including recovery
    - multiple pumping wells
    - multiple observation wells
    - partially penetrating wells (early-time solution)
    - boundaries
  - o Estimated Parameters
    - T (transmissivity)
    - S (storativity)
    - r/B' (leakage parameter, first aquitard)
    - β' (leakage parameter, first aquitard)
    - r/B" (leakage parameter, second aquitard)
    - β'' (leakage parameter, second aquitard)

    The Report also shows aquitard properties (K'/b' and K'; K"/b" and K")
      computed from the leakage parameters (r/B' and r/B").

    Early-Time Solution
    - T (transmissivity)
    - S (storativity)
    - β (leakage parameter)
    - Kz/Kr (hydraulic conductivity anisotropy ratio)
    - b (saturated thickness)

- o Curve Matching Tips

  - Use the Cooper-Jacob (1946) solution to obtain preliminary estimates of aquifer properties.

  - Choose Match>Visual to perform visual curve matching using the procedure for type curve solutions.

  - Use active type curves for more effective visual matching with variable-rate pumping tests.

  - Select values of r/B, β and Kz/Kr from the **Family** and **Curve** drop-down lists on the toolbar.

  - Use parameter tweaking to perform visual curve matching and sensitivity analysis.

  - Perform visual curve matching prior to automatic estimation to obtain reasonable starting values for the aquifer properties.

  - For β < 0.5, all of the type curves in the early-time solution have a similar shape (Kruseman and de Ridder 1991); hence, it is often difficult to obtain a unique match with the early-time solution when 0 β 0.5.

- o References

  - Hantush, M.S., 1960. Modification of the theory of leaky aquifers, Jour. of Geophys. Res., vol. 65, no. 11, pp. 3713-3725.

  - 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.

  - Hantush, M.S., 1964. Hydraulics of wells, in: <u>Advances in Hydroscience</u>, V.T. Chow (editor), Academic Press, New York, pp. 281-442.

Related Topics

Cooley-Case (1973) Solution for a Pumping Test in a Confined Aquifer Overlain by a Water-Table Aquitard

(Match > Solution)

Cooley and Case (1973) derived a solution for unsteady flow to a fully penetrating well in a homogeneous, isotropic leaky confined aquifer overlain by a water-table aquitard. The solution assumes a line source for the pumped well and therefore neglects wellbore storage.

The Cooley-Case solution can simulate variable-rate tests including recovery using

the principle of superposition in time. Use this solution to analyze both pumping and recovery data from constant- or variable-rate pumping tests.

- o Illustration
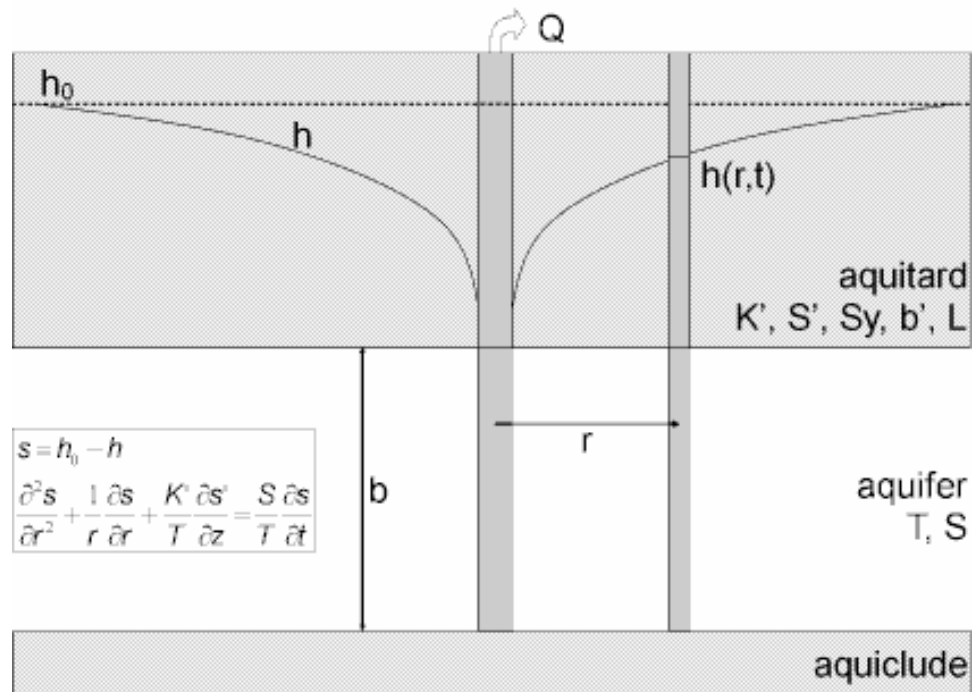
- o Equations

Cooley and Case (1973) derived a solution for unsteady flow to a fully penetrating well in a homogeneous, isotropic leaky confined aquifer overlain by a water-table aquitard. The Laplace transform solution is as follows:

$$\bar{s}_D = \frac{2K_0(x)}{p}$$

$$x = (p + \bar{q}_D)^{1/2}$$

$$\bar{q}_D = 4\sqrt{p}\,\beta\coth\left(\frac{4\sqrt{p}\,\beta}{(r/B)^2}\right) + \left[p\,\mathrm{sech}^2\left(\frac{4\sqrt{p}\,\beta}{(r/B)^2}\right)\right]\left[p\frac{L/b'}{(r/B)^2} + \frac{(r/B)^2}{16\beta^2}\frac{S'}{S_y} + \frac{\sqrt{p}}{4\beta}\tanh\left(\frac{4\sqrt{}}{(r/}\right)\right]$$

$$B = \sqrt{\frac{T(b'+L)}{K'}}$$

$$\beta = \frac{r}{4}\sqrt{\frac{K'S'}{b'TS}}$$

$$t_D = \frac{Tt}{Sr^2}$$

$$s_D = \frac{4\pi T}{Q}s$$

where

- b' is thickness of the aquitard [L]

- K' is vertical hydraulic conductivity of the aquitard [L/T]

- K_i is modified Bessel function of second kind, order i

- L is height of capillary fringe [L]

- p is Laplace transform variable

- Q is pumping rate [L^3/T]

- r is radial distance [L]

- s is drawdown [L]

- S is storativity [dimensionless]

- S' is storativity of the aquitard [dimensionless]

- S_y is specific yield of the aquitard [dimensionless]

- t is time [T]

- T is transmissivity [L^2/T]

○ Assumptions

- aquifer has infinite areal extent

- aquifer is homogeneous and of uniform thickness

- pumping well is fully penetrating

- flow to pumping well is horizontal

- aquifer is leaky 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

- confining bed has infinite areal extent, uniform vertical hydraulic

conductivity, storage coefficient, specific yield and thickness

- flow is vertical in the aquitard

o Data Requirements

- pumping and observation well locations

- pumping rate(s)

- observation well measurements (time and displacement)

o Solution Options

- constant or variable pumping rate including recovery

- multiple pumping wells

- multiple observation wells

- boundaries

o Estimated Parameters

- T (transmissivity)

- S (storativity)

- r/B (leakage parameter)

- β (leakage parameter)

- S'/Sy (storage ratio in aquitard)

- L/b' (dimensionless height of capillary fringe)

The Report also shows aquitard properties (K'/b' and K') computed from the leakage parameter (r/B).

o Curve Matching Tips

- Use the Cooper-Jacob (1946) solution to obtain preliminary estimates of aquifer properties.

- Choose Match>Visual to perform visual curve matching using the procedure for type curve solutions.

- Use active type curves for more effective visual matching with variable-rate pumping tests.

- Select values of r/B and β from the **Family** and **Curve** drop-down lists on the toolbar.

- Use parameter tweaking to perform visual curve matching and sensitivity analysis.

- Perform visual curve matching prior to automatic estimation to obtain

reasonable starting values for the aquifer properties.

- o References

  - Cooley, R.L. and C.M. Case, 1973. Effect of a water table aquitard on drawdown in an underlying pumped aquifer, Water Resources Research, vol. 9, no. 2, pp. 434-447.

Related Topics

Neuman-Witherspoon (1969) Solution for a Pumping Test in a Leaky Aquifer

(Match > Solution)

Neuman and Witherspoon (1969) derived a solution for unsteady flow to a fully penetrating well in a confined two-aquifer system. The solution assumes a line source for the pumped well and therefore neglects wellbore storage.

The Neuman-Witherspoon solution can simulate variable-rate tests including recovery through the application of the principle of superposition in time. Use this solution to analyze both pumping and recovery data from constant- or variable-rate pumping tests.

You may analyze data from wells screened in the pumped aquifer, unpumped aquifer or aquitard with the Neuman-Witherspoon solution. Wells in the aquifers are assumed to be fully penetrating; wells in the aquitard may be partially penetrating.

- o Illustration
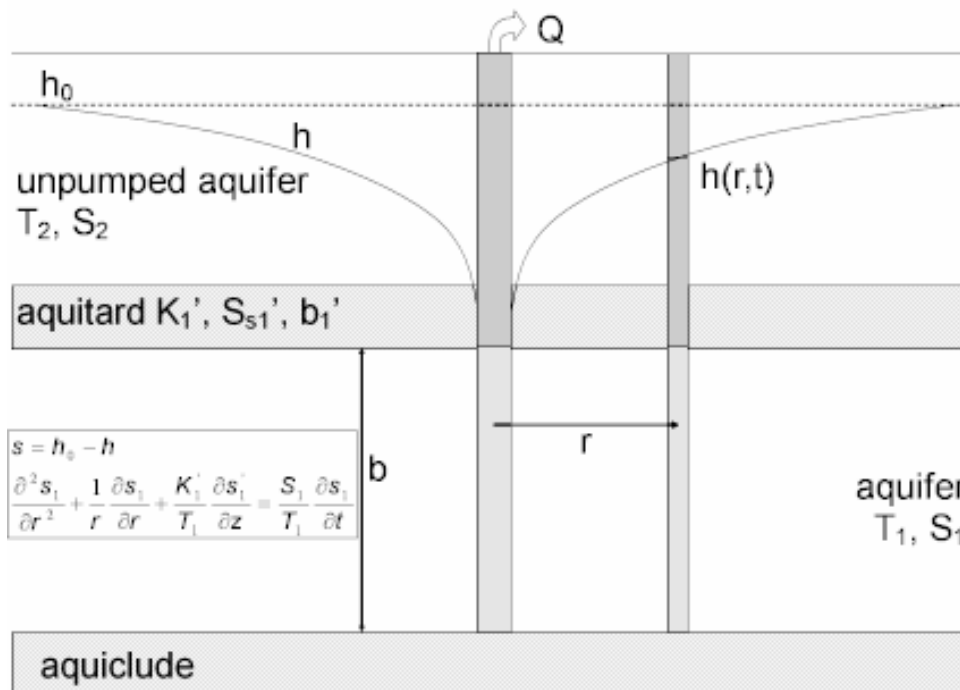
- Equations

  Neuman and Witherspoon (1969) derived the following equations for drawdown in a confined two-aquifer system:

$$S_1 = \frac{Q}{4\pi T} \int_0^\infty (1 - e^{-y^2 t_{D1}})\{[1 + G(y)]J_0(\omega_1(y)) + [1 - G(y)]J_0(\omega_2(y))\} \frac{dy}{y}$$

$$s_1' = \frac{Q}{4\pi T} \frac{2}{\pi} \sum_0^\infty \frac{1}{n} \sin\frac{n\pi z}{b_1'} \int_0^\infty [1 - e^{-n^2 \pi t_{D1}} + \frac{e^{-n^2 \pi t_{D1}} - e^{-y^2 t_{D1}}}{1 - y^2/(n^2\pi^2)}]\{[\frac{2(r/B_{21})^2(-1)^n y}{F(y)\sin y} - G(y) - 1]J_0$$

$$-[\frac{2(r/B_{21})^2(-1)}{F(y)\sin y} - G(y) + 1]J_0(\omega_2(y))\} \frac{dy}{y}$$

$$S_2 = \frac{Q}{4\pi T} \int_0^\infty (1 - e^{-y^2 t_{D1}}) \frac{2(r/B_{21})^2}{F(y)} [J_0(\omega_1(y)) - J_0(\omega_2(y))] \frac{dy}{\sin y}$$

$$t_{D1} = \frac{T_1 t}{r^2 S_1}$$

$$\bar{t}_{D1} = t_{D1}(r/B_{11})^4/(4\beta_{11})^2$$

$$r/B_{ij} = r\sqrt{K_i'/T_i b_i'}$$

$$\beta_i = \frac{r}{4b_i}\sqrt{\frac{K_j' S_{sj}'}{K_i S_{si}}}$$

$$G(y) = M(y)/F(y)$$

$$\omega_1^2(y) = \frac{1}{2}[N(y) + F(y)]$$

$$\omega_2^2(y) = \frac{1}{2}[N(y) - F(y)]$$

$$F^2(y) = M^2(y) + \left[\frac{2(r/B_{11})(r/B_{21})y}{\sin y}\right]^2$$

$$M(y) = \left[\frac{(r/B_{11})^4}{(4\beta_{11})^2} - \frac{(r/B_{21})^4}{(4\beta_{21})^2} \right] y^2 - \left[(r/B_{11})^2 - (r/B_{21})^2 \right] y \cot y$$

$$N(y) = \left[\frac{(r/B_{11})^4}{(4\beta_{11})^2} + \frac{(r/B_{21})^4}{(4\beta_{21})^2} \right] y^2 - \left[(r/B_{11})^2 + (r/B_{21})^2 \right] y \cot y$$

$$s_D = \frac{4\pi T}{Q} s$$

$$t_D = \frac{Tt}{r^2 S}$$

where

- b_i is thickness of aquifer i [L]

- b_j' is thickness of aquitard j [L]

- J_0 is Bessel function of first kind, zero order

- K_i is horizontal hydraulic conductivity in aquifer i [L/T]

- K_j' is vertical hydraulic conductivity in aquitard j [L/T]

- Q is pumping rate [L^3/T]

- r is radial distance [L]

- s_1 is drawdown in the pumped aquifer [L]

- s'_1 is drawdown in the aquitard [L]

- s_2 is drawdown in the unpumped aquifer [L]

- S, S_1 is storativity in the pumped aquifer [dimensionless]

- t is time [T]

- T, T_1 is transmissivity in the pumped aquifer [L^2/T]

Expressions for drawdown in the aquitard for fully or partially penetrating wells can be found by averaging the drawdown over the length of the well screen.

  o 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 leaky 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

- confining bed(s) has infinite areal extent, uniform vertical hydraulic conductivity, storage coefficient and thickness

- flow is vertical in the aquitard(s)l

o Data Requirements

- pumping and observation well locations

- pumping rate(s)

- observation well measurements (time and displacement)

- partial penetration depths (optional; aquitard only)

- aquitard thickness, b' (for partially penetrating wells)

o Solution Options

- constant or variable pumping rate including recovery

- multiple pumping wells

- multiple observation wells

- boundaries

o Estimated Parameters

- T (transmissivity in pumped aquifer = T_1)

- S (storativity in pumped aquifer = S_1)

- r/B (leakage parameter = r/B_{11})

- β (leakage parameter = β_{11})

- T2 (transmissivity in unpumped aquifer = T_2)

- S2 (storativity in unpumped aquifer = S_2)

The Report also shows aquitard properties (K'/b' and K') computed from the leakage parameter (r/B).

- o Curve Matching Tips

  - Use the Cooper-Jacob (1946) solution to obtain preliminary estimates of aquifer properties.

  - Choose Match>Visual to perform visual curve matching using the procedure for type curve solutions.

  - Use active type curves for more effective visual matching with variable-rate pumping tests.

  - For partially penetrating wells, select values of r/B and β from the **Family** and **Curve** drop-down lists on the toolbar.

  - Use parameter tweaking to perform visual curve matching and sensitivity analysis.

  - Perform visual curve matching prior to automatic estimation to obtain reasonable starting values for the aquifer properties.

- o References

  - 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.

Related Topics

Moench (1985) Solution for a Pumping Test in a Leaky Aquifer

(Match > Solution)

Moench (1985) derived a solution for unsteady flow to a fully penetrating, finite-diameter well with wellbore storage and wellbore skin in a homogeneous, isotropic leaky confined aquifer.

AQTESOLV uses the principle of superposition in time to simulate variable-rate tests including recovery with the Moench solution. Use this solution to analyze both pumping and recovery data from constant- or variable-rate pumping tests.

Wellbore storage has a distinct signature in the early-time response of a pumped well. Use the radial flow and derivative-time plots to detect the wellbore storage effect.

When you choose a solution, AQTESOLV provides three configurations for simulating a leaky confined aquifer with aquitard storage using the Moench (1985) solution.

- **Case 1** assumes constant-head source aquifers supply leakage across overlying and underlying aquitards.

- **Case 2** replaces both constant-head boundaries in Case 1 with no-flow

boundaries.

- **Case 3** replaces the underlying constant-head boundary in Case 1 with a no-flow boundary.
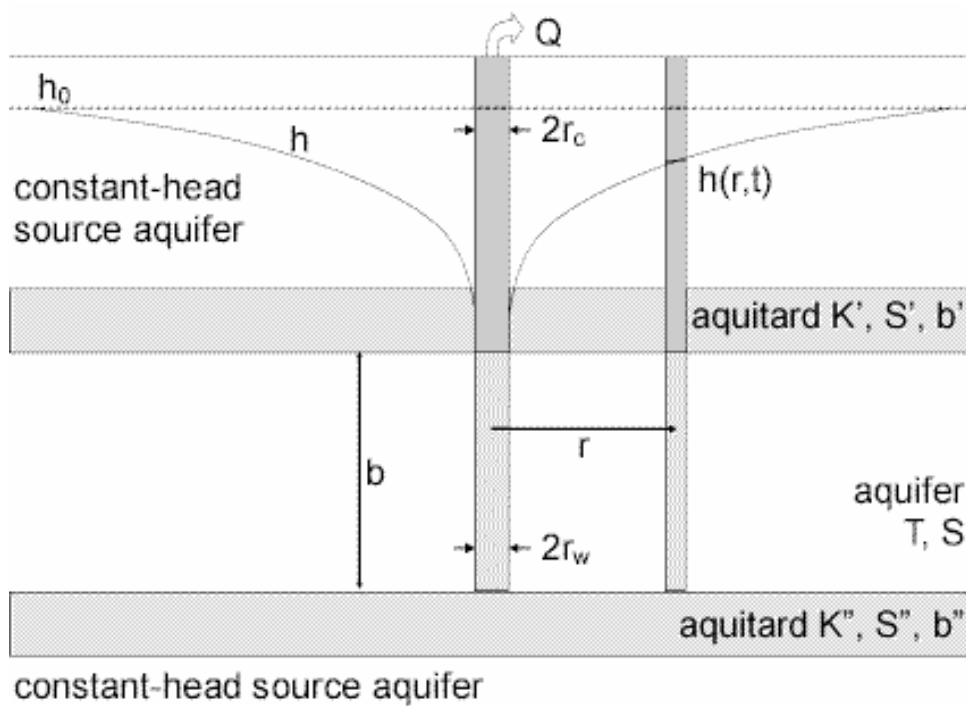
o Illustration

Boundaries in illustration refer to Case 1.

o Equations

Moench (1985) derived an analytical solution for predicting water-level displacements in response to pumping in a leaky confined aquifer assuming fully penetrating wells, wellbore storage and wellbore skin.

The Laplace transform solution for dimensionless drawdown in the pumped well is as follows:

$$\overline{h}_{wD} = \frac{2[K_0(x) + xS_w K_1(x)]}{p\{pW_D[K_0(x) + xS_w K_1(x)] + xK_1(x)\}}$$

The follow equation is the Laplace transform solution for dimensionless drawdown in an observation well:

$$\overline{h}_D = \frac{2K_0(r_D x)}{p\{pW_D[K_0(x) + xS_w K_1(x)] + xK_1(x)\}}$$

$$x = (p + \overline{q}_D)^{1/2}$$

$$\bar{q}_D = \gamma'^2 m' \coth(m') + \gamma''^2 m'' \coth(m'') \quad (Case\ 1)$$

$$\bar{q}_D = \gamma'^2 m' \tanh(m') + \gamma''^2 m'' \tanh(m'') \quad (Case\ 2)$$

$$\bar{q}_D = \gamma'^2 m' \coth(m') + \gamma''^2 m'' \tanh(m'') \quad (Case\ 3)$$

$$m' = \frac{(\sigma' p)^{1/2}}{\gamma'}$$

$$m'' = \frac{(\sigma'' p)^{1/2}}{\gamma''}$$

$$\gamma' = r_w \left(\frac{K'}{K b b'} \right)^{1/2}$$

$$\gamma'' = r_w \left(\frac{K''}{K b b''} \right)^{1/2}$$

$$\sigma' = \frac{S'_s b'}{S_s b}$$

$$\sigma'' = \frac{S''_s b''}{S_s b}$$

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

$$W_D = \frac{\pi r_c^2}{2 \pi r_w^2 S_s b}$$

$$t_D = \frac{K t}{S_s r_w^2}$$

$$h_D = \frac{4 \pi K b}{Q} (h_0 - h)$$

where

- b is aquifer thickness [L]
- b' is thickness of first aquitard [L]

- b" is thickness of second aquitard [L]

- K is aquifer hydraulic conductivity [L/T]

- K' is vertical hydraulic conductivity of first aquitard [L/T]

- K" is vertical hydraulic conductivity of second aquitard [L/T]

- K_i is modified Bessel function of second kind, order i

- p is the Laplace transform variable

- Q is pumping rate [L^3/T]

- r is radial distance [L]

- r_c is casing radius [L]

- r_w is well radius [L]

- S_s is aquifer specific storage [1/L]

- S_s' is specific storage of first aquitard [1/L]

- $S_s"$ is specific storage of second aquitard [1/L]

- S_w is wellbore skin factor [dimensionless]

- t is time [T]

In the Laplace transform solution, S_w is limited to positive values; however, using the effective well radius concept, we also may simulate a negative skin (Hurst, Clark and Brauer 1969).

If you enter a radius for downhole equipment, AQTESOLV uses the effective casing radius instead of the nominal casing radius in the equations for this solution.

AQTESOLV reports the aquitard properties in terms of the more familiar parameters from the Hantush (1960) solution, which one can readily compute from Moench's parameters as follows:

$$r / B = \gamma r_D$$

$$\beta = \frac{\gamma}{4} \sigma^{1/2} r_D$$

- o Assumptions

  - aquifer has infinite areal extent

  - aquifer is homogeneous, isotropic and of uniform thickness

  - aquifer potentiometric surface is initially horizontal

  - pumping and observation wells are fully penetrating

- flow to pumping well is horizontal

- flow is unsteady

- aquifer is leaky confined

- 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 (case 1) or no-flow boundary (case 2)

- vertical flow in the aquitard(s)

o 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)

- downhole equipment radius (optional)

- saturated thickness

o Solution Options

- constant or variable pumping rate including recovery

- multiple pumping wells

- multiple observation wells

- boundaries

o Estimated Parameters

- T (transmissivity)

- S (storativity)

- r/B' (dimensionless leakage parameter, aquitard 1)

- β' (dimensionless leakage parameter, aquitard 1)

- r/B" (dimensionless leakage parameter, aquitard 2)

- β'' (dimensionless leakage parameter, aquitard 2)

- Sw (wellbore skin factor)

- r(w) (well radius)

- r(c) (nominal casing radius)

The Report also shows aquitard properties (K'/b' and K'; K"/b" and K")
computed from the leakage parameters (r/B' and r/B").

- Curve Matching Tips

  - Use radial flow plots to help diagnose wellbore storage.

  - Match the Cooper-Jacob (1946) solution to late-time data to obtain preliminary estimates of aquifer properties.

  - Match early-time data affected by wellbore storage by adjusting **r(c)** with parameter tweaking.

  - If you estimate **r(c)** for the test well, the estimated value replaces the nominal casing radius and AQTESOLV still performs the correction for downhole equipment.

  - Choose Match>Visual to perform visual curve matching using the procedure for type curve solutions.

  - Use active type curves for more effective visual matching with variable-rate pumping tests.

  - Select values of r/B and β from the **Family** and **Curve** drop-down lists on the toolbar.

  - Use parameter tweaking to perform visual curve matching and sensitivity analysis.

  - Perform visual curve matching prior to automatic estimation to obtain reasonable starting values for the aquifer properties.

- References

  - 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.

Related Topics

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

(Match > Solution)

The Theis (1935) solution is applicable to unconfined aquifers through the correction of drawdown data as follows (Kruseman and de Ridder 1990):
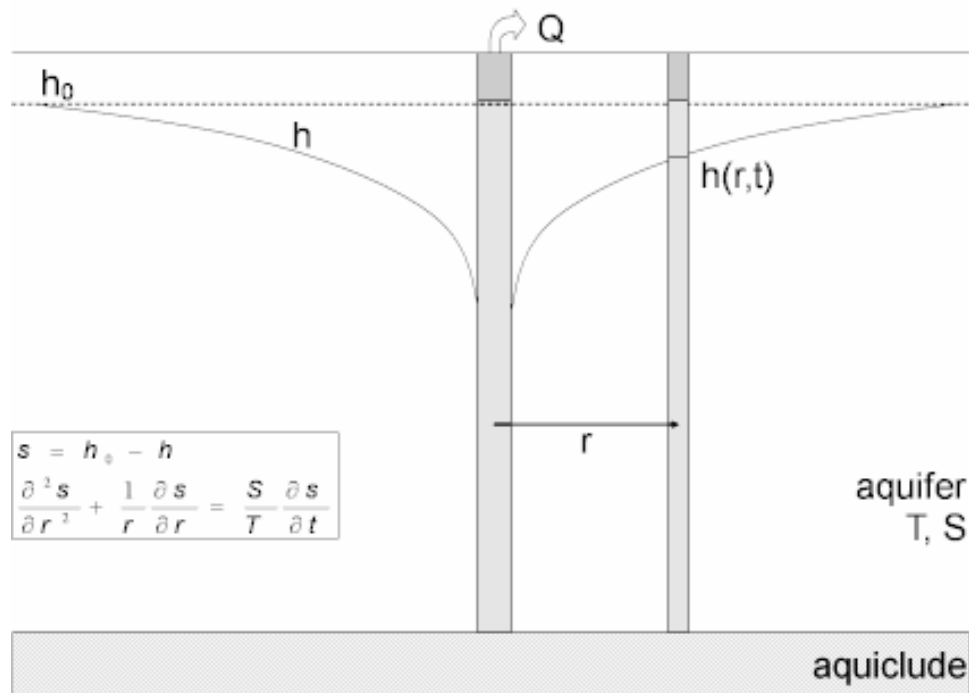
$s' = s - s^2/2b$

where s' is corrected displacement [L], s is observed displacement [L] and b is saturated aquifer thickness [L]. This correction attributed to C.E. Jacob only applies to pumping tests in which water is extracted from an unconfined aquifer; the correction 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.

For more information regarding this method or to apply the solution without the dewatering correction, refer to the Theis (1935) solution for confined aquifers.

- o   Illustration
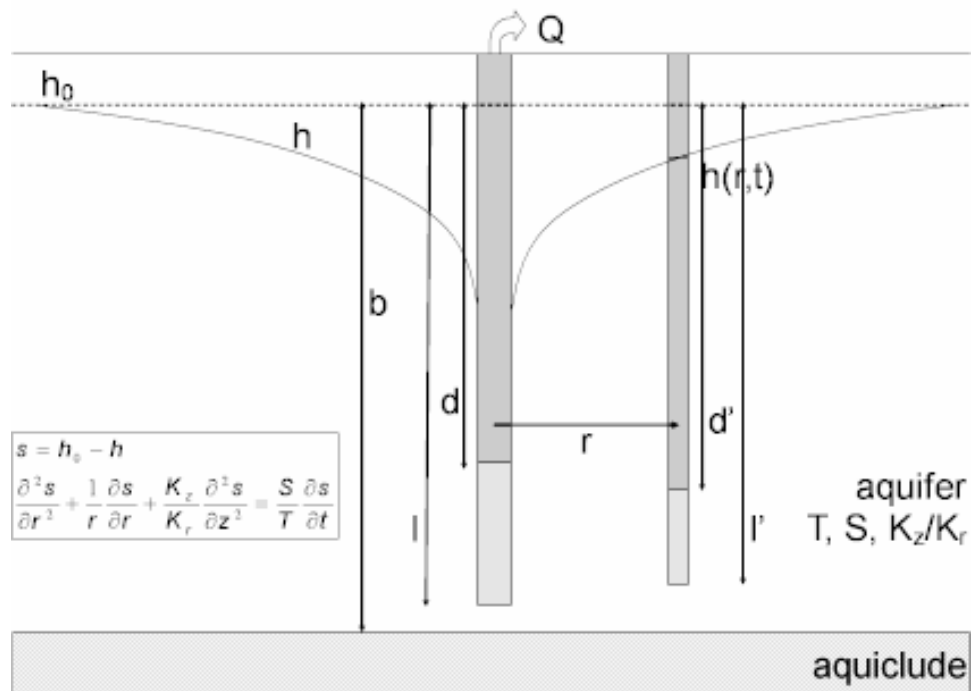
- o Equations

  Refer to the Theis (1935) solution for fully or partially penetrating wells in a confined aquifer.

- o 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 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

  - low 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

- o Data Requirements

  - pumping and observation well locations

  - pumping rate(s)

  - observation well measurements (time and displacement)

  - partial penetration depths (optional)

  - saturated thickness

  - hydraulic conductivity anisotropy ratio (for partially penetrating wells)

- o Solution Options

  - constant or variable pumping rate including recovery

  - multiple pumping wells

  - multiple observation wells

- partially penetrating wells

  o Estimated Parameters

    - T (transmissivity)

    - S (storativity)

    - Kz/Kr (hydraulic conductivity anisotropy ratio)

    - b (saturated thickness)

  o Curve Matching Tips

    - Use the Cooper-Jacob (1946) solution to obtain preliminary estimates of aquifer properties.

    - Choose Match>Visual to perform visual curve matching using the procedure for type curve solutions.

    - Use active type curves for more effective visual matching with variable-rate pumping tests.

    - For partially penetrating wells, select values of Kz/Kr from the **Family** and **Curve** drop-down lists on the toolbar.

    - Use parameter tweaking to perform visual curve matching and sensitivity analysis.

    - Perform visual curve matching prior to automatic estimation to obtain reasonable starting values for the aquifer properties.

  o 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.

Related Topics

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

(Match > Solution)

The Cooper-Jacob(1946) solution is applicable to unconfined aquifers through the correction of drawdown data as follows (Kruseman and de Ridder 1990):

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

where s' is corrected displacement [L], s is observed displacement [L] and b is

saturated aquifer thickness [L]. This correction attributed to C.E. Jacob only applies to pumping tests in which water is extracted from an unconfined aquifer; the correction 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.

For more information regarding this method or to apply the solution without the dewatering correction, refer to the Cooper-Jacob (1946) solution for a confined aquifer.

- o Illustration

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

- o Equations

  Refer to the Cooper-Jacob(1946) solution for fully penetrating wells in a confined aquifer.

- o 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

- low 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

- o Data Requirements

  - pumping and observation well locations

  - pumping rate(s)

  - observation well measurements (time and displacement)

  - saturated thickness

- o Solution Options

  - constant or variable pumping rate including recovery

  - multiple observation wells

- o Estimated Parameters

  - T (transmissivity)

  - S (storativity)

- o Curve Matching Tips

  - Choose Match>Visual to perform visual curve matching using the procedure for straight-line solutions.

  - Use parameter tweaking to perform visual curve matching and sensitivity analysis.

  - Choose View>Options to display the critical value of u on the plot.

  - Perform visual curve matching prior to automatic estimation to obtain reasonable starting values for the aquifer properties.

- Use Agarwal plots to analyze recovery data.

- You may use the Cooper-Jacob solution to analyze drawdown data from the start of the test up to the first recovery period (a recovery period is any period with a rate equals zero).

- If your data set contains more than one recovery period, you may use the Cooper-Jacob solution to analyze recovery data in the first recovery period.

- If your data set contains more than one pumping well, AQTESOLV uses the **first** pumping well in the well data to match test data with the Cooper-Jacob solution.

  For more tips and information, refer to the Cooper-Jacob (1946) solution for a confined aquifer.

  o 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.

Related Topics

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

(Match > Solution)

Neuman (1972, 1974) derived an analytical solution for unsteady flow to a fully or partially penetrating well in a homogeneous, anisotropic unconfined aquifer with delayed gravity response. The Neuman model assumes instantaneous drainage at the water table. The solution also assumes a line source for the pumped well and therefore neglects wellbore storage.

AQTESOLV applies the principle of superposition in time to simulate variable-rate tests including recovery. You may use the Neuman solution to analyze both pumping and recovery data from constant- or variable-rate pumping tests.

AQTESOLV uses computational enhancements by Moench (1996) to calculate type curves for the Neuman solution.

o   Illustration
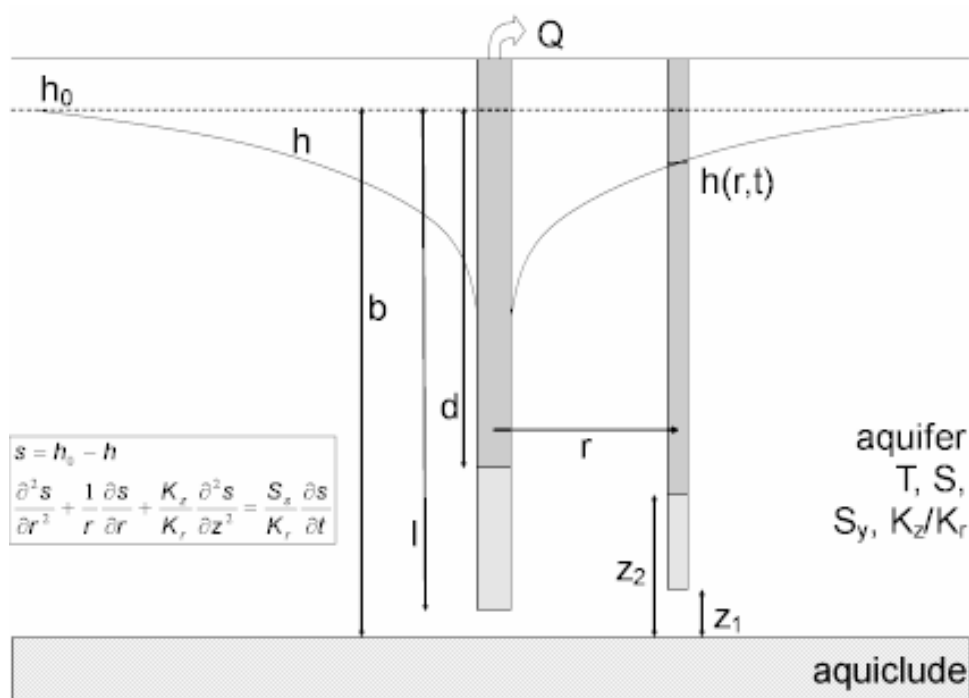
o   Equations

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

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

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

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

$$t_s = \frac{Tt}{Sr^2}$$

$$s_D = \frac{4\pi T}{Q} s$$

where

*   b is aquifer thickness [L]

- K_r is radial hydraulic conductivity [L/T]

- K_z is vertical hydraulic conductivity [L/T]

- Q is pumping rate [L³/T]

- r is radial distance [L]

- s is drawdown [L]

- S is storativity [dimensionless]

- S_y is specific yield [dimensionless]

- t is time [T]

- T is transmissivity [L²/T]

The drawdown in a piezometer is found using the following equations:

$$u_0(y) = \frac{[1-\exp(-t_s\beta(y^2-\gamma_0^2))]\cosh(\gamma_0 z_D)}{[y^2+(1+\sigma)\gamma_0^2-(y^2-\gamma_0^2)^2/\sigma]\cosh(\gamma_0)} \cdot \frac{\sinh(\gamma_0(1-d_D))-\sinh(\gamma_0(1-l_D))}{(l_D-d_D)\sinh(\gamma_0)}$$

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

The drawdown in a partially penetrating observation well is found using the following equations:

$$u_0(y) = \frac{[1-\exp(-t_s\beta(y^2-\gamma_0^2))][\sinh(\gamma_0 z_{2D})-\sinh(\gamma_0 z_{1D})]}{[y^2+(1+\sigma)\gamma_0^2-(y^2-\gamma_0^2)^2/\sigma]\cosh(\gamma_0)} \cdot \frac{\sinh(\gamma_0(1-d_D))-\sinh(\gamma_0(}{(z_{2D}-z_{1D})(l_D-d_D)\sinh}$$

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

The gamma terms are the roots of the following equations:

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

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

where

- d_D is dimensionless depth to top of pumping well screen (d/b)

- J_0 is Bessel function of first kind, zero order

- l_D is dimensionless depth to bottom of pumping well screen (l/b)

- z_D is dimensionless elevation of piezometer opening above base of aquifer (z/b)

- z_{1D} is dimensionless elevation of bottom of observation well screen above base of aquifer (z_1/b)

- z_{2D} is dimensionless elevation of top of observation well screen above base of aquifer (z_2/b)

Subsequent work by Moench (1993, 1996) presented improved methods for evaluating the Neuman solution.

- Assumptions

  - aquifer has infinite areal extent

  - aquifer is homogeneous and has uniform thickness

  - aquifer potentiometric surface is initially horizontal

  - pumping well is fully or partially penetrating

  - aquifer is unconfined with delayed gravity response

  - 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

- Estimated Parameters

  - T (transmissivity)

  - S (storativity)

- S_y (specific yield)

- β or Kz/Kr (hydraulic conductivity anisotropy ratio)

  AQTESOLV displays β for tests with a single observation well or Kz/Kr for multiple observation wells.

  o Curve Matching Tips

  - Use the Cooper-Jacob (1946) solution to obtain preliminary estimates of aquifer properties. Determine T by matching a straight line to late-time data. If the wells are fully penetrating, you also may estimate Sy from the late-time match. Estimate S from early-time data.

  - Choose Match>Visual to perform visual curve matching using the procedure for type curve solutions.

  - Use active type curves for more effective visual matching with variable-rate pumping tests.

  - Select values of β or Kz/Kr from the **Family** and **Curve** drop-down lists on the toolbar.

  - Use parameter tweaking to perform visual curve matching and sensitivity analysis.

  - Perform visual curve matching prior to automatic estimation to obtain reasonable starting values for the aquifer properties.

  o 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.

  - Neuman, S.P., 1972. Theory of flow in unconfined aquifers considering delayed gravity response of the water table, Water Resources Research, vol. 8, no. 4, pp. 1031-1045.

  - 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.

Related Topics

Moench (1997) Solution for a Pumping Test in an Unconfined Aquifer

(Match > Solution)

Moench (1997) derived an analytical solution for unsteady flow to a fully or partially

penetrating, finite-diameter well with wellbore storage and wellbore skin in a homogeneous, anisotropic unconfined aquifer with delayed gravity response. The Moench solution also includes a correction for delayed observation well response.

AQTESOLV uses the principle of superposition in time to simulate variable-rate tests including recovery with the Moench solution. Use this solution to analyze both pumping and recovery data from constant- or variable-rate pumping tests.

Wellbore storage has a distinct signature in the early-time response of a pumped well. Use the radial flow and derivative-time plots to detect the wellbore storage effect.

- o Illustration

$$s = h_o - h$$

$$\frac{\partial^2 s}{\partial r^2} + \frac{1}{r}\frac{\partial s}{\partial r} + \frac{K_z}{K_r}\frac{\partial^2 s}{\partial z^2} = \frac{S_s}{K_r}\frac{\partial s}{\partial t}$$
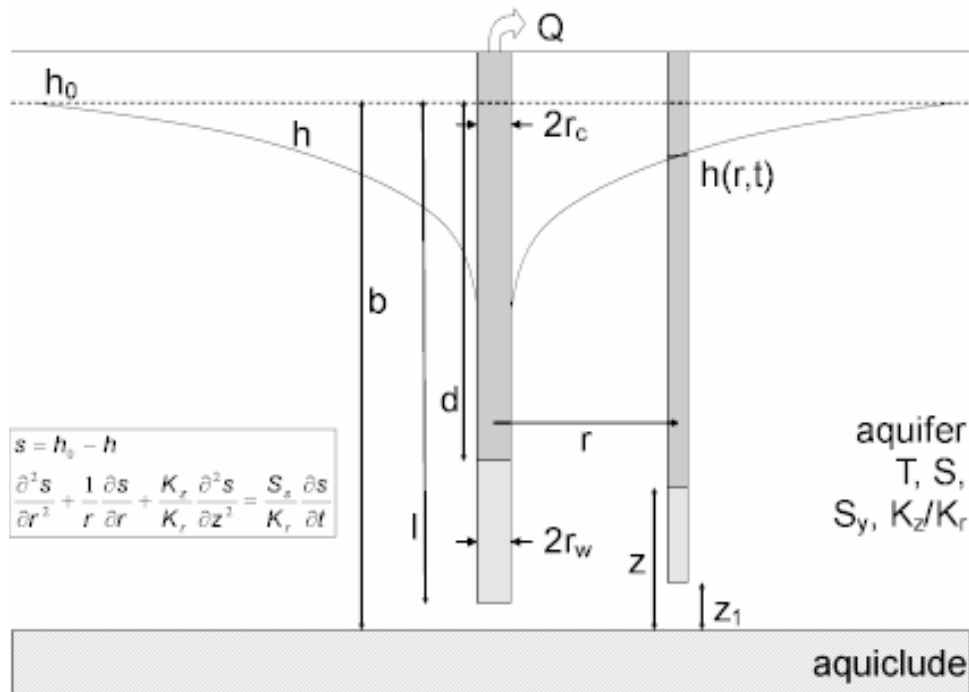
- o Equations

Moench (1997) derived an analytical solution for predicting drawdown in response to pumping in a homogeneous, anisotropic unconfined aquifer assuming partially penetrating wells, wellbore storage, wellbore skin and delayed gravity response. The solution also includes a correction for delayed observation well response.

The Laplace transform solution for dimensionless drawdown in the pumped well is as follows:

$$\bar{h}_{wD} = \frac{2(A + S_w)}{p(l_D - d_D)[1 + pW_D(A + S_w)]}$$

The following equation is the Laplace transform solution for dimensionless drawdown in a piezometer:

$$\overline{h}_D = \frac{2E}{p(l_D - d_D)[1 + pW_D(A + S_w)]}$$

The equation for dimensionless drawdown in an observation well is:

$$\overline{h}'_D = \frac{2E'}{p(l_D - d_D)[1 + pW_D(A + S_w)]}$$

$$A = \frac{2}{(l_D - d_D)} \sum_{n=0}^{\infty} \frac{K_0(q_n)\{\sin[\varepsilon_n(1-d_D)] - \sin[\varepsilon_n(1-l_D)]\}^2}{\varepsilon_n q_n K_1(q_n)[\varepsilon_n + 0.5\sin(2\varepsilon_n)]}$$

$$E = 2\sum_{n=0}^{\infty} \frac{K_0(q_n r_D)\cos(\varepsilon_n z_D)\sin[\varepsilon_n(1-d_D)] - \sin[\varepsilon_n(1-l_D)]}{q_n K_1(q_n)[\varepsilon_n + 0.5\sin(2\varepsilon_n)]}$$

$$E' = 2\sum_{n=0}^{\infty} \frac{K_0(q_n r_D)[\sin(\varepsilon_n z_{2D}) - \sin(\varepsilon_n z_{1D})]\{\sin[\varepsilon_n(1-d_D)] - \sin[\varepsilon_n(1-l_D)]\}}{(z_{2D} - z_{1D})\varepsilon_n q_n K_1(q_n)[\varepsilon_n + 0.5\sin(2\varepsilon_n)]}$$

$$W_D = \frac{\pi r_c^2}{2\pi r_w^2 S_s(l-d)}$$

$$q_n = \sqrt{\varepsilon^2 \beta_w + p}$$

$$q_n r_D = \sqrt{\varepsilon^2 \beta + p r_D^2}$$

$$\beta_w = \frac{r_w^2 K_z}{b^2 K_r}$$

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

$$t_D = \frac{Kt}{S_s r_w^2}$$

$$h_D = \frac{4\pi K b}{Q}(h_0 - h)$$

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

$$\sigma = \frac{S_s b}{S_y}$$

$$\gamma = \alpha_1 b S_y / K_z$$

ε_n are the roots of

$$\varepsilon_n \tan(\varepsilon_n) = \frac{p}{(\sigma\beta + p / \gamma)}$$

where

- α_1 is an empirical constant (fitting parameter) for noninstantaneous drainage [1/T]

- b is aquifer thickness [L]

- d is distance from water table to top of pumping well screen [L]

- d_D is d/b

- K, K_r is radial hydraulic conductivity [L/T]

- K_z is vertical hydraulic conductivity [L/T]

- K_i is modified Bessel function of second kind, order i

- l is distance from water table to bottom of pumping well screen [L]

- l_D is l/b

- p is the Laplace transform variable

- Q is pumping rate [L^3/T]

- r is radial distance [L]

- r_c is casing radius [L]

- r_w is well radius [L]

- S_s is specific storage [1/L]

- S_w is wellbore skin factor [dimensionless]

- S_y is specific yield [dimensionless]

- t is time [T]

- z is elevation of piezometer above base of aquifer [L]

- z_D is z/b

- z_1 is elevation of bottom of observation well screen above base of aquifer [L]

- z_{1D} is z_1/b

- z_2 is elevation of top of observation well screen above base of aquifer [L]

- z_{2D} is z_2/b

In the Laplace transform solution, S_w is limited to positive values; however, using the effective well radius concept, we also may simulate a negative skin (Hurst, Clark and Brauer 1969).

If you enter a radius for downhole equipment, AQTESOLV uses the effective casing radius instead of the nominal casing radius in the equations for this solution.

Moench (1997) also included a correction for delayed water-level response in a fully or partially penetrating observation well based on the work of Black and Kipp (1977):

$$\bar{h}_{Do} = \frac{\bar{h}_D}{1 + W_D' p}$$

$$W_D' = \frac{\pi r_{co}^2}{2 \pi r_w^2 S_s F'}$$

$$F' = \frac{z_2 - z_1}{\ln[(z_2 - z_1)/2\sqrt{K_z/K_r}\, r_{wo} + \sqrt{1 + ((z_2 - z_1)/2\sqrt{K_z/K_r}\, r_{wo})^2}]}$$

where

- r_{co} is casing radius of observation well [L]

- r_{wo} is well radius of observation well [L]

The correction is based on the quasi-steady-state flow model of Hvorslev (1951) for a slug test. AQTESOLV uses the standard definition of the shape factor given by Butler (1998) which depends on the position of the well screen in the aquifer. Note that delayed response diminishes as r_{co} approaches zero; therefore, to eliminate the correction for delayed response, enter a small value for the casing radius of the observation well.

- Assumptions

  - aquifer has infinite areal extent

  - aquifer is homogeneous and of uniform thickness

  - aquifer potentiometric surface is initially horizontal

- pumping and observation wells are fully or partially penetrating

- flow is unsteady

- aquifer is unconfined with delayed gravity response

- 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)

  - downhole equipment radius (optional)

  - saturated thickness

  - partial penetration depths (optional)

- Solution Options

  - constant or variable pumping rate including recovery

  - multiple pumping wells

  - multiple observation wells

  - partially penetrating wells

  - boundaries

- Estimated Parameters

  - T (transmissivity)

  - S (storativity)

  - β

  - Sy (specific yield)

  - Sw (dimensionless wellbore skin factor)

  - r(w) (well radius)

  - r(c) (nominal casing radius)

  - α_1 (Moench's empirical constant for noninstantaneous drainage at the water table)

- Curve Matching Tips

  - Use radial flow plots to help diagnose wellbore storage.

  - Match the Cooper-Jacob (1946) solution to late-time data to obtain

preliminary estimates of aquifer properties.

- Match early-time data affected by wellbore storage by adjusting **r(c)** with parameter tweaking.

- If you estimate **r(c)** for the test well, the estimated value replaces the nominal casing radius and AQTESOLV still performs the correction for downhole equipment.

- Choose Match>Visual to perform visual curve matching using the procedure for type curve solutions.

- Use active type curves for more effective visual matching with variable-rate pumping tests.

- Select values of β from the **Family** and **Curve** drop-down lists on the toolbar.

- Use parameter tweaking to perform visual curve matching and sensitivity analysis.

- Perform visual curve matching prior to automatic estimation to obtain reasonable starting values for the aquifer properties.

- Enter a large value for α_1 (the drainage parameter) to achieve instantaneous drainage at the water table (Neuman's model).

  o References

  - 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.

Related Topics

Tartakovsky-Neuman (2007) Solution for a Pumping Test in an Unconfined Aquifer

(Match > Solution)

Tartakovsky and Neuman (2007) derived an analytical solution for unsteady flow to a fully or partially penetrating well in a homogeneous, anisotropic unconfined aquifer with delayed gravity response considering three-dimensional flow in the saturated and unsaturated zones. Unlike the Neuman (1974) solution, the Tartakovsky-Neuman solution allows for noninstantaneous drainage at the water table. The solution assumes a line source for the pumped well and therefore neglects wellbore storage.

AQTESOLV applies the principle of superposition in time to simulate variable-rate tests including recovery. You may use the Tartakovsky-Neuman solution to analyze both pumping and recovery data from constant- or variable-rate pumping tests.

The Tartakovsky-Neuman solution includes a parameter (κ_D) that characterizes the properties of the unsaturated medium. As κ_D approaches , the Tartakovsky-Neuman

- o Illustration
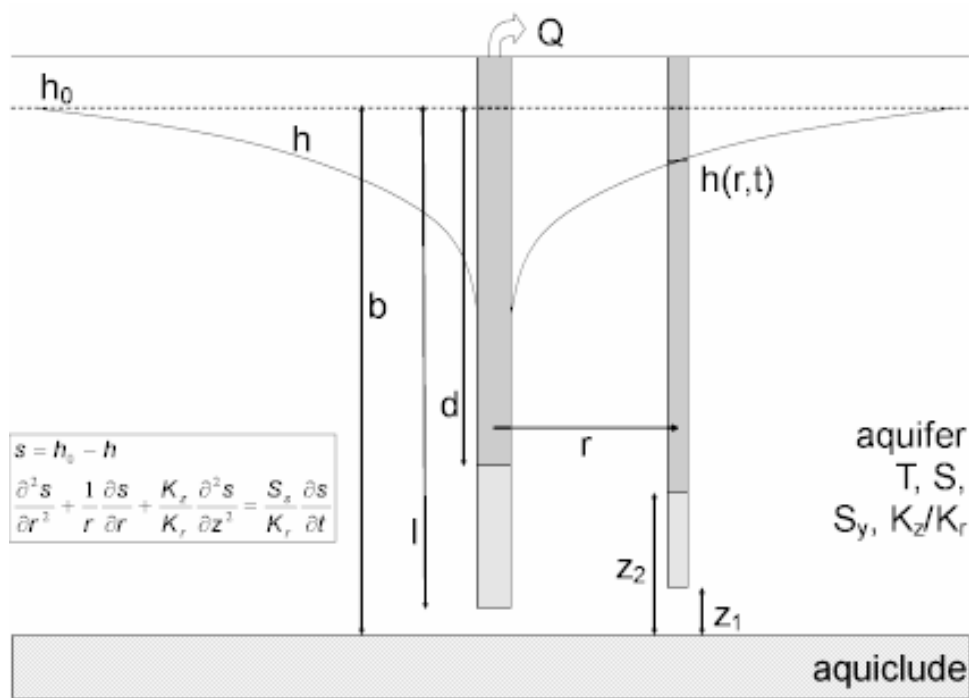
- o Equations

Tartakovsky and Neuman (2007) developed a Laplace transform solution for unsteady flow to a partially penetrating well in an unconfined aquifer with three-dimensional flow in the saturated and unsaturated zones:

$$\bar{s} = \frac{Qt}{2\pi T p_D} \int_0^\infty \frac{\eta \sinh(\eta)}{\cosh(\eta)\gamma - \eta \sinh(\eta)} \exp[\gamma(z_D - 1)] \frac{\sinh[\eta(1-l_D)] - \sinh[\eta(1-d_D)]}{\eta^2 (l_D - d_D)\sinh(\eta)} y J_0(y\sqrt{}$$

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

$$\mu^2 = y^2 + \frac{p_D}{t_s \beta}$$

$$\nu^2 = y^2 + \frac{p_D}{t_s \varphi \beta}$$

$$\varphi = \frac{S}{\kappa_D S_y}$$

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$$\gamma = \frac{\kappa_D}{2} - \sqrt{\frac{\kappa_D^2}{4} + \nu^2}$$

$$t_s = \frac{Tt}{Sr^2}$$

$$p_D = tp$$

$$s_D = \frac{4\pi T}{Q} s$$

where

- b is aquifer thickness [L]

- d_D is dimensionless depth to top of pumping well screen (d/b)

- J_0 is Bessel function of first kind, zero order

- K_r is radial hydraulic conductivity [L/T]

- K_z is vertical hydraulic conductivity [L/T]

- κ_D is dimensionless Gardner parameter for the unsaturated zone (κb)

- l_D is dimensionless depth to bottom of pumping well screen (l/b)

- p is Laplace transform variable [T^{-1}]

- Q is pumping rate [L^3/T]

- r is radial distance [L]

- s is drawdown [L]

- S is storativity [dimensionless]

- S_y is specific yield [dimensionless]

- t is time [T]

- T is transmissivity [L^2/T]

- y is variable of integration

- z_D is dimensionless elevation of piezometer opening above base of aquifer (z/b)

Expressions for fully and partially penetrating observations wells are obtained by vertically averaging the drawdown computed with the piezometer equation over the length of the observation well screen.

As κ_D approaches , the effect of the unsaturated zone dies out and the

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solution behaves like the model of Neuman (1974).

- o Assumptions
  - aquifer has infinite areal extent
  - aquifer is homogeneous and has uniform thickness
  - aquifer potentiometric surface is initially horizontal
  - pumping well is fully or partially penetrating
  - aquifer is unconfined with delayed gravity response
  - the unsaturated zone has infinite thickness
  - flow is unsteady
  - diameter of pumping well is very small so that storage in the well can be neglected
- o Data Requirements
  - pumping and observation well locations
  - pumping rate(s)
  - observation well measurements (time and displacement)
  - aquifer saturated thickness
  - partial penetration depths (optional)
- o Solution Options
  - variable pumping rates
  - multiple pumping wells
  - multiple observation wells
  - partially penetrating wells
- o Estimated Parameters
  - T (transmissivity)
  - S (storativity)
  - S_y (specific yield)
  - Kz/Kr (hydraulic conductivity anisotropy ratio)
  - k(D) (dimensionless Gardner parameter)
- o Curve Matching Tips
  - Choose Match>Visual to perform visual curve matching using the

procedure for type curve solutions.

- Use active type curves for more effective visual matching with variable-rate pumping tests.

- Use parameter tweaking to perform visual curve matching and sensitivity analysis.

- Perform visual curve matching prior to automatic estimation to obtain reasonable starting values for the aquifer properties.

- Change convergence levels to optimize the speed and accuracy of computations for the solution. The default setting is suitable for all cases. The fastest level works well for fully penetrating wells or partially penetrating wells with longer screens. Use higher convergence levels to check the performance of lower settings.

o References

- Tartakovsky, G.D. and S.P. Neuman, 2007. Three-dimensional saturated-unsaturated flow with axial symmetry to a partially penetrating well in a compressible unconfined aquifer, Water Resources Research, W01410, doi:1029/2006WR005153.

- Neuman, S.P., 1972. Theory of flow in unconfined aquifers considering delayed gravity response of the water table, Water Resources Research, vol. 8, no. 4, pp. 1031-1045.

- 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.

Related Topics

Fractured Aquifers

Moench (1984) Solution for a Pumping Test in a Fractured Aquifer

(Match > Solution)

Moench (1984) derived an analytical solution for unsteady flow to a fully penetrating, finite-diameter well with wellbore storage and wellbore skin in an isotropic fractured aquifer assuming a double-porosity model with slab or spherical matrix blocks and fracture skin.

Moench (1988) extended the method to include partially penetrating wells and anisotropy based on the solution by Dougherty and Babu (1984). When you choose the Moench solution in AQTESOLV, you may analyze data for fully or partially penetrating wells. The solution also includes delayed response in an observation well based on the work of Moench (1997).
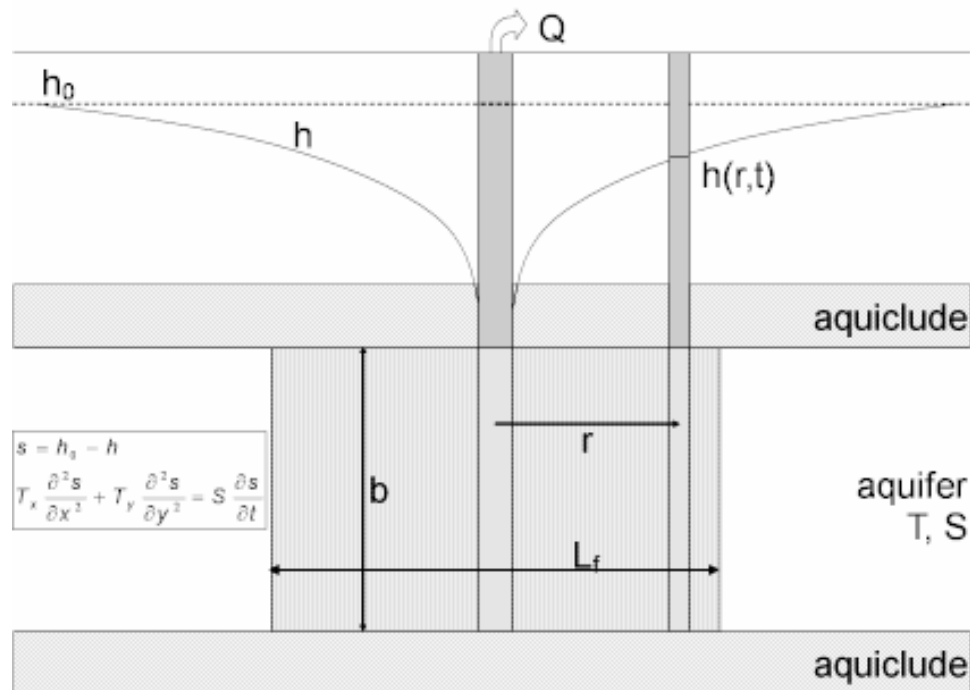
AQTESOLV uses the principle of superposition in time to simulate variable-rate tests including recovery with the Moench solution. Use this solution to analyze both pumping and recovery data from constant- or variable-rate pumping tests.

Wellbore storage has a distinct signature in the early-time response of a pumped well. Use the radial flow and derivative-time plots to detect the wellbore storage effect.

When you choose a solution, AQTESOLV provides two configurations for simulating a double-porosity aquifer with the Moench solution: slab-shaped and spherical blocks.

- o   Illustration
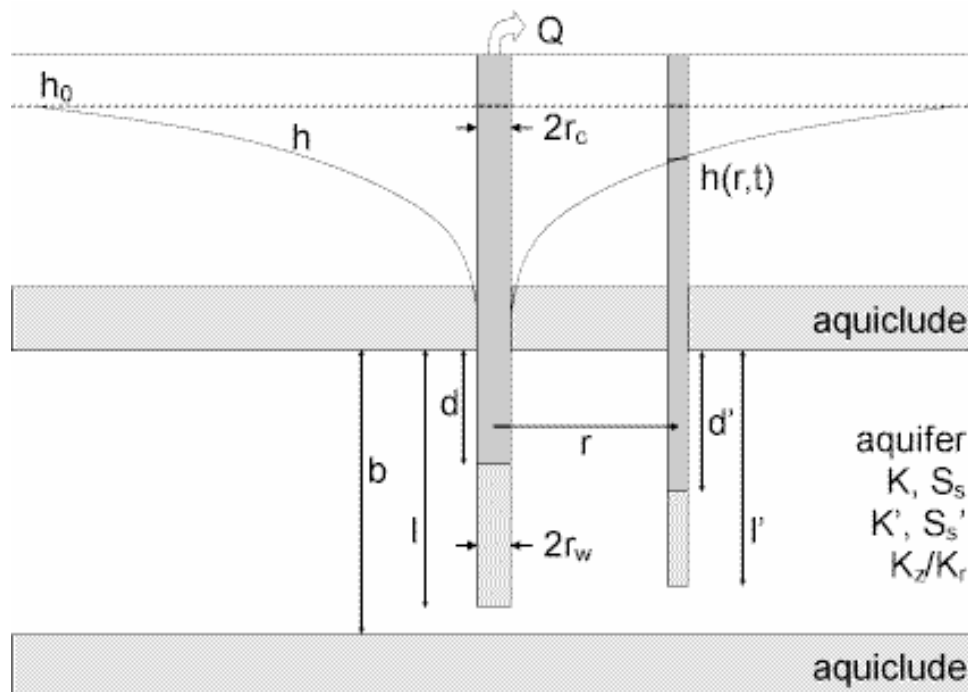
- o Equations

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:

$$\overline{h}_{wD} = \frac{2[K_0(x) + xS_wK_1(x)]}{p\{pW_D[K_0(x) + xS_wK_1(x)] + xK_1(x)\}}$$

The following equation is the Laplace transform solution for dimensionless drawdown in an observation well:

$$\overline{h}_D = \frac{2K_0(r_D x)}{p\{pW_D[K_0(x) + xS_wK_1(x)] + xK_1(x)\}}$$

$$x = (p + \overline{q}_D)^{1/2}$$

For slab blocks:

$$\overline{q}_D = \frac{\gamma^2 m \tanh(m)}{1 + S_r m \tanh(m)}$$

For spherical blocks:

$$\overline{q}_D = \frac{3\gamma^2[m \coth(m) - 1]}{1 + S_r[m \coth(m) - 1]}$$

$$m = \frac{(\sigma p)^{1/2}}{\gamma}$$

$$\gamma = \frac{r_w}{b_f}\left(\frac{K'}{K}\right)^{1/2}$$

$$\sigma = \frac{S_s{}'}{S_s}$$

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

$$S_f = \frac{K'b_s}{K_s b'}$$

$$W_D = \frac{\pi r_c^2}{2\pi r_w^2 S_s b}$$

$$t_D = \frac{Kt}{S_s r_w^2}$$

$$h_D = \frac{4\pi Kb}{Q}(h_0 - h)$$

where

- b is aquifer thickness [L]
- b' is block thickness [L]
- b_s is fracture skin thickness [L]
- K is aquifer hydraulic conductivity [L/T]
- K' is matrix hydraulic conductivity [L/T]
- K_s is fracture skin hydraulic conductivity [L/T]
- K_i is modified Bessel function of second kind, order i
- p is the Laplace transform variable
- Q is pumping rate [L^3/T]
- r is radial distance [L]
- r_c is casing radius [L]
- r_w is well radius [L]
- S_f is fracture skin factor [dimensionless]
- S_s is fracture specific storage [1/L]
- S_s' is matrix specific storage [1/L]
- S_w is wellbore skin factor [dimensionless]
- t is time [T]

Moench (1988) extended the method to include partial penetration and anisotropy based on the work of Dougherty and Babu (1984). The anisotropy ratio, Kz/Kr, refers to the hydraulic conductivity of the fracture system.

In the Laplace transform solution, S_w is limited to positive values; however, using the effective well radius concept, we also may simulate a negative skin (Hurst, Clark and Brauer 1969).

If you enter a radius for downhole equipment, AQTESOLV uses the effective casing radius instead of the nominal casing radius in the equations for this solution.

Refer to the Moench (1997) solution for the equations relating to delayed response in an observation well.

- o Assumptions

  - aquifer has infinite areal extent

  - aquifer has uniform thickness

  - pumping and observation wells are fully or partially penetrating

  - aquifer is confined with double porosity

  - matrix blocks are slab shaped or spherical

  - flow is unsteady

  - water is released instantaneously from storage with decline of hydraulic head

- o 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)

  - downhole equipment radius (optional)

  - saturated thickness

  - thickness of slab blocks or diameter of spherical blocks

- o Solution Options

  - constant or variable pumping rate including recovery

  - multiple pumping wells

  - multiple observation wells

  - boundaries

- o Estimated Parameters

  - K (fracture hydraulic conductivity)

- Ss (fracture specific storage)

- K' (matrix hydraulic conductivity)

- Ss' (matrix specific storage)

- Sw (wellbore skin factor)

- Sf (fracture skin factor)

- r(w) (well radius)

- r(c) (nominal casing radius)

o Curve Matching Tips

- Use radial flow plots to help diagnose wellbore storage.

- Match the Cooper-Jacob (1946) solution to late-time data to obtain preliminary estimates of aquifer properties.

- Match early-time data affected by wellbore storage by adjusting **r(c)** with parameter tweaking.

- If you estimate **r(c)** for the test well, the estimated value replaces the nominal casing radius and AQTESOLV still performs the correction for downhole equipment.

- Choose Match>Visual to perform visual curve matching using the procedure for type curve solutions.

- Use active type curves for more effective visual matching with variable-rate pumping tests.

- Select values of Sf from the **Family** and **Curve** drop-down lists on the toolbar.

- Use parameter tweaking to perform visual curve matching and sensitivity analysis.

- Perform visual curve matching prior to automatic estimation to obtain reasonable starting values for the aquifer properties.

o References

- 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.

- Moench, A.F., 1988. The response of partially penetrating wells to pumpage from double-porosity aquifers, Proceedings of the International Conference on Fluid Flow in Fractured Rocks, Atlanta, GA, May 16-18, 1988.

- Dougherty, D.E and D.K. Babu, 1984. Flow to a partially penetrating well in a double-porosity reservoir, Water Resources Research, vol. 20, no. 8,

Related Topics

Gringarten-Witherspoon (1972) Solution for a Pumping Test in a Fractured Aquifer

(Match > Solution)

Gringarten and Witherspoon (1972) and Gringarten, Ramey and Raghavan (1974) presented an analytical solution for unsteady flow to a fully penetrating well intersecting a single uniform-flux vertical fracture in an anisotropic confined aquifer. The pumped well bisects the fracture which is represented in the solution by a fully penetrating vertical plane source oriented parallel to the x axis. In contrast to the infinite-conductivity solution for a vertical fracture, drawdown in the uniform-flux formulation varies along the fracture.

AQTESOLV uses the principle of superposition in time to simulate variable-rate tests including recovery with the Gringarten-Witherspoon solution. Use this solution to analyze both pumping and recovery data from constant- or variable-rate pumping tests.

The early-time response of a pumped well intersecting a vertical fracture has a distinct signature that you can diagnose with a linear flow plot.

TIP Due to anisotropy, use of a distance-drawdown plot with the Gringarten-Witherspoon solution is limited to wells located on the x-coordinate axis.

o   Illustration

The equations shown in the illustration:

$$s = h_0 - h$$

$$T_x \frac{\partial^2 s}{\partial x^2} + T_y \frac{\partial^2 s}{\partial y^2} = S \frac{\partial s}{\partial t}$$

- Equations

  The following equation by Gringarten and Witherspoon (1972) predicts drawdown in a confined aquifer with a uniform-flux vertical fracture:

  $$S = \frac{Q}{4\pi\sqrt{T_x T_y}} \frac{\sqrt{\pi}}{2} \int_0^{t_D} \left[erf\frac{1-x_D}{2\sqrt{\tau}} + erf\frac{1+x_D}{2\sqrt{\tau}} \right] e^{-\frac{y_D^2 T_x}{4\pi T_t}} \frac{d\tau}{\sqrt{\tau}}$$

  $$t_D = \frac{T_x t}{S x_f^2}$$

  $$x_D = \frac{x}{x_f}$$

  $$y_D = \frac{y}{x_f}$$

  $$S_D = \frac{4\pi\sqrt{T_x T_y}}{Q} S$$

  where

  - Q is pumping rate [L^3/T]

  - s is drawdown [L]

  - S is storativity [dimensionless]

  - t is time [T]

  - T_x is transmissivity in x direction [L^2/T]

  - T_y is transmissivity in y direction [L^2/T]

  - x and y are coordinate distances [L]

  - x_f is the half-length of the fracture in the x direction [L]

- 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

- length of vertical fracture

○ Solution Options

- constant or variable pumping rate including recovery

- multiple pumping wells

- multiple observation wells

- boundaries

○ Estimated Parameters

- Kx (hydraulic conductivity in x direction)

- Ss (specific storage)

- Ky/Kx (hydraulic conductivity anisotropy ratio)

- Lf (length of fracture)

○ Curve Matching Tips

- Use linear flow plots to help diagnose fracture flow.

- Use the Cooper-Jacob (1946) solution to obtain preliminary estimates of aquifer properties.

- Choose Match>Visual to perform visual curve matching using the procedure for type curve solutions.

- Use active type curves for more effective visual matching with variable-rate pumping tests.

- Select values of Ky/Kx from the **Family** and **Curve** drop-down lists on the toolbar.

- Use parameter tweaking to perform visual curve matching and sensitivity

analysis.

- Perform visual curve matching prior to automatic estimation to obtain reasonable starting values for the aquifer properties.

  o References

  - 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.

  - Gringarten, A.C., Ramey, H.J., Jr. and R. Raghavan, 1974. Unsteady-state pressure distributions created by a well with single infinite-conductivity vertical fracture, Soc. Petrol. Engrs. J., pp. 347-360.

Related Topics

Gringarten-Ramey-Raghavan (1974) Solution for a Pumping Test in a Fractured Aquifer

(Match > Solution)

Gringarten, Ramey and Raghavan (1974) presented an analytical solution for unsteady flow to a fully penetrating well intersecting a single infinite-conductivity vertical fracture in an anisotropic confined aquifer. The pumped well bisects the fracture which is represented in the solution by a fully penetrating vertical plane source oriented parallel to the x axis. In contrast to the uniform-flux solution for a vertical fracture, drawdown in the infinite-conductivity formulation is uniform along the fracture.

AQTESOLV uses the principle of superposition in time to simulate variable-rate tests including recovery with the Gringarten et al. solution. Use this solution to analyze both pumping and recovery data from constant- or variable-rate pumping tests.

The early-time response of a pumped well intersecting a vertical fracture has a distinct signature that you can diagnose with a linear flow plot.

> TIP Due to anisotropy, use of a distance-drawdown plot with the Gringarten et al. solution is limited to wells located on the x-coordinate axis.

- Illustration
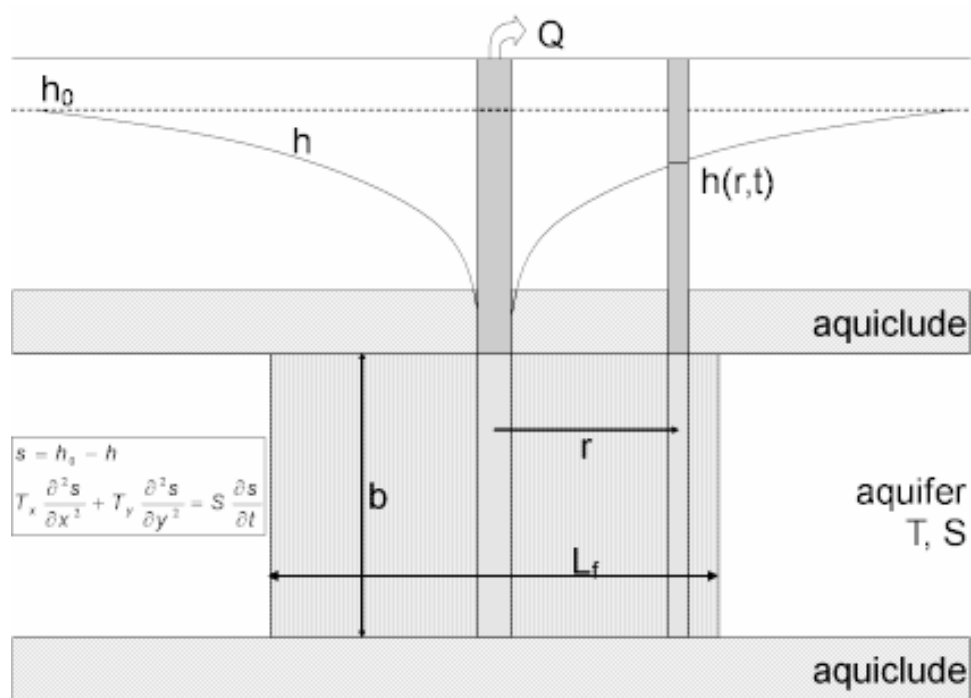
- Equations

The following equation by Gringarten and Witherspoon (1972) predicts drawdown in an anisotropic confined aquifer with a uniform-flux vertical fracture:

$$S = \frac{Q}{4\pi\sqrt{T_x T_y}} \frac{\sqrt{\pi}}{2} \int_0^{t_D} \left[erf \frac{1-x_D}{2\sqrt{\tau}} + erf \frac{1+x_D}{2\sqrt{\tau}} \right] e^{-\frac{y_D^2 T_x}{4\tau T_t}} \frac{d\tau}{\sqrt{\tau}}$$

$$t_D = \frac{T_x t}{S x_f^2}$$

$$x_D = \frac{x}{x_f}$$

$$y_D = \frac{y}{x_f}$$

$$S_D = \frac{4\pi\sqrt{T_x T_y}}{Q} S$$

where

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- Q is pumping rate [L^3/T]

- s is drawdown [L]

- S is storativity [dimensionless]

- t is time [T]

- T_x is transmissivity in x direction [L^2/T]

- T_y is transmissivity in y direction [L^2/T]

- x and y are coordinate distances [L]

- x_f is the half-length of the fracture in the x direction [L]

Gringarten, Ramey and Raghavan (1974) found that the foregoing solution could be used to predict the drawdown in an infinite-conductivity fracture by simply using $x_D = 0.732$ to compute drawdown in the pumped well.

o 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

o Data Requirements

- pumping and observation well locations

- pumping rate(s)

- observation well measurements (time and displacement)

- saturated thickness

- length of vertical fracture

o Solution Options

- constant or variable pumping rate including recovery

- multiple pumping wells

- multiple observation wells

- boundaries

o Estimated Parameters

- Kx (hydraulic conductivity in x direction)

- Ss (specific storage)

- Ky/Kx (hydraulic conductivity anisotropy ratio)

- Lf (length of fracture)

o Curve Matching Tips

- Use linear flow plots to help diagnose fracture flow.

- Use the Cooper-Jacob (1946) solution to obtain preliminary estimates of aquifer properties.

- Choose Match>Visual to perform visual curve matching using the procedure for type curve solutions.

- Use active type curves for more effective visual matching with variable-rate pumping tests.

- Select values of Ky/Kx from the **Family** and **Curve** drop-down lists on the toolbar.

- Use parameter tweaking to perform visual curve matching and sensitivity analysis.

- Perform visual curve matching prior to automatic estimation to obtain reasonable starting values for the aquifer properties.

o References

- Gringarten, A.C., Ramey, H.J., Jr. and R. Raghavan, 1974. Unsteady-state pressure distributions created by a well with single infinite-conductivity vertical fracture, Soc. Petrol. Engrs. J., pp. 347-360.

- 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.

Related Topics

Gringarten-Ramey (1974) Solution for a Pumping Test in a Fractured Aquifer

(Match > Solution)

Gringarten and Ramey (1974) presented an analytical solution for unsteady flow to a well intersecting a single uniform-flux horizontal fracture in an anisotropic confined aquifer. The solution assumes the fracture is a planar, disc-shaped source with the pumped well located at its center.

AQTESOLV uses the principle of superposition in time to simulate variable-rate tests including recovery with the Gringarten-Ramey solution. Use this solution to analyze both pumping and recovery data from constant- or variable-rate pumping tests.

The early-time response of a pumped well intersecting a horizontal fracture has a distinct signature that you can diagnose with a linear flow plot.

- Illustration
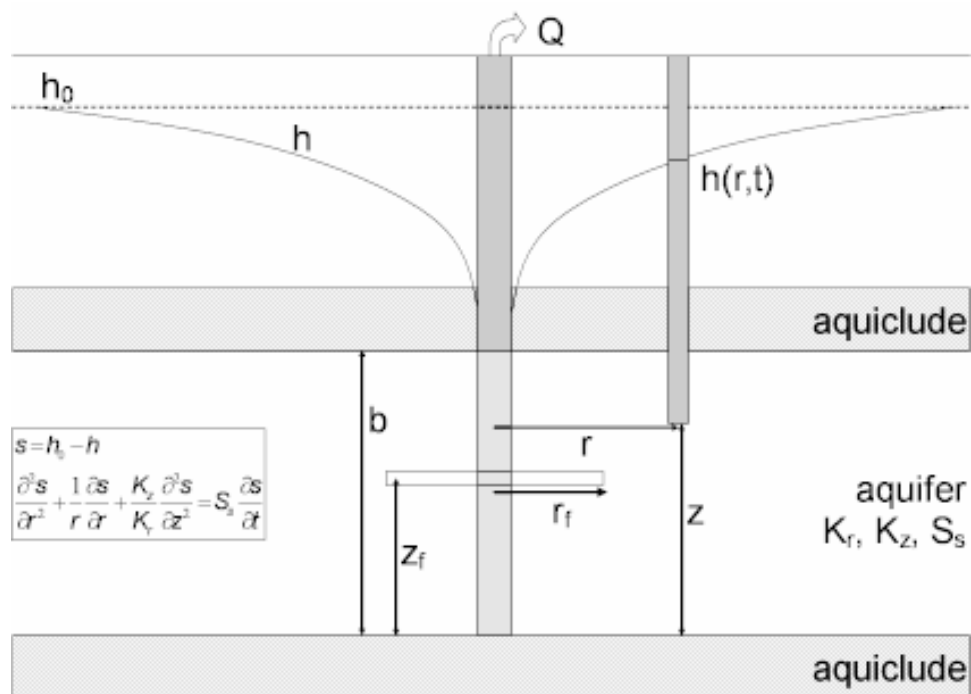
- Equations

The following equation by Gringarten and Ramey (1974) predicts drawdown at a fixed point (piezometer) in an anisotropic confined aquifer with a uniform-flux horizontal fracture:

$$s = \frac{Q}{4\pi\sqrt{K_r K_z}} \frac{2}{H_D} \int_0^{t_D} P \cdot Z \frac{d\tau}{\tau}$$

$$t_D = \frac{K_r t}{S_s r_f^2}$$

$$P = e^{-\frac{r_D^2}{4\tau}} \int_0^1 I_0\left(\frac{r_D \upsilon}{2\tau}\right) e^{-\frac{\upsilon^2}{4\tau}} \upsilon \, d\upsilon$$

$$Z = 1 + 2\sum_{n=1}^{\infty} e^{-\frac{n^2 \pi^2 \tau}{H_D^2}} \cos\left(n\pi\frac{Z_f}{b}\right) \cos\left(n\pi\frac{Z}{b}\right)$$

$$H_D = \frac{b}{r_f}\sqrt{K_r / K_z}$$

$$r_D = \frac{r}{r_f}$$

$$s_D = \frac{4\pi T}{Q} s$$

where

- b is saturated thickness [L]

- I_0 is modified Bessel function of first kind, zero order

- K_r radial hydraulic conductivity [L/T]

- K_z is vertical hydraulic conductivity [L/T]

- Q is pumping rate [L^3/T]

- r is radial distance [L]

- r_f is the radius of the fracture [L]

- s is drawdown [L]

- S_s is specific storage [1/L]

- t is time [T]

- z is the z coordinate [L]

Drawdown in an observation well may be found by integrating the preceding equations with respect to z.

- o Assumptions

  - aquifer has infinite areal extent

- aquifer has uniform thickness

- aquifer potentiometric surface is initially horizontal

- 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

o Data Requirements

- pumping and observation well locations

- pumping rate(s)

- observation well measurements (time and displacement)

- saturated thickness

- radius and depth of horizontal fracture

o Solution Options

- constant or variable pumping rate including recovery

- multiple pumping wells

- multiple observation wells

- boundaries

o Estimated Parameters

- Kr (radial hydraulic conductivity)

- Ss (specific storage)

- Kz/Kr (hydraulic conductivity anisotropy ratio)

- Rf (radius of fracture)

o Curve Matching Tips

- Use linear flow plots to help diagnose fracture flow.

- Use the Cooper-Jacob (1946) solution to obtain preliminary estimates of aquifer properties.

- Choose Match>Visual to perform visual curve matching using the procedure for type curve solutions.

- Use active type curves for more effective visual matching with variable-rate pumping tests.

- Select values of Kz/Kr from the **Family** and **Curve** drop-down lists on the toolbar.

- Use parameter tweaking to perform visual curve matching and sensitivity analysis.

- Perform visual curve matching prior to automatic estimation to obtain reasonable starting values for the aquifer properties.

  o References

  - 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.

Related Topics

Barker (1988) Solution for a Pumping Test in a Fractured Aquifer

(Match > Solution)

Barker (1988) derived a generalized radial flow model for unsteady, n-dimensional flow to a fully penetrating source in an isotropic, single- or double-porosity fractured aquifer. The source is an n-dimensional sphere (projected through three-dimensional space) of finite radius (r_w), storage capacity (β) and skin factor (S_w).

As described by Doe (1990), the spatial dimension (n) determines the change in conduit area with distance from the source. In a two-dimensional system (n=2), the source is a finite cylinder, the typical configuration for analyzing cylindrical flow to a well.

AQTESOLV uses the principle of superposition in time to simulate variable-rate tests including recovery with the Barker solution. Use this solution to analyze both pumping and recovery data from constant- or variable-rate pumping tests.

Wellbore storage has a distinct signature in the early-time response of a pumped well in a cylindrical system (n=2). Use the radial flow and derivative-time plots to detect the wellbore storage effect.

The early-time response of a source in a linear system (n=1) has a distinct signature that you can diagnose with a linear flow plot.

When you choose a solution, AQTESOLV provides three configurations for the Barker generalized radial flow model:

- single-porosity (confined/fractured aquifer)

- double-porosity with slab-shaped blocks (fractured aquifer)
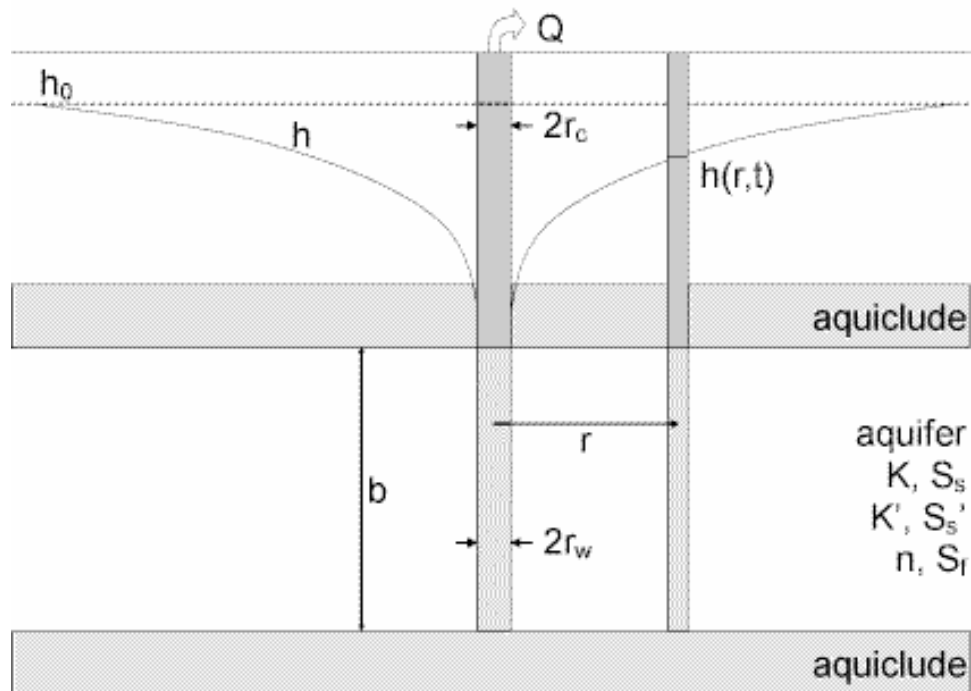
o Illustration

Diagram illustrating two-dimensional, cylindrical flow system (n=2).

o Equations

Barker (1988) derived a generalized radial flow model for unsteady, n-dimensional flow to a fully penetrating source in an isotropic, single- or double-porosity fractured aquifer.

The Laplace transform solution for drawdown in the pumped well (source) is as follows:

$$\bar{h}_w = \frac{Q[1+S_w\Phi(x)]}{p[p\beta[1+S_w\Phi(x)]+Kb^{3-n}\alpha_n r_w^{2-n}\Phi(x)]}$$

The following equation is the Laplace transform solution for drawdown in an observation well:

$$\bar{h} = \frac{Qr_D^v K_v(xr_D)/K_v(x)}{p[p\beta[1+S_w\Phi_v(x)]+Kb^{3-n}\alpha_n r_w^{n-2}\Phi_v(x)]}$$

$$v = 1 - n/2$$

$$\lambda^2 = pS_s/K$$

$$\mu = \lambda r_w$$

$$r_D = r / r_w$$

$$\Phi_v(z) = z K_{v-1}(z) / K_v(z)$$

$$\alpha_n = 2\pi^{n/2} / \Gamma(n/2)$$

$$\beta = \pi r_c^2$$

For single-porosity models, we have:

$$X = \mu$$

For double-porosity models, we use the functions of Moench (1984) for slab and spherical blocks including fracture skin.

$$X = (\mu^2 + \overline{q}_{rD})^{1/2}$$

slab blocks:

$$\overline{q}_{rD} = \frac{\gamma^2 m \tanh(m)}{1 + S_r m \tanh(m)}$$

spherical blocks:

$$\overline{q}_{rD} = \frac{3\gamma^2 [m \coth(m) - 1]}{1 + S_r [m \coth(m) - 1]}$$

$$m = \frac{(\sigma \mu^2)^{1/2}}{\gamma}$$

$$\gamma = \frac{r_w}{b_f} \left(\frac{K'}{K}\right)^{1/2}$$

$$\sigma = \frac{S_s'}{S_s}$$

$$S_r = \frac{K' b_s}{K_s b'}$$

where

- b is extent of flow region [L]

- b' is block thickness [L]

- b_s is fracture skin thickness [L]

- K is aquifer/fracture hydraulic conductivity [L/T]

- K' is matrix hydraulic conductivity [L/T]

- K_s is fracture skin hydraulic conductivity [L/T]

- K_v is modified Bessel function of second kind, order v

- n is flow dimension [dimensionless]

- p is the Laplace transform variable

- Q is pumping rate [L^3/T]

- r is radial distance [L]

- r_c is casing radius [L]

- r_w is well radius [L]

- S_f is fracture skin factor [dimensionless]

- S_s is aquifer/fracture specific storage [1/L]

- S_s' is matrix specific storage [1/L]

- S_w is wellbore skin factor [dimensionless]

- t is time [T]

The parameter b, the flow region extent, has a simple interpretation for integral flow dimensions. For one-dimensional flow (n=1), it is the square root of the conduit flow area (normal to the flow direction). For n=2 (two-dimensional radial flow), b is the thickness of the aquifer. For spherical flow (n=3), the parameter b, which is raised to the power of 3-n, has no significance. For nonintegral flow dimensions, b has no simple interpretation (Barker 1988).

In the Laplace transform solution, S_w is limited to positive values; however, using the effective well radius concept, we also may simulate a negative skin (Hurst, Clark and Brauer 1969).

If you enter a radius for downhole equipment, AQTESOLV uses the effective casing radius instead of the nominal casing radius in the equations for this solution.

o Assumptions

- aquifer has infinite extent

- aquifer has uniform extent of flow region

- pumping and observation wells are fully penetrating

- aquifer is confined with single or double porosity

- matrix blocks in double-porosity models are slab shaped or spherical

- 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)

  - downhole equipment radius (optional)

  - extent of flow region

  - thickness of slab blocks or diameter of spherical blocks (double-porosity models)

- Solution Options

  - constant or variable pumping rate including recovery

  - multiple pumping wells

  - multiple observation wells

  - boundaries

- Estimated Parameters

  - K (fracture hydraulic conductivity)

  - Ss (fracture specific storage)

  - K' (matrix hydraulic conductivity)

  - Ss' (matrix specific storage)

  - n (flow dimension)

  - b (extent of flow region)

  - Sf (fracture skin factor)

  - Sw (wellbore skin factor)

  - r(w) (well radius)

  - r(c) (nominal casing radius)

- Curve Matching Tips

  - Use radial flow plots to help diagnose wellbore storage.

  - Use linear flow plots to help diagnose linear flow.

  - Match the Cooper-Jacob (1946) solution to late-time data to obtain preliminary estimates of aquifer properties.

  - Match early-time data affected by wellbore storage by adjusting **r(c)** with parameter tweaking.

  - If you estimate **r(c)** for the test well, the estimated value replaces the nominal casing radius and AQTESOLV still performs the correction for downhole equipment.

  - Choose Match>Visual to perform visual curve matching using the procedure for type curve solutions.

  - Use active type curves for more effective visual matching with variable-rate pumping tests.

  - Select values of n, Sf and Sw from the **Family** and **Curve** drop-down lists on the toolbar.

  - Use parameter tweaking to perform visual curve matching and sensitivity analysis.

  - Perform visual curve matching prior to automatic estimation to obtain reasonable starting values for the aquifer properties.

- References

  - Barker, J.A., 1988. A generalized radial flow model for hydraulic tests in fractured rock, Water Resources Research, vol. 24, no. 10, pp. 1796-1804.

  - 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.

Related Topics

Overview (Slug Test Solutions)

AQTESOLV provides the following solutions for slug tests in confined, unconfined and fractured aquifers.

Confined	Bouwer-Rice (1976)
Confined	Hvorslev (1951)
Confined	Cooper-Bredehoeft-Papadopulos (1967)
Confined	Dougherty-Babu (1984)
Confined	KGS Model (1994)
Confined	Butler (1998) inertial
Confined	Butler-Zhan (2004) inertial
Confined	Peres et al. (1989) deconvolution
Confined	McElwee-Zenner (1998) nonlinear
Unconfined	Bouwer-Rice (1976)
Unconfined	Hvorslev (1951)
Unconfined	KGS Model (1994)
Unconfined	Springer-Gelhar (1991) inertial
Unconfined	Dagan (1978) with partially submerged screen
Fractured	Barker-Black (1983)

- Choose Match>Solution to select a slug test solution.

- Follow guidelines developed by Butler (1998) for applying slug test models.

Related Topics

Overdamped Slug Test Solutions

The familiar response of a slug test is overdamped, in contrast to an underdamped response (i.e., an oscillatory response due to inertial effects) sometimes observed in high-K aquifers.

Example: Overdamped Slug Test Response

Falling-Head Slug Test

Obs. Wells
□ Well 1

Aquifer Model
Unconfined

Solution
KGS Model

Parameters
Kr = 0.0004874 cm/sec
Ss = 0.0001738 ft^{-1}
Kz/Kr = 1.

Falling-Head Slug Test

Obs. Wells
□ Well 1

Aquifer Model
Unconfined

Solution
Bouwer-Rice

Parameters
K = 0.0003482 cm/sec
y0 = 1.063 ft
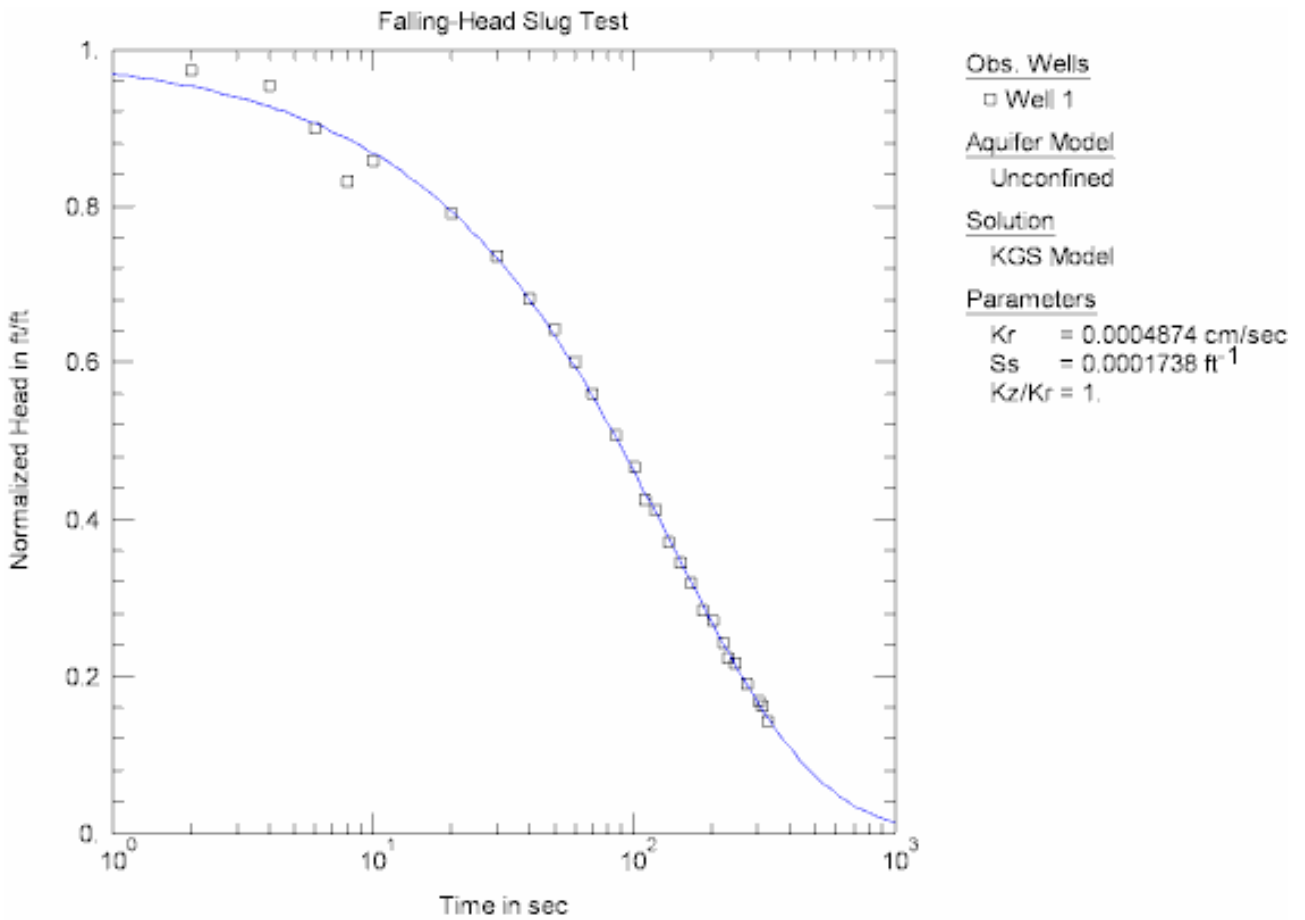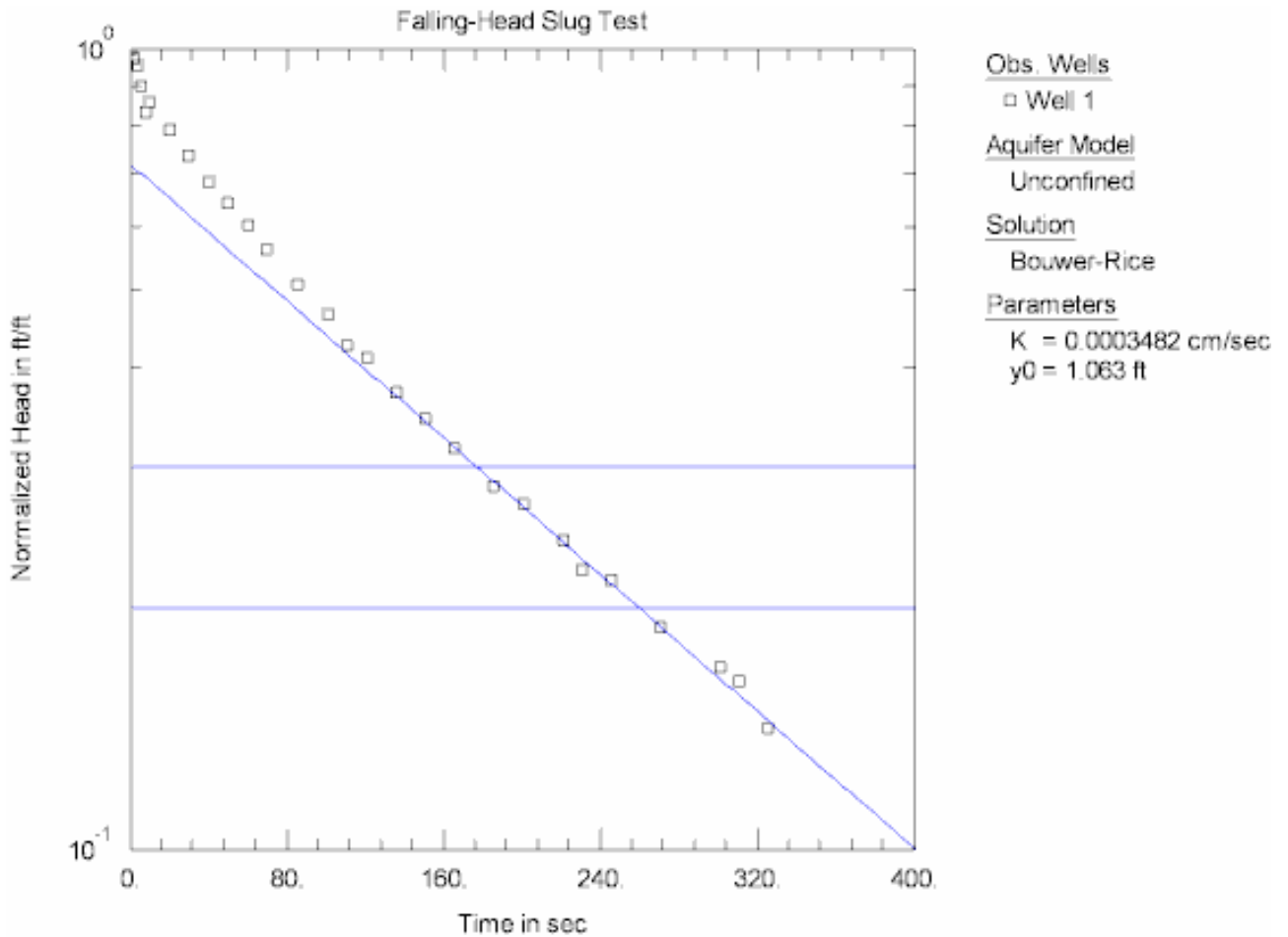
The following slug test solutions simulate the overdamped case in confined, unconfined and fractured aquifers.

Confined	Bouwer-Rice (1976)
Confined	Hvorslev (1951)
Confined	Cooper-Bredehoeft-Papadopulos (1967)
Confined	Dougherty-Babu (1984)
Confined	KGS Model (1994)
Confined	Peres et al. (1989) deconvolution
Unconfined	Bouwer-Rice (1976)
Unconfined	Hvorslev (1951)
Unconfined	KGS Model (1994)
Unconfined	Dagan (1978)
Fractured	Barker-Black (1983)

- Choose Match>Solution to select a slug test solution.

Related Topics

Underdamped Slug Test Solutions

Slug tests in high hydraulic conductivity (high-K) aquifers sometimes exhibit underdamped (oscillatory) response due to inertial effects in the well.

➡️ Example: Underdamped Slug Test Response

DP43C - 0.61 m Screen

Obs. Wells
□ DP43C

Aquifer Model
Confined

Solution
Butler
Critically damped when C(D)=2

Parameters
K = 87.55 m/day
Le = 10.19 m
C(D) = 0.3534
L = 10.56 m
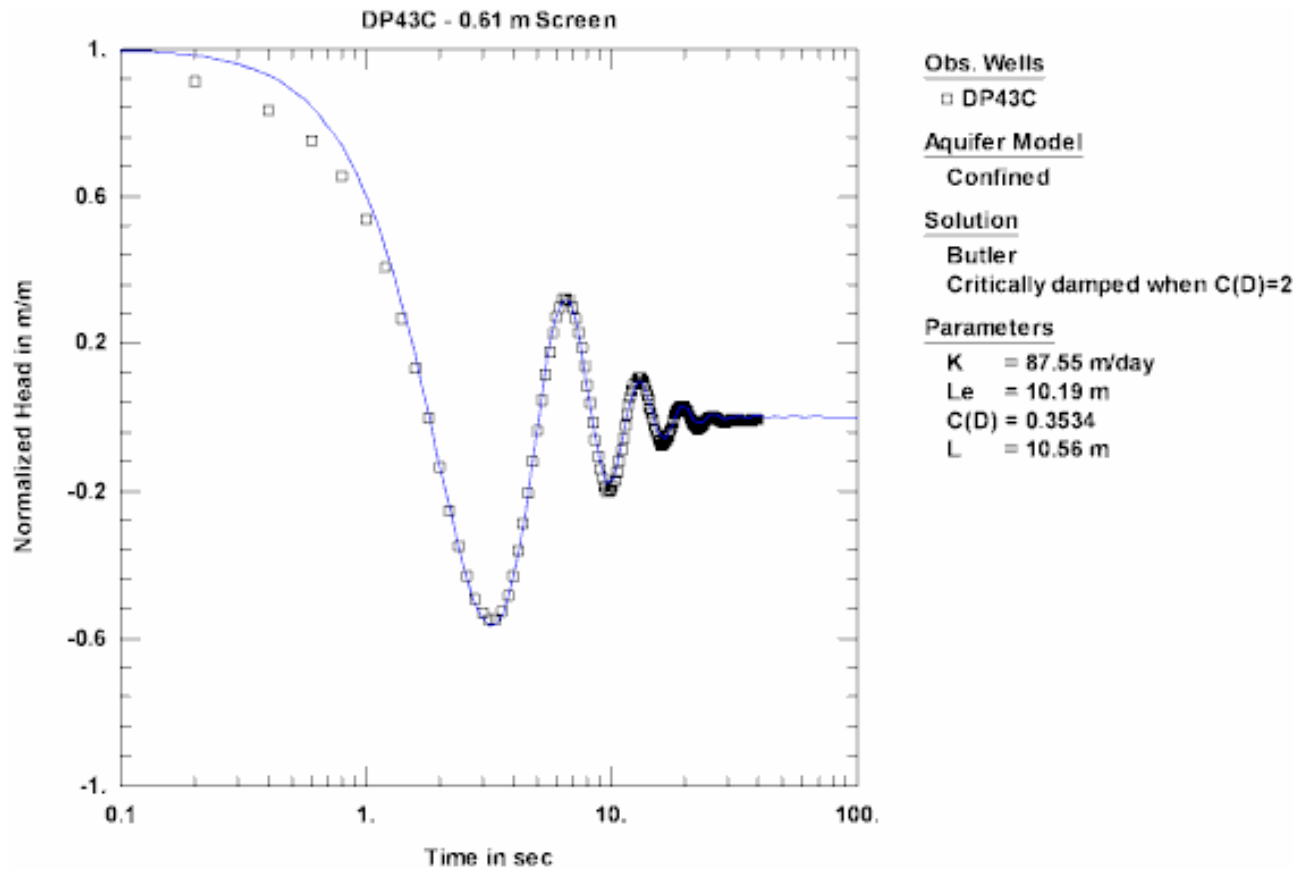
The following slug test solutions simulate oscillatory response in confined and unconfined aquifers.

Confined	Butler (1998)
Confined	Butler-Zhan (2004)
Confined	McElwee-Zenner (1998) nonlinear
Unconfined	Springer-Gelhar (1991)

TIPS

- Choose Match>Solution to select a slug test solution.

- The Butler-Zhan (2004) solution simulates inertial effects in the test well and observation wells.

- Butler et al. (2003) provide guidelines for performing and analyzing slug tests in high-K aquifers.

Multiwell Slug Test Solutions

You may use any of the slug test solutions in AQTESOLV for the analysis of single-well slug tests. In addition, AQTESOLV provides the following solutions for multiwell slug tests in confined, unconfined and fractured aquifers.

➡ Example: Multiwell Slug Test
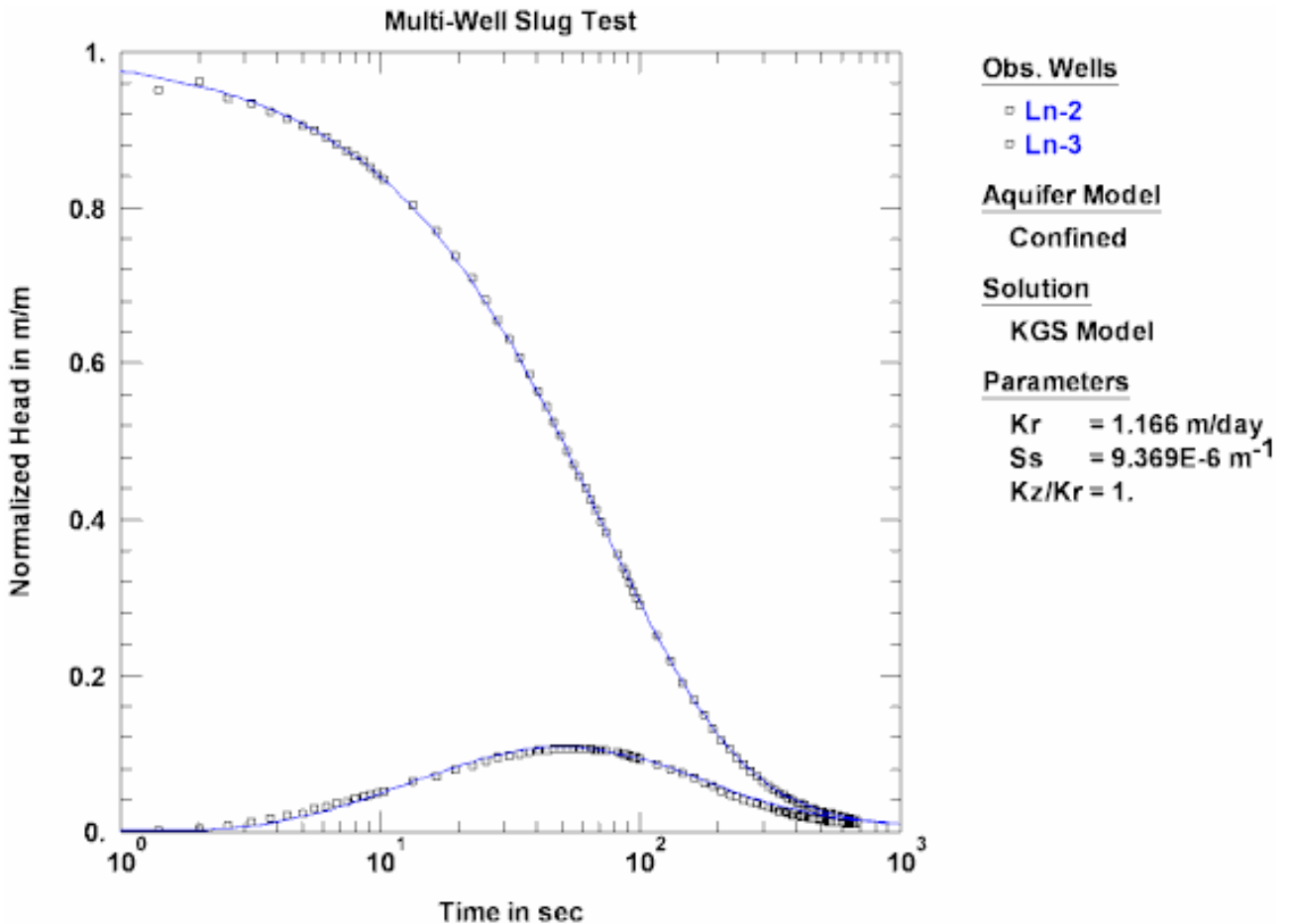
Confined	Dougherty-Babu (1984)
Confined	KGS Model (1994)
Confined	Butler-Zhan (2004) inertial
Unconfined	KGS Model (1994)
Fractured	Barker-Black (1983)

- Choose Match>Solution to select a slug test solution.

- Use the Butler-Zhan (2004) solution for cases identified in the slug test analysis guidelines by Butler (1998) that would require the solution by Chu

and Grader (1991), i.e., multiwell slug tests with wellbore storage effects in observation well(s).

Slug Test Solutions for Wells Screened Across Water Table

AQTESOLV includes the following slug test solutions for wells screened across the water table.

➡ Example: Well Screen Across Water Table
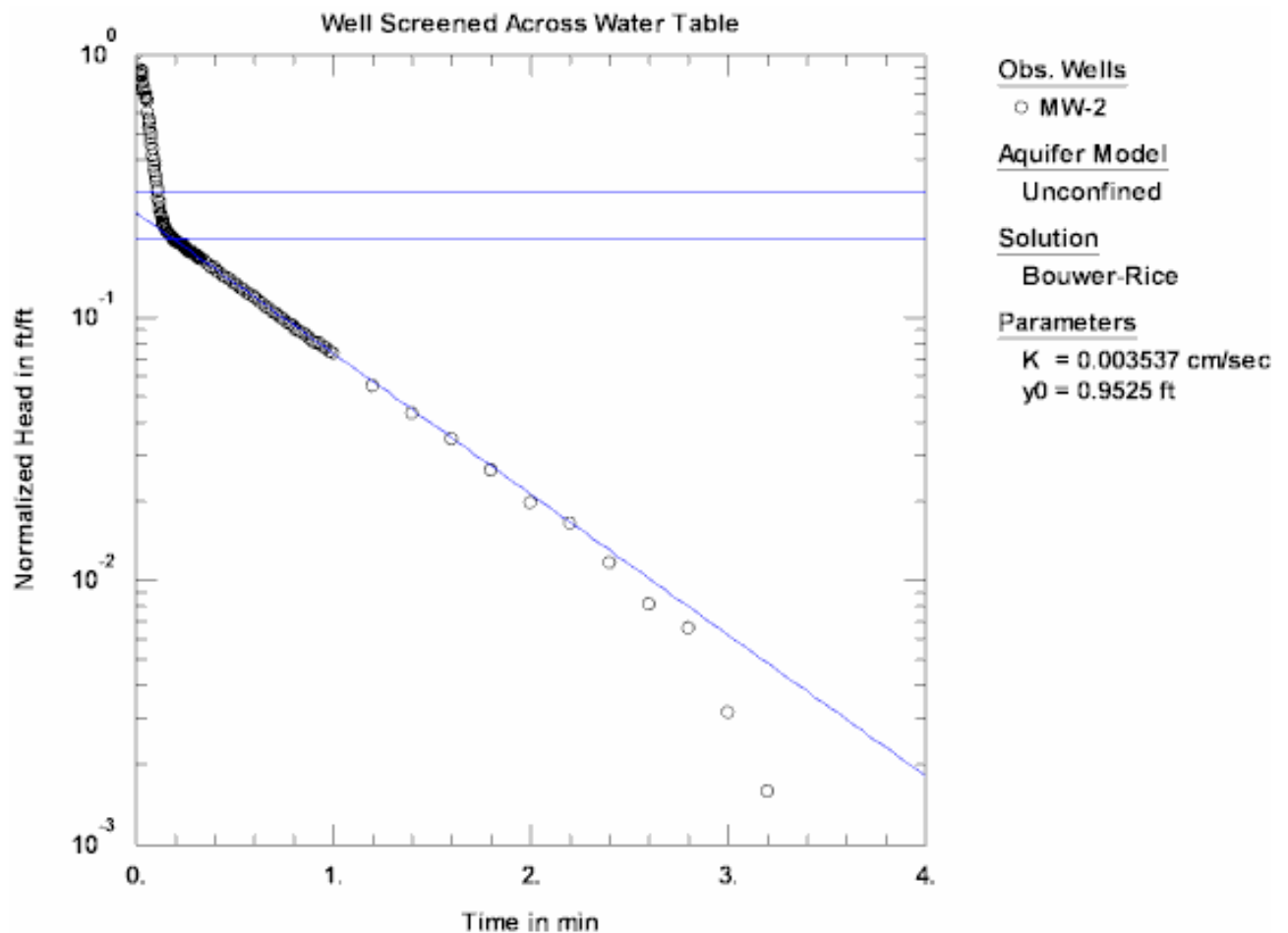
Unconfined	Bouwer-Rice (1976)
Unconfined	Dagan (1978)

TIPS

- Choose Match>Solution to select a slug test solution.

Nonlinear Slug Test Solutions

The following slug test models account for nonlinear mechanisms including time-varying water column length and turbulent flow in the well.

Confined	McElwee-Zenner (1998)

- Choose Match>Solution to select a slug test solution.

- A systematic lack of fit by standard linear theory for repeat tests with different initial displacements is an indication that nonlinear effects may be important (McElwee and Zenner 1998).

Related Topics

Guidelines for Slug Test Analysis

Overdamped Slug Tests

Butler (1998) developed the following sets of guidelines for overdamped slug tests in confined and unconfined aquifers:

- Single-well test in a fully penetrating well in an confined aquifer

- Single-well test in a partially penetrating well in an confined aquifer

- Single-well test in a well screened below water table in an unconfined aquifer

- Single-well test in a well screened across water table in an unconfined aquifer

Underdamped Slug Tests

Butler (1998), Zurbuchen et al. (2002) and Butler et al. (2003) provide guidance for the analysis of underdamped slug tests.

- Slug tests in high-K aquifers

Related Topics

Confined Aquifers

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

(Match > Solution)

Hvorslev (1951) developed a semi-analytical method for the analysis of an overdamped slug test in a fully or partially penetrating well in a homogeneous, anisotropic confined aquifer. The Hvorslev method employs a quasi-steady-state model that ignores elastic storage in the aquifer.

In cases of noninstantaneous test initiation, apply the translation method of Pandit and Miner (1986) prior to analyzing the data.

- o Illustration
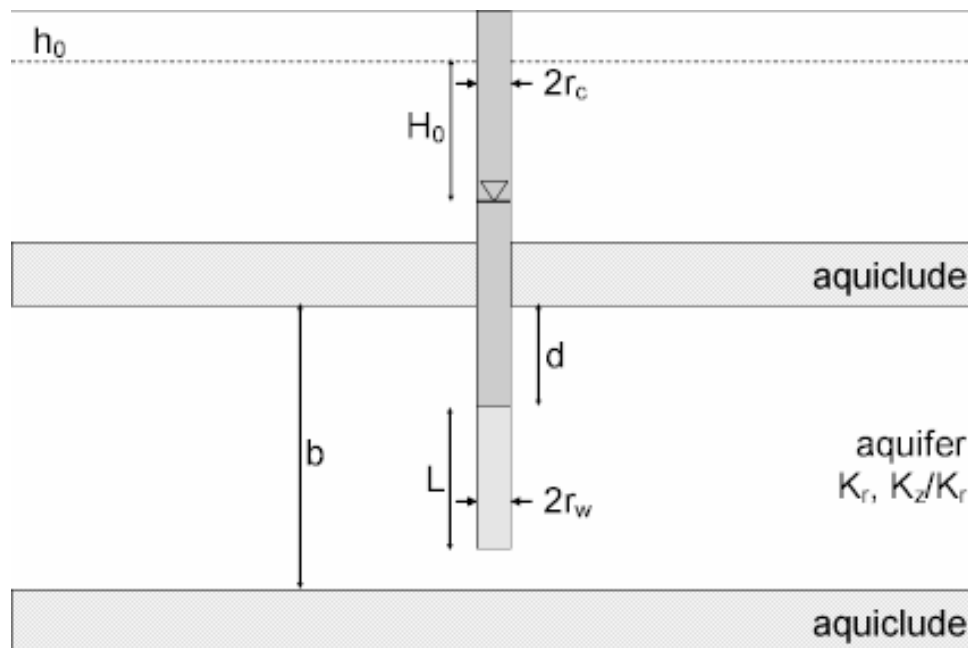
- o Equations

    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:

$$\ln(H_0) - \ln(h) = \frac{2KLt}{r_{ce}^2 \ln(L/2r_{we} + \sqrt{1 + (L/2r_{we})^2})}$$

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

    where

- h is displacement at time t [L]

- H_0 is initial displacement [L]

- K, K_r is radial hydraulic conductivity [L/T]

- K_z is vertical hydraulic conductivity [L/T]

- L is screen length [L]

- r_c is casing radius [L]

- r_{ce} is effective casing radius (= r_c in confined aquifers) [L]

- r_w is well radius [L]

- r_{we} is equivalent well radius [L]

- t is time [T]

The above equations assume that the well screen does not contact any impermeable boundaries. When the well screen abuts a confining unit, the two occurrences of the term $2r_{we}$ are replaced by r_{we}.

For a fully penetrating well, the argument in the logarithmic term of the governing equation is replaced by 200 (Butler 1998).

Zlotnik (1994) proposed an equivalent well radius (r_{we}) for a partially penetrating well in an anisotropic aquifer. Enter the anisotropy ratio in the aquifer data for the slug test well; the well radius is unchanged when the anisotropy ratio is set to unity (1.0).

- o Assumptions

  - aquifer has infinite areal extent

  - aquifer is homogeneous and of uniform thickness

  - test well is fully or partially penetrating

  - aquifer is unconfined

  - flow to well is quasi-steady-state (storage is negligible)

  - volume of water, V, is injected into or discharged from the well instantaneously

- o Data Requirements

  - test well measurements (time and displacement)

  - initial displacement

  - casing radius and well radius

  - depth to top of well screen and screen length

- saturated thickness

- porosity of gravel pack for well screened across water table (optional)

- hydraulic conductivity anisotropy ratio (for partially penetrating wells)

- o Estimated Parameters

  - K (hydraulic conductivity)

  - y0 (intercept of line on y axis)

- o Curve Matching Tips

  - Follow guidelines developed by Butler (1998) for analyzing slug tests.

  - Choose Match>Visual to perform visual curve matching using the procedure for straight-line solutions.

  - 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.

  - Choose View>Options 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).

- o 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.

  - 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.

  - Zlotnik, V., 1994. Interpretation of slug and packer tests in anisotropic aquifers, Ground Water, vol. 32, no. 5, pp. 761-766.

Related Topics

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

(Match > Solution)

Bouwer (1989) observed that the Bouwer-Rice (1976) model for a slug test in an

unconfined aquifer also could be applied to approximate conditions in confined aquifers. This is due to the fact that the water-table boundary in an unconfined aquifer has little effect on slug test response unless the top of the well screen is positioned close to the boundary.

In cases of noninstantaneous test initiation, apply the translation method of Pandit and Miner (1986) prior to analyzing the data.

- o Illustration
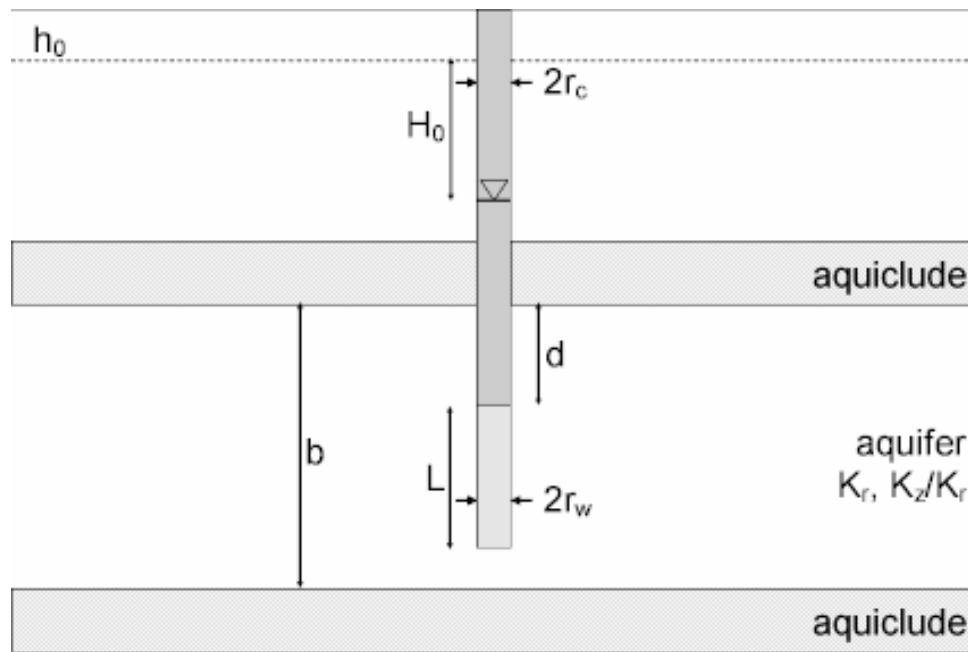
- o Equations

  Refer to the equations for the Bouwer-Rice (1976) solution which Bouwer (1989) proposed to use for both confined and unconfined aquifers.

  Note that the correction for filter pack porosity only applies to wells screened across the water table. For the confined variant of the Bouwer-Rice solution, the filter pack correction is unnecessary.

- o Assumptions

  - aquifer has infinite areal extent

  - aquifer is homogeneous and of uniform thickness

  - test well is fully or partially penetrating

  - aquifer is confined

  - flow to well is quasi-steady-state (storage is negligible)

  - volume of water, V, is injected into or discharged from the well instantaneously

- o Data Requirements

  - test well measurements (time and displacement)

  - initial displacement

  - casing radius and well radius

  - depth to top of well screen and screen length

  - saturated thickness

  - hydraulic conductivity anisotropy ratio (for partially penetrating wells)

- o Estimated Parameters

  - K (hydraulic conductivity)

  - y0 (intercept of line on y axis)

- o Curve Matching Tips

  - Follow guidelines developed by Butler (1998) for analyzing slug tests.

  - Choose Match>Visual to perform visual curve matching using the procedure for straight-line solutions.

  - 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.

  - Choose View>Options 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).

- o 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.

Related Topics

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

(Match > Solution)

Cooper, Bredehoeft and Papadopulos (1967) derived a fully transient solution for a slug test in a fully penetrating well in a confined aquifer.

Butler (1998) suggests using the Cooper et al. solution as a screening tool for most overdamped slug tests in confined and unconfined aquifers with the exception of wells screened across the water table.

For fully penetrating wells in a confined aquifer, the Cooper et al. solution is identical to the KGS Model. For partially penetrating wells in a confined aquifer, you may use either the KGS Model or the Dougherty-Babu (1984) solution.

- o Illustration
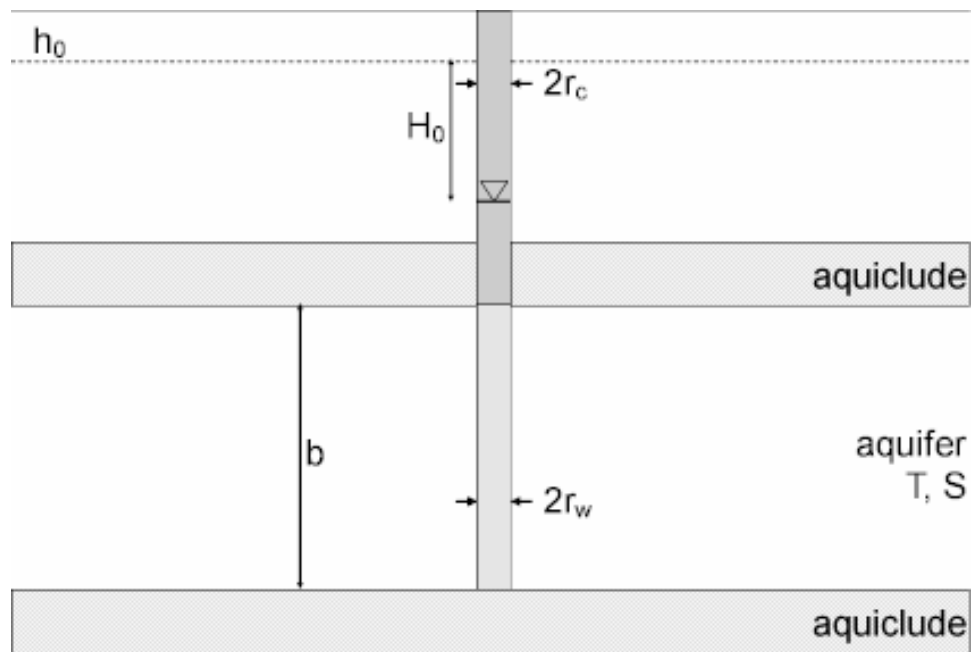
- o Equations

    The equations for the Laplace transform solution derived by Cooper, Bredehoeft and Papadopulos (1967) is as follows:

$$\bar{h} = \frac{H_0 r_w S K_0(rq)}{Tq[r_w q K_0(r_w q) + 2\alpha K_1(r_w q)]}$$

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

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

where

- $\overline{h}$ is the Laplace transform of h, the head in the well [L]

- H_0 is the initial displacement in the well [L]

- K_i is modified Bessel function of second kind, order i

- p is the Laplace transform variable

- r_c is casing radius [L]

- r_w is well radius [L]

- S is storativity [dimensionless]

- t is time [T]

- T is transmissivity [L^2/T]

If you enter a radius for downhole equipment or select a casing radius correction, AQTESOLV uses the effective casing radius instead of the nominal casing radius in the equations for this solution.

- o Assumptions

  - aquifer has infinite areal extent

  - aquifer is homogeneous, isotropic and of uniform thickness

  - 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

  - volume of water, V, is injected into or discharged from the well instantaneously

- o Data Requirements

  - test well measurements (time and displacement)

  - initial displacement

  - casing radius and well radius

- downhole equipment radius (optional)

- saturated thickness

o Estimated Parameters

- T (transmissivity)

- S (storativity)

o Curve Matching Tips

- Follow guidelines developed by Butler (1998) for analyzing slug tests.

- Choose Match>Visual to perform visual curve matching using the procedure for type-curve solutions.

- Select values of S from the **Family** and **Curve** drop-down lists on the toolbar.

- Use parameter tweaking to perform visual curve matching and sensitivity analysis.

- Perform visual curve matching prior to automatic estimation to obtain reasonable starting values for the aquifer properties.

o References

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

Related Topics

Dougherty-Babu (1984) Solution for a Slug Test in a Confined Aquifer

(Match > Solution)

Dougherty and Babu (1984) derived a fully transient analytical solution for an overdamped slug test in a confined aquifer for fully and partially wells. The solution simulates water-level response at the test and observation wells and includes wellbore skin. Based on the work of Moench (1988), we can extend the method to include anisotropy. The Dougherty-Babu solution also includes delayed response in an observation well based on the work of Moench (1997).

For fully penetrating wells in a confined aquifer, the Dougherty-Babu solution is equivalent to the Cooper et al. (1967) solution. For partially penetrating wells in a confined aquifer without wellbore skin, the Dougherty-Babu solution and KGS Model are identical.

The Dougherty-Babu solution allows you to analyze data from multiwell slug tests assuming no wellbore storage in observation wells. Use the Butler-Zhan (2004) solution if you need to simulate the wellbore storage effect in observation wells.

o   Illustration
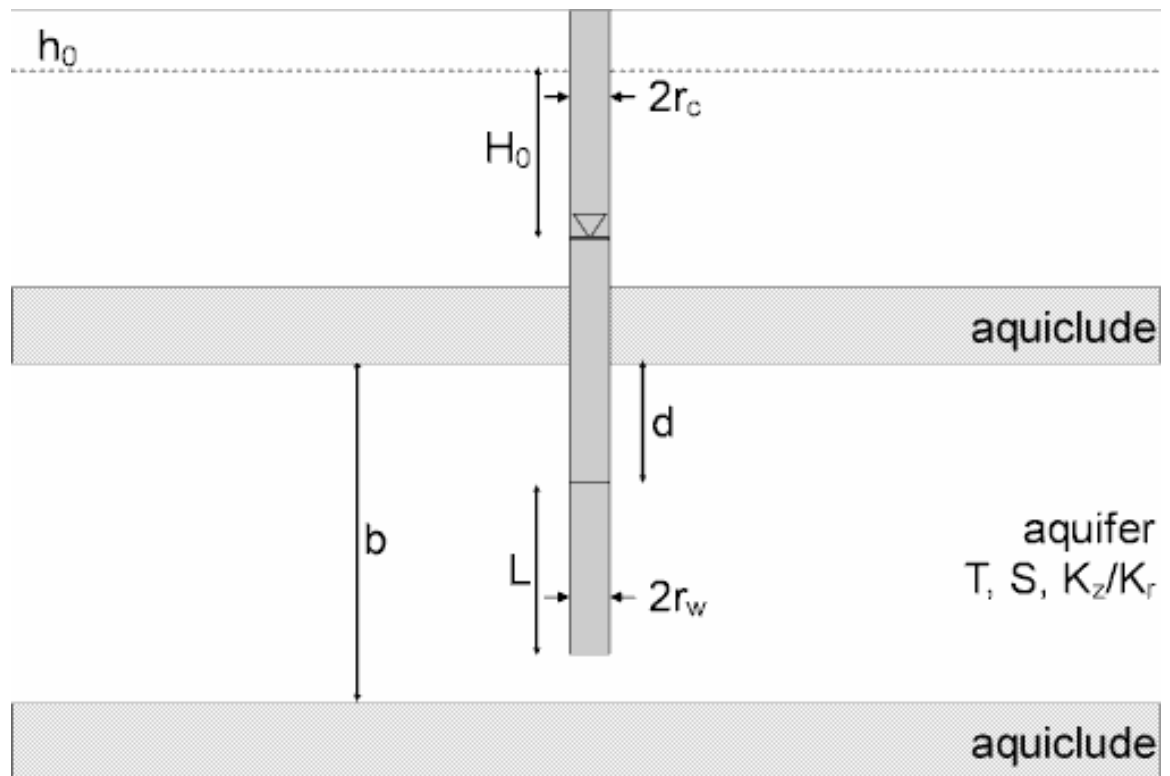
o   Equations

Dougherty and Babu (1984) derived an analytical solution describing the water-level response due to the instantaneous injection or withdrawal of water from a fully or partially penetrating well in a homogeneous, isotropic confined aquifer. Moench extended the method to include anisotropy. The equation for the Laplace transform solution for head in the test well is as follows:

$$\overline{h}_{wD} = \frac{W_D(A_0 + A + S_w)}{1 + pW_D(A_0 + A + S_w)}$$

The following equation is the Laplace transform solution for dimensionless drawdown in a piezometer:

$$\overline{h}_D = \frac{W_D(E_0 + E)}{1 + pW_D(A_0 + A + S_w)}$$

The equation for dimensionless drawdown in an observation well is:

$$\overline{h}'_D = \frac{W_D(E'_0 + E')}{1 + pW_D(A_0 + A + S_w)}$$

$$A_0 = \frac{(l_D - d_D)K_0(q_0)}{q_0 K_1(q_0)}$$

$$A = \frac{2}{(l_D - d_D)}\sum_{n=1}^{\infty}\frac{K_0(q_n)[\sin(n\pi l_D) - \sin(n\pi d_D)]^2}{n^2\pi^2 q_n K_1(q_n)}$$

$$E_0 = E_0' = \frac{(l_D - d_D)K_0(q_0 r_D)}{q_0 K_1(q_0)}$$

$$E = 2\sum_{n=1}^{\infty}\frac{K_0(\overline{q}_n r_D)\cos(n\pi z_D)[\sin(n\pi l_D) - \sin(n\pi d_D)]}{n\pi \overline{q}_n K_1(\overline{q}_n)}$$

$$E' = 2\sum_{n=1}^{\infty}\frac{K_0(q_n r_D)[\sin(n\pi l_D') - \sin(n\pi d_D')][\sin(n\pi l_D) - \sin(n\pi d_D)]}{(l_D' - d_D')n^2\pi^2 q_n K_1(q_n)}$$

$$W_D = \frac{\pi r_c^2}{2\pi r_w^2 S_s (l - d)}$$

$$q_n = \sqrt{\frac{r_w^2 n^2 \pi^2}{b^2}\frac{K_z}{K_r} + p}$$

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

$$t_D = \frac{Kt}{S_s r_w^2}$$

$$h_D = \frac{(h_0 - h)}{H_0}$$

where

- b is aquifer thickness [L]
- d is distance from water table to top of pumping well screen [L]
- d_D is d/b
- H_0 is initial displacement [L]
- K, K_r is radial hydraulic conductivity [L/T]
- K_z is vertical hydraulic conductivity [L/T]

- K_i is modified Bessel function of second kind, order i

- l is distance from water table to bottom of pumping well screen [L]

- l_D is l/b

- p is the Laplace transform variable

- Q is pumping rate [L^3/T]

- r is radial distance [L]

- r_c is casing radius [L]

- r_w is well radius [L]

- S_s is specific storage [1/L]

- S_w is wellbore skin factor [dimensionless]

- t is time [T]

- z is elevation of piezometer above base of aquifer [L]

- z_D is z/b

- z_1 is elevation of bottom of observation well screen above base of aquifer [L]

- z_{1D} is z_1/b

- z_2 is elevation of top of observation well screen above base of aquifer [L]

- z_{2D} is z_2/b

In the Laplace transform solution, S_w is limited to positive values; however, using the effective well radius concept, we also may simulate a negative skin (Hurst, Clark and Brauer 1969).

If you enter a radius for downhole equipment, AQTESOLV uses the effective casing radius instead of the nominal casing radius in the equations for this solution.

- o Assumptions

  - aquifer has infinite areal extent

  - aquifer is homogeneous and of uniform thickness

  - aquifer potentiometric surface is initially horizontal

  - test and observation wells are fully or partially penetrating

  - aquifer is confined

  - flow is unsteady

- water is released instantaneously from storage with decline of hydraulic head

- a volume of water, V, is injected into or discharged from the well instantaneously

o Data Requirements

- test well measurements (time and displacement)

- initial displacement

- casing radius and well radius

- saturated thickness

- well depth and screen length

o Estimated Parameters

- T (transmissivity)

- S (storativity)

- Kz/Kr (hydraulic conductivity anisotropy ratio)

- Sw (dimensionless wellbore skin factor)

o Curve Matching Tips

- Follow guidelines developed by Butler (1998) for analyzing slug tests.

- Choose Match>Visual to perform visual curve matching using the procedure for type-curve solutions.

- Select values of Ss, Kz/Kr and Sw from the **Family** and **Curve** drop-down lists on the toolbar.

- Use parameter tweaking to perform visual curve matching and sensitivity analysis.

o References

- Dougherty, D.E and D.K. Babu, 1984. Flow to a partially penetrating well in a double-porosity reservoir, Water Resources Research, vol. 20, no. 8, pp. 1116-1122.

- Moench, A.F., 1988. The response of partially penetrating wells to pumpage from double-porosity aquifers, Proceedings of the International Conference on Fluid Flow in Fractured Rocks, Atlanta, GA, May 16-18, 1988.

Related Topics

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

(Match > Solution)

Hyder et al. (1994) developed a fully transient model, also known as the **KGS Model**, for an overdamped slug test in a confined aquifer for fully and partially penetrating wells. The solution simulates water-level response at the test and observation wells and includes a skin zone of finite thickness enveloping the test well.

For fully penetrating wells in a confined aquifer, the KGS Model is equivalent to the Cooper et al. (1967) solution. For partially penetrating wells in a confined aquifer without wellbore skin, the KGS Model and the Dougherty-Babu (1984) solution are identical.

The KGS Model allows you to analyze data from multiwell slug tests assuming no wellbore storage in observation wells. Use the Butler-Zhan (2004) solution if you need to simulate the wellbore storage effect in observation wells.

> When you choose a solution, AQTESOLV provides two configurations for simulating a slug test with the KGS Model. One configuration omits the well skin and the other includes it.

- o Illustration

- o Equations

    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 fully or partially penetrating well in a homogeneous, anisotropic confined aquifer. The equation for the Laplace

transform solution for head in the test well is as follows:

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

$$\alpha = \frac{2r_2^2 S_{s2} L}{r_c^2}$$

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

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

$$f_1 = \frac{[\Delta_2 K_0(\upsilon_1) - \Delta_1 I_0(\upsilon_1)]}{\upsilon_1[\Delta_2 K_1(\upsilon_1) + \Delta_1 I_1(\upsilon_1)]}$$

$$\eta = z/L$$

$$\varsigma = d/L$$

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

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

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

$$a = L/r_w$$

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

$$R_2 = \alpha/2$$

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

$$\Delta_1 = K_0(\upsilon_1 \xi_{sk})K_1(\upsilon_2 \xi_{sk}) - \frac{N}{\gamma}K_0(\upsilon_2 \xi_{sk})K_1(\upsilon_1 \xi_{sk})$$

$$\Delta_2 = I_0(\upsilon_1 \xi_{sk})K_1(\upsilon_2 \xi_{sk}) + \frac{N}{\gamma}K_0(\upsilon_2 \xi_{sk})I_1(\upsilon_1 \xi_{sk})$$

$$N = \upsilon_1/\upsilon_2$$

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

$$F_c(\omega) = \text{finite fourier cosine transform of } B(z)$$

$$F_c^{-1} = \text{inverse finite fourier cosine transform}$$

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

where

- the subscript i = 1, 2 refers to the aquifer and well skin, respectively
- d is depth to top of well screen [L]
- I is modified Bessel function of first kind, order i
- K_r is radial hydraulic conductivity [L/T]
- K_z is vertical hydraulic conductivity [L/T]
- K_i is modified Bessel function of second kind, order i
- L is screen length [L]
- p is the Laplace transform variable
- r is radial distance [L]
- r_c is casing radius [L]
- r_{sk} is well skin radius [L]
- r_w is well radius [L]
- S_s is specific storage [1/L]
- z is depth below top of aquifer [L]

o Assumptions

- aquifer has infinite areal extent
- aquifer is homogeneous and of uniform thickness
- aquifer potentiometric surface is initially horizontal
- test and observation wells are fully or partially penetrating
- aquifer is confined
- flow is unsteady
- water is released instantaneously from storage with decline of hydraulic

head

- a volume of water, V, is injected into or discharged from the well instantaneously

○ Data Requirements

- test and observation well measurements (time and displacement)

- initial displacement

- casing radius, well radius and outer radius of well skin for test well

- saturated thickness

- well depth and screen length

○ Estimated Parameters

- Kr (radial hydraulic conductivity in aquifer)

- Ss (specific storage in aquifer)

- Kz/Kr (anisotropy ratio in aquifer)

- Kr' (radial hydraulic conductivity in skin)

- Ss' (specific storage in skin)

- Kz/Kr' (anisotropy ratio in skin)

○ Curve Matching Tips

- Follow guidelines developed by Butler (1998) for analyzing slug tests.

- Choose Match>Visual to perform visual curve matching using the procedure for type-curve solutions.

- Select values of Ss and Kz/Kr from the **Family** and **Curve** drop-down lists on the toolbar.

- Use parameter tweaking to perform visual curve matching and sensitivity analysis.

○ References

- 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.

Related Topics

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

(Match > Solution)

Butler (1998) extended the Hvorslev (1951) solution for a single-well slug test in a homogeneous, anisotropic confined aquifer to include inertial effects in the test well. The solution accounts for oscillatory water-level response sometimes observed in aquifers of high hydraulic conductivity. Butler (2002) amended the method to incorporate frictional well loss in small-diameter wells.

The Butler solution predicts the theoretical change in water level in the test well; however, McElwee (2001) and Zurbuchen et al. (2002) have noted that transducer readings vary with depth and thus may not accurately measure the water-level position. Butler et al. (2003) recommend placing the transducer close to the static water surface in the well to avoid this problem.

- o   Illustration
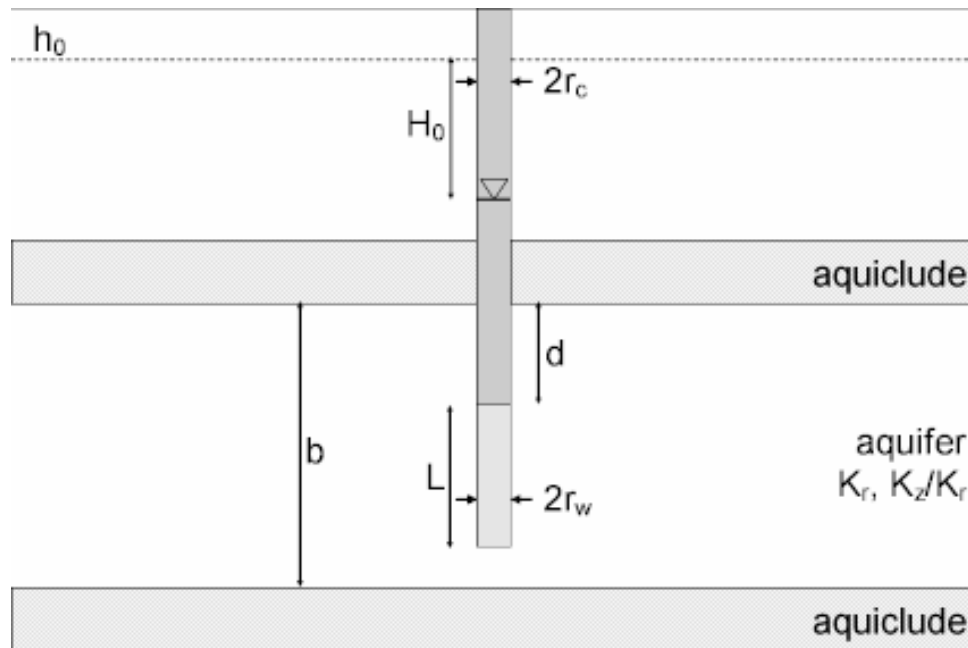
- o   Equations

The Butler (1998) solution accounts for underdamped (oscillatory) water-level response sometimes observed in aquifers of high hydraulic conductivity:

$$w_D(t_D) = \begin{cases} e^{-C_D t_D}\left(\cos(\omega_D t_D) + \dfrac{C_D}{\omega_D}\sin(\omega_D t_D)\right), & C_D < 1 \\[2mm] e^{-t_D}(1+t_D), & C_D = 1 \\[2mm] -\left(\dfrac{1}{\omega_D^+ - \omega_D^-}\right)\left(\omega_D^- e^{\omega_D^+ t_D} - \omega_D^+ e^{\omega_D^- t_D}\right), & C_D > 1 \end{cases}$$

$$w_D = s/H_0$$

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

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

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

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

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

where

- g is gravitational acceleration [L/T^2]

- H_0 is initial displacement [L]

- K_r is radial hydraulic conductivity [L/T]

- K_z is vertical hydraulic conductivity [L/T]

- L is screen length [L]

- L_e is effective water column length [L]

- r_c is casing radius [L]

- r_w is well radius [L]

- s is displacement [L]

- t is time [T]

If you enter a radius for downhole equipment, AQTESOLV uses the effective casing radius instead of the nominal casing radius in the equations for this solution.

In the foregoing equations, the dimensionless damping factor, C_D, is termed critically damped when its value equals 1. Certain publications (e.g., Butler 1998) use an alternate convention in which the equations are critically damped when C_D equals 2. In cases where the well screen abuts an impermeable boundary, the two occurrences of terms 2ψ are replaced by ψ.

Butler (2002) modified the definition of C_D to include frictional well loss:

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

where

- ℓ is length of water column above top of well screen [L]

- υ is kinematic viscosity [L^2/T]

o Assumptions

- aquifer has infinite areal extent

- aquifer is homogeneous and of uniform thickness

- test well is partially penetrating

- aquifer is confined

- flow is quasi-steady state

- volume of water, V, is injected into or discharged from the well instantaneously

o Data Requirements

- test well measurements (time and displacement)

- initial displacement

- static water column height

- casing radius and well radius

- depth to top of well screen and screen length

- saturated thickness

- hydraulic conductivity anisotropy ratio

- kinematic viscosity of water (optional)

- gravitational acceleration constant (optional)

- o Estimated Parameters

  - K (hydraulic conductivity)

  - Le (effective water column length in test well)

  For reference, AQTESOLV also displays the parameter L (theoretical effective water column length) determined from well geometry data. One normally expects Le to be close to the value of L.

- o Curve Matching Tips

  - Choose Match>Visual to perform visual curve matching using the procedure for type-curve solutions. Move the mouse up and down to adjust the amplitude of the curve. Move the mouse left and right to adjust the period.

  - Select values of Le from the **Family** and **Curve** drop-down lists on the toolbar.

  - Use parameter tweaking to perform visual curve matching and sensitivity analysis.

  - When performing automatic curve matching, save time by setting weights to zero for any observations that have recovered to static near the end of the test.

  - Choose View>Options to change the critically damped value of dimensionless damping factor, C(D) (i.e., 1 or 2).

- o 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.

  - Butler, J.J., Jr., Garnett, E.J. and J.M. Healey, 2003. Analysis of slug tests in formations of high hydraulic conductivity, Ground Water, vol. 41, no. 5, pp. 620-630.

  - 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.

  - Zurbuchen, B. R., V.A. Zlotnik and J.J. Butler, Jr., 2002. Dynamic interpretation of slug tests in highly permeable aquifers, Water Resources Research, vol. 38, no. 3., 1025, doi:10.1029/2001WR000354.

Related Topics

Butler-Zhan (2004) Solution for a Slug Test in a Confined Aquifer

(Match > Solution)

Butler and Zhan (2004) derived an analytical solution for a slug test in fully or partially penetrating wells in a confined high-K aquifer that accounts for frictional loss in small-diameter wells and inertial effects in the test and observation wells. The Butler-Zhan solution allows you to analyze data from underdamped or overdamped single- or multi-well slug tests.

McElwee (2001) and Zurbuchen et al. (2002) have noted that transducer readings vary with depth in the well and thus may not accurately measure the water-level position. Butler et al. (2003) recommend placing the transducer close to the static water surface in the well to avoid this problem. If the transducer depth is below the top of the well screen, AQTESOLV uses the Butler-Zhan solution to compute the head in the well screen.

Use the Butler-Zhan solution when you need to simulate the wellbore storage effect in observation wells. If wellbore storage is not present in the observation wells (e.g., through the use of a packer and transducer), you may choose the KGS Model for multiwell tests.

In the guidelines by Butler (1998) for the analysis of multiwell slug tests, you may substitute the more versatile Butler-Zhan solution for the Chu and Grader (1991) method.

When you choose a solution, AQTESOLV provides two configurations for simulating inertial effects in a slug test with the Butler-Zhan solution. Both configurations allow you to analyze data from the test well and observation wells.

- **Test well** includes the inertial effect in the test well only.

- **All wells** includes inertial effects in both test and observation wells.

o Illustration
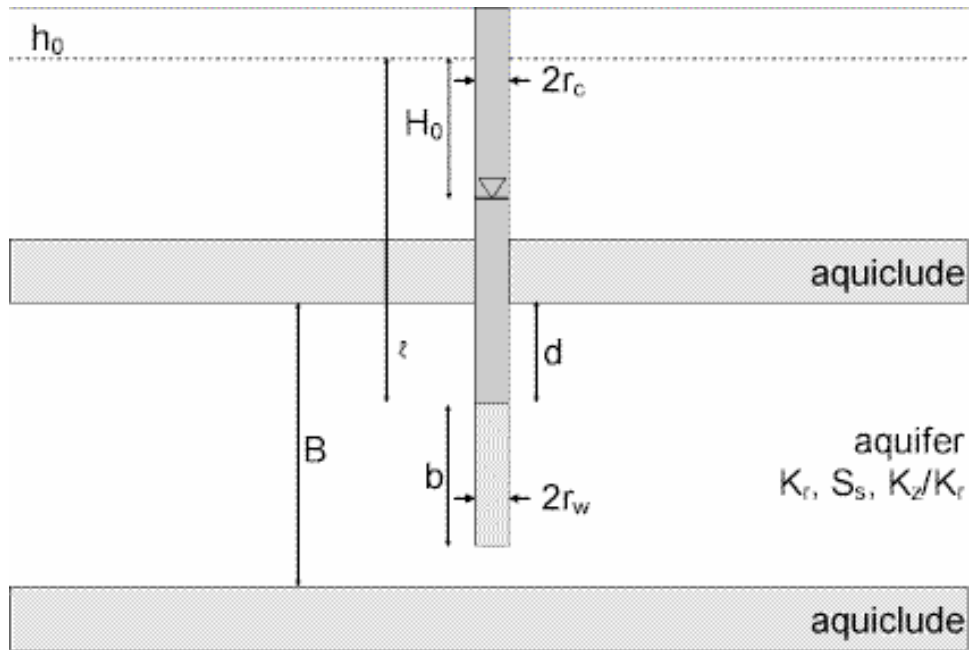
o Equations

Butler and Zhan (2004) derived an analytical solution for a single- or multi-well slug test in fully or partially penetrating wells in a confined high-K aquifer that accounts for frictional loss in small-diameter wells and inertial effects in the test and observation wells.

Assuming inertial effect in only the test well, the Laplace transform solutions for dimensionless head in the well, screen and aquifer are as follows:

$$\overline{\Phi}(p) = \frac{\alpha^2 \beta \Phi_0 p^2 + \alpha F_i \Phi_0 p - \alpha \beta q p + (\alpha \Phi_0 p - q)\Omega_w(p) + \alpha^2 \beta \Phi_0' p}{p(1 + \alpha F_i p + \alpha^2 \beta p^2 + \Omega_w(p)\alpha p)}$$

$$\overline{\phi}_s(\eta, p) = \frac{(\alpha \Phi_0 p - \alpha^3 \Phi_0' p^2 - q - \alpha F_i q p)\Omega_a(\xi = 1, \eta, p)}{p(1 + \alpha F_i p + \alpha^2 \beta p^2 + \Omega_w(p)\alpha p)} \quad \varsigma < \eta < \varsigma + 1$$

$$\overline{\phi}(\xi, \eta, p) = \frac{(\alpha \Phi_0 p - \alpha^3 \Phi_0' p^2 - q - \alpha F_i q p)\Omega_a(\xi, \eta, p)}{p(1 + \alpha F_i p + \alpha^2 \beta p^2 + \Omega_w(p)\alpha p)} \quad \varsigma \geq 1$$

$$\Phi = \frac{H(t)}{Q_0}$$

$$\phi_s = \frac{h_s(z, t)}{Q_0}$$

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$$\phi = \frac{h(r,z,t)}{Q_0}$$

$$\Phi_0 = \frac{H_0}{Q_0}$$

$$\Phi_0' = \frac{H_0' r_w^2 S_s}{Q_0 K_r}$$

$$\xi = r / r_w$$

$$\eta = z / b$$

$$\mathrm{B} = B / b$$

$$\zeta = d / b$$

$$\tau = \frac{t K_r}{r_w^2 S_s}$$

$$F_l = \frac{16 b \upsilon L K_r}{g r_c^2}$$

$$L = \ell + \frac{r_c^4}{r_w^4} \frac{b}{2}$$

$$\psi = \sqrt{\frac{r_w^2 K_z}{b^2 K_r}}$$

$$\alpha = \frac{r_c^2}{2 r_w^2 b S_s}$$

$$\beta = \frac{4 L_e b^2 K_r^2}{g r_c^4}$$

$$q = \frac{Q}{2\pi K_r b Q_0} = 1 \; for \; pumping \; tests; = 0 \; for \; slug \; tests$$

$$\Omega_w(p) = \int_\varsigma^{\varsigma+1} \Omega_a(\xi=1,\eta,p)\,d\eta$$

$$\Omega_a(\xi,\eta,p) = \frac{1}{B}\frac{K_0(\sqrt{p}\xi)}{K_1(\sqrt{p})\sqrt{p}} + \frac{4}{\pi}\sum_{n=1}^{\infty}\frac{\sin\left(\frac{n\pi}{2B}\right)\cos\left(\frac{n\pi}{2B}+\frac{n\pi}{B}\varsigma\right)K_0\left(\sqrt{\psi^2\left(\frac{n\pi}{B}\right)^2+p}\,\xi\right)}{nK_1\left(\sqrt{\psi^2\left(\frac{n\pi}{B}\right)^2+p}\right)\sqrt{\psi^2\left(\frac{n\pi}{B}\right)^2+p}}\cos\left(\frac{n\pi}{B}\eta\right)$$

where

- b is test well screen length [L]

- B is aquifer thickness [L]

- d is depth to top of test well screen [L]

- g is gravitational acceleration constant [L/T^2]

- h(r,z,t) is displacement in aquifer [L]

- h_s(z,t) is displacement in test well screen [L]

- H(t) is displacement in test well [L]

- H_0 is initial displacement in test well [L]

- H'_0 is initial water-level velocity due to test initiation [L]

- K_r is radial hydraulic conductivity [L/T]

- K_z is vertical hydraulic conductivity [L/T]

- K_i is modified Bessel function of second kind, order i

- ℓ is length of static water column above top of test well screen [L]

- L_e is effective water column length in test well [L]

- p is the Laplace transform variable

- Q_0 is normalizing parameter, = H_0 for a slug test [L]

- r is radial distance from center of test well [L]

- r_c is test well casing radius [L]

- r_w is test well radius [L]

- S_s is specific storage [1/L]

- t is time [T]

- υ is kinematic viscosity of water [L^2/T]

- z is vertical coordinate [L]

Ordinarily, AQTESOLV computes the water level change in the test well, H(t); however, the program computes the head in the test well screen, $h_s(z,t)$ if the transducer depth is below the top of the well screen.

Taking into account inertial effect in the observation well, the Laplace transform solutions for dimensionless water level in the observation well, head in the observation well screen and head in the aquifer are as follows:

$$\overline{\Phi}_o(p) = \frac{\Omega_{aL}(p)}{\alpha_o^2 \beta_o R_w^2 p^2 + \alpha_o F_{lo} R_w p + 1 + \Omega_{ow}(p)\alpha_o R_w p}$$

$$\overline{\phi}_{so}(\eta_o,p) = -\frac{\alpha_o R_w p \Omega_{aL}(p) \Omega_a(1,\eta_o,p)}{\alpha_o^2 \beta_o R_w^2 p^2 + \alpha_o F_{lo} R_w p + 1 + \Omega_{ow}(p)\alpha_o R_w p}$$

$$\overline{\phi}_o(\xi_o,\eta_o,p) = -\frac{\alpha_o R_w p \Omega_{aL}(p) \Omega_a(\xi_o,\eta_o,p)}{\alpha_o^2 \beta_o R_w^2 p^2 + \alpha_o F_{lo} R_w p + 1 + \Omega_{ow}(p)\alpha_o R_w p}$$

$$\Phi_o = \frac{W_o(t)}{Q_0}$$

$$\phi_{so} = \frac{h_{so}(z,t)}{Q_0}$$

$$\phi_o = \frac{h_o(r,z,t)}{Q_0}$$

$$\xi_o = r_o / r_{wo}$$

$$\eta_o = z / b_o$$

$$B_o = B / b_o$$

$$\zeta_o = d_o / b_o$$

$$R_w = r_{wo}^2 / r_w^2$$

$$F_{lo} = \frac{16 b_o \upsilon L_o K_r}{g r_\infty^2}$$

$$L_o = \ell_o + \frac{r_\infty^2}{r_{wo}^2} \frac{b_o}{2}$$

$$\psi_o = \sqrt{\frac{r_{wo}^2 K_z}{b_o^2 K_r}}$$

$$\alpha_o = \frac{r_{co}^2}{2 r_{wo}^2 b_o S_s}$$

$$\beta_o = \frac{4 L_{eo} b_o^2 K_r^2}{g r_\infty^4}$$

where

- b_o is test well screen length [L]

- d_o is depth to top of test well screen [L]

- $h_o(r,z,t)$ is displacement in aquifer due to perturbation in observation well [L]

- $h_{so}(z,t)$ is displacement in observation well screen due to perturbation in observation well [L]

- ℓ_o is length of static water column above top of observation well screen [L]

- L_{eo} is effective water column length in observation well [L]

- r_o is radial distance from center of observation well [L]

- r_{co} is observation well casing radius [L]

- r_{wo} is observation well radius [L]

- $W_o(t)$ is displacement in observation well [L]

If you enter a radius for downhole equipment, AQTESOLV uses the effective casing radius instead of the nominal casing radius in the equations for this solution.

o Assumptions

- aquifer has infinite areal extent

- aquifer is homogeneous and of uniform thickness

- test well is fully or partially penetrating

- aquifer is confined

- flow is unsteady

- water is released instantaneously from storage with decline of hydraulic head

- volume of water, V, is injected into or discharged from the well instantaneously

o Data Requirements

- test and observation well measurements (time and displacement)

- initial displacement

- static water column height

- casing radius and well radius

- depth to top of well screen and screen length

- saturated thickness

- hydraulic conductivity anisotropy ratio

- kinematic viscosity of water (optional)

- gravitational acceleration constant (optional)

o Estimated Parameters

- K (hydraulic conductivity)

- Ss (specific storage)

- Kz/Kr (anisotropy ratio)

- Le (effective water column length in test well)

- Le(o) (effective water column length in observation well)

For reference, AQTESOLV also displays the parameters L and L(o) (see equations) determined from well geometry data. One normally expects Le and Le(o) to be close to the values of L and L(o).

o Curve Matching Tips

- Use the Butler (1998) solution to obtain preliminary estimates of aquifer properties.

- Choose Match>Visual to perform visual curve matching using the procedure for type-curve solutions.

- Select values of Ss from the **Family** and **Curve** drop-down lists on the toolbar.

- Use parameter tweaking to perform visual curve matching and sensitivity analysis. When performing visual curve matching with this tool, first tweak

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the values of Le and Le(o) to align the peaks of the curve(s) with the data. Next, adjust the value of Kr to match the amplitude of the curve(s) with the data.

- Change the convergence level for this solution to enhance visual curve matching.

- Use the curve resolution settings to optimize performance for specific tasks such as visual curve matching or printing report graphics.

- When performing automatic curve matching, save time by setting weights to zero for any observations that have recovered to static near the end of the test.

o Convergence Settings

- Choose Match>Toolbox and click **Options** to select convergence levels for this solution.

- The default level (1) applies convergence settings given in a program by Butler and Zhan.

- Select a faster setting to enhance visual curve matching.

o References

- Butler, J.J., Jr. and X. Zhan, 2004. Hydraulic tests in highly permeable aquifers, Water Resources Research, vol. 40, W12402, doi:10.1029/2003WR002998.

- Butler, J.J., Jr., Garnett, E.J. and J.M. Healey, 2003. Analysis of slug tests in formations of high hydraulic conductivity, Ground Water, vol. 41, no. 5, pp. 620-630.

- 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.

- Zurbuchen, B. R., V.A. Zlotnik and J.J. Butler, Jr., 2002. Dynamic interpretation of slug tests in highly permeable aquifers, Water Resources Research, vol. 38, no. 3., 1025, doi:10.1029/2001WRR000354.

Related Topics

Peres-Onur-Reynolds (1989) Solution for a Slug Test in a Confined Aquifer

(Match > Solution)

Peres, Onur and Reynolds (1989) derived a fully transient solution for a slug test in a fully penetrating well in a confined aquifer. The Peres et al. method is based on an exact equation for transforming slug test data into equivalent head data for a constant-rate pumping test with wellbore storage and skin effect. Through the use of an approximate deconvolution technique, the method further eliminates wellbore

storage from the transformed equivalent head data, thereby making it possible to analyze the equivalent heads using the Cooper-Jacob solution for a constant-rate pumping test.

The Peres et al. method can be advantageous in determining the hydraulic conductivity of an aquifer when nonideal conditions exist near the well (e.g., wellbore skin). To use the method effectively, Butler (1998) recommends taking measurements at closely spaced intervals and running the slug test to complete recovery.

- o Illustration
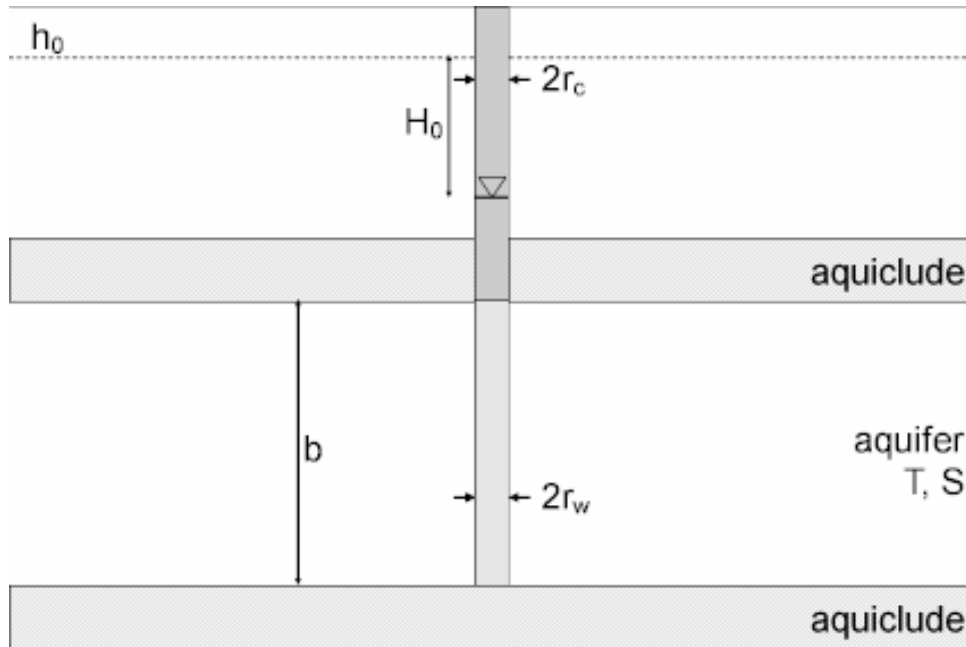
- o Equations

  The equations for the approximate deconvolution solution derived by Peres, Onur and Reynolds (1989) is as follows:

$$S = \int_0^t \frac{H(\tau)}{H_0} d\tau$$

$$\frac{ds}{d\ln t} = t \frac{H(t)}{H_0}$$

$$\overline{s} = \frac{s}{1 - (ds/d\ln t)/t}$$

  where

  - H_0 is the initial displacement due to slug test in well [L]

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- H(t) is displacement due to slug test at time t [L]

- s is equivalent drawdown for a constant-rate pumping test with wellbore storage [T]

- $\overline{s}$ is equivalent drawdown for a constant-rate pumping test with wellbore storage removed [T]

By matching a straight line to a plot of $\overline{s}$ versus time, one can determine the transmissivity of the aquifer using modified versions of the familiar Cooper-Jacob equations for a constant-rate pumping test as follows:

$$\overline{s} = \frac{2.303 r_c^2}{4T} \log\left(\frac{4Tt}{S r_w^2}\right)$$

$$T = \frac{2.303 r_c^2}{4 \Delta \overline{s}}$$

$$S = \frac{4Tt_0}{r_w^2}$$

where

- $\Delta \overline{s}$ is change in $\overline{s}$ over one log cycle [T]

- r_c is effective casing radius corrected for downhole equipment [L]

- r_w is well radius [L]

- S is storativity [dimensionless]

- t is time [T]

- t_0 is intercept of line on time axis [T]

- T is transmissivity [L^2/T]

o Assumptions

- aquifer has infinite areal extent

- aquifer is homogeneous, isotropic and of uniform thickness

- 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

- volume of water, V, is injected into or discharged from the well instantaneously

  o Data Requirements

  - test well measurements (time and displacement)

  - initial displacement

  - casing radius and well radius

  - downhole equipment radius (optional)

  - saturated thickness

  o Estimated Parameters

  - T (transmissivity)

  - S (storativity)

  o Curve Matching Tips

  - Follow guidelines developed by Butler (1998) for analyzing slug tests.

  - Use parameter tweaking to perform visual curve matching and sensitivity analysis.

  - Perform visual curve matching prior to automatic estimation to obtain reasonable starting values for the aquifer properties.

  o References

  - Peres, A.M., Onur, M. and A.C. Reynolds, 1989. A new analysis procedure for determining aquifer properties from slug test data, Water Resources Research, vol. 25, no. 7, pp. 1591-1602.

Related Topics

McElwee-Zenner (1998) Solution for a Slug Test in a Confined Aquifer

(Match > Solution)

McElwee and Zenner (1998) developed a model for a single-well slug test in a homogeneous confined aquifer that includes various nonlinear mechanisms including time-dependent water column length and turbulent flow in the well. The solution accounts for the complete range of water-level response from overdamped to underdamped.

The McElwee-Zenner (1998) solution predicts the theoretical change in water level in the test well; however, McElwee (2001) noted that transducer readings vary with

depth and thus may not accurately measure the water-level position. The McElwee-Zenner solution includes a correction for transducer depth. Alternatively, Butler et al. (2003) recommend placing the transducer close to the static water surface in the well to circumvent this problem.

- o Illustration
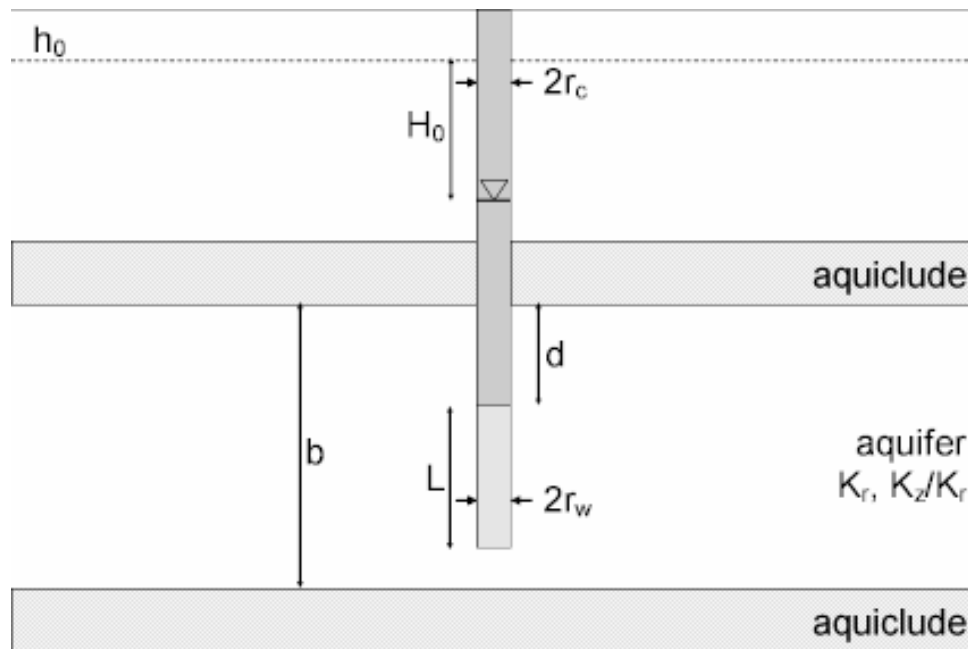
- o Equations

  The McElwee-Zenner (1998) solution accounts for overdamped and underdamped (oscillatory) water-level response from a slug test in a confined aquifer:

  $$(h + z_0 + L + \beta) \frac{d^2 h}{dt^2} + A \left| \frac{dh}{dt} \right| \frac{dh}{dt} + \frac{g \pi r_c^2}{F K_r} \left(\frac{dh}{dt} \right) + gh = 0$$

  $$F = \left[\ln(L / 2r_{we} + \sqrt{1 + (L / 2r_{we})^2}) \right]^{-1}$$

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

  $$h(t)' = h(t) + \frac{a}{g}[h(t) + Z_s] - \frac{v^2}{2g}$$

  where

  - a is acceleration of water column [L/T^2]

  - A is a nonlinear parameter related to velocities in the well [dimensionless]

- β is a correction parameter related to the effective length of the water column in the well [L]

- Hvorslev form factor [dimensionless]

- g is gravitational acceleration [L/T^2]

- h, h(t) is head (displacement) in well [L]

- h(t)' is the apparent head in the well measured by transducer [L]

- H_0 is initial displacement [L]

- K_r is radial hydraulic conductivity [L/T]

- K_z is vertical hydraulic conductivity [L/T]

- L is screen length [L]

- r_c is casing radius [L]

- r_w is well radius [L]

- t is time [T]

- v is water column velocity [L/T]

- Z_0 is the static height of the water column above the top of the well screen [L]

- Z_s is transducer depth below static water surface [L]

The McElwee-Zenner solution uses the Hvorslev model to describe flow between the well and the aquifer. The Hvorslev solution is a quasi-steady-state model that neglects storage in the aquifer. Like the Hvorslev model, $2r_{we}$ replaces each occurrence of r_{we} in the definition of F when the well screen abuts an impermeable boundary.

If you enter a radius for downhole equipment, AQTESOLV uses the effective casing radius instead of the nominal casing radius in the equations for this solution.

McElwee and Zenner (1998) defined the following Reynolds number for flow in the well:

$$R_e = \frac{|v|2r}{\upsilon}$$

where

- r is packer or casing radius [L]

- Re is Reynolds number [dimensionless]

- v is velocity [L/T]

- υ is kinematic viscosity [L^2/T]

For turbulent flow, the parameter A relates frictional forces to the square of velocities in the well. In the McElwee-Zenner model, flow is deemed turbulent when Re 3400. Under turbulent conditions, A is assumed to equal a constant when a packer is present (i.e., $r_p > 0$). In the absence of a packer, A is a function of the wetted length of borehole (static water column length above the top of the well screen).

When Re < 3400, the McElwee-Zenner model assumes flow is laminar. The value of A is set to zero and the model adds a term representing frictional (viscous) loss in the well:

$$F_L = \frac{8\upsilon(H_0 + Z_0 + L)}{r_c^2} \frac{dh}{dt}$$

where

- F_L is frictional loss [L]

F_L equals zero when flow is turbulent.

The McElwee-Zenner solution is solved using a finite-difference algorithm (McElwee 2001).

- Assumptions

  - aquifer has infinite areal extent

  - aquifer is homogeneous and of uniform thickness

  - test well is partially penetrating

  - aquifer is confined

  - flow is quasi-steady state

  - volume of water, V, is injected into or discharged from the well instantaneously

- Data Requirements

  - test well measurements (time and displacement)

  - initial displacement

  - static water column height

  - casing radius and well radius

  - equipment radius and packer radius (optional)

  - depth to top of well screen and screen length

  - saturated thickness

- hydraulic conductivity anisotropy ratio

- kinematic viscosity of water (optional)

- gravitational acceleration constant (optional)

- Estimated Parameters

  - K (hydraulic conductivity)

  - β (correction for water column length in test well)

  - A (nonlinear flow parameter)

  - v(0) (initial velocity in well)

- Curve Matching Tips

  - Use parameter tweaking to perform visual curve matching and sensitivity analysis.

  - When performing automatic curve matching, save time by using a match window or setting weights to zero for any observations that have recovered to static near the end of the test.

- References

  - McElwee, C.D. and M. Zenner, 1998. A nonlinear model for analysis of slug-test data, Water Resources Research, vol. 34, no. 1, pp. 55-66.

  - McElwee, C.D., 2001. Application of a nonlinear slug test model, Ground Water, vol. 39, no. 5, pp. 737-744.

Related Topics

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

(Match > Solution)

Bouwer and Rice (1976) developed a semi-analytical method for the analysis of an overdamped slug test in a fully or partially penetrating well in an unconfined aquifer. The Bouwer-Rice method employs a quasi-steady-state model that ignores elastic storage in the aquifer.

In cases of noninstantaneous test initiation, apply the translation method of Pandit and Miner (1986) prior to analyzing the data.

If the test well is screened across the water table, you may apply an optional correction for the effective porosity of the filter pack. When the test well is fully submerged (i.e., screened below the water table) or the aquifer is confined, the correction is unnecessary.

o Illustration
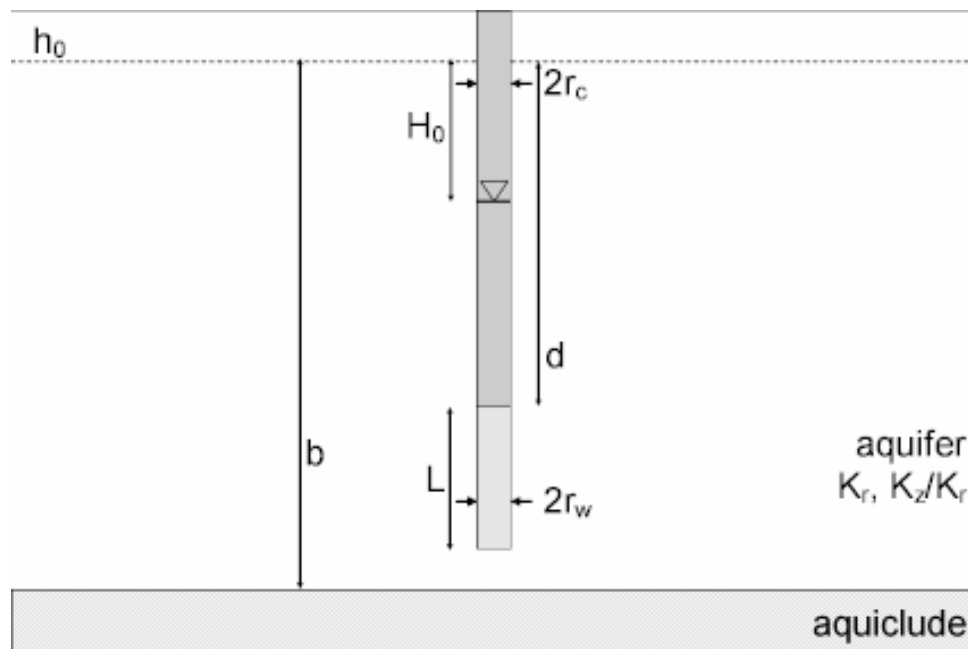
o Equations

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:

$$\ln(H_0) - \ln(h) = \frac{2KLt}{r_{ce}^2 \ln(r_e / r_{we})}$$

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

where

- h is displacement at time t [L]

- H_0 is initial displacement [L]

- K, K_r is radial hydraulic conductivity [L/T]

- K_z is vertical hydraulic conductivity [L/T]

- L is screen length [L]

- n_e is filter pack effective porosity [dimensionless]

- r_c is nominal casing radius [L]

- r_{ce} is effective casing radius (= r_c when well screen is fully submerged) [L]

- r_e is external radius [L]

- r_w is well radius [L]

- r_{we} is equivalent well radius [L]

- t is time [T]

The term $\ln(r_e/r_{we})$ is an empirical quantity that accounts for well geometry (Bouwer and Rice 1976).

Zlotnik (1994) proposed an equivalent well radius (r_{we}) for a partially penetrating well in an anisotropic aquifer. Enter the anisotropy ratio in the aquifer data for the slug test well; the well radius is unchanged when the anisotropy ratio is set to unity (1.0).

- o Assumptions

  - aquifer has infinite areal extent

  - aquifer is homogeneous and of uniform thickness

  - test well is fully or partially penetrating

  - aquifer is unconfined

  - flow to well is quasi-steady-state (storage is negligible)

  - volume of water, V, is injected into or discharged from the well instantaneously

- o Data Requirements

  - test well measurements (time and displacement)

  - initial displacement

- casing radius and well radius

- depth to top of well screen and screen length

- saturated thickness

- porosity of gravel pack for well screened across water table (optional)

- hydraulic conductivity anisotropy ratio (for partially penetrating wells)

  o Estimated Parameters

  - K (hydraulic conductivity)

  - y0 (intercept of line on y axis)

  o Curve Matching Tips

  - Follow guidelines developed by Butler (1998) for analyzing slug tests.

  - Choose Match>Visual to perform visual curve matching using the procedure for straight-line solutions.

  - 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.

  - Choose View>Options 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).

  o 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.

Related Topics

Hvorslev (1951) Solution for a Slug Test in an Unconfined Aquifer

(Match > Solution)

For slug tests in an unconfined aquifer, the preferred quasi-steady-state method is

the Bouwer-Rice (1976) solution; however, Bouwer (1989) observed that the water-table boundary in an unconfined aquifer has little effect on slug test response unless the top of the well screen is positioned close to the boundary. Thus, in many cases, we may apply the Hvorslev (1951) solution for confined aquifers to approximate unconfined conditions when the well screen is below the water table.

In cases of noninstantaneous test initiation, apply the translation method of Pandit and Miner (1986) prior to analyzing the data.

- o Illustration
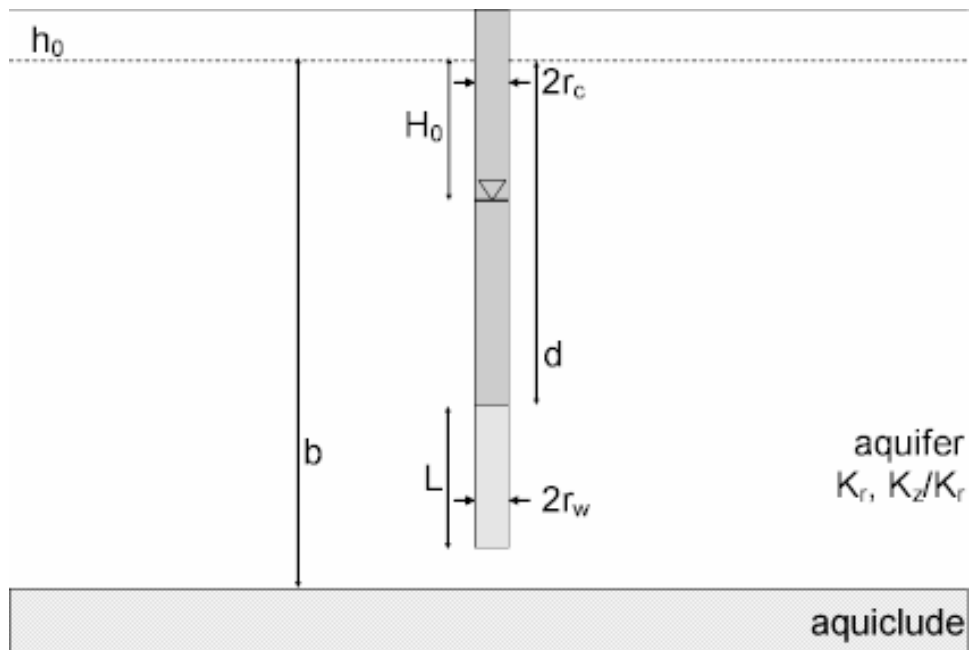
- o Equations

  Refer to the equations for the Hvorslev (1951) solution for a confined aquifer.

  For the unconfined variant of the Hvorslev solution, AQTESOLV applies the correction for filter pack porosity for wells screened across the water table. For the confined Hvorslev solution, the filter pack correction is unnecessary.

- o Assumptions

  - aquifer has infinite areal extent

  - aquifer is homogeneous and of uniform thickness

  - test well is fully or partially penetrating

  - aquifer is confined

  - flow to well is quasi-steady-state (storage is negligible)

  - volume of water, V, is injected into or discharged from the well instantaneously

- o Data Requirements

  - test well measurements (time and displacement)

  - initial displacement

  - casing radius and well radius

  - depth to top of well screen and screen length

  - saturated thickness

  - hydraulic conductivity anisotropy ratio (for partially penetrating wells)

- o Estimated Parameters

  - K (hydraulic conductivity)

  - y0 (intercept of line on y axis)

- o Curve Matching Tips

  - Follow guidelines developed by Butler (1998) for analyzing slug tests.

  - Choose Match>Visual to perform visual curve matching using the procedure for straight-line solutions.

  - 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.

  - Choose View>Options 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).

- o References

  - Bouwer, H., 1989. The Bouwer and Rice slug test--an update, Ground Water, vol. 27, no. 3, pp. 304-309.

  - 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.

Related Topics

Dagan (1978) Solution for a Slug Test in an Unconfined Aquifer

(Match > Solution)

Dagan (1978) developed a semi-analytical method for an overdamped slug test in a well screened across the water table in a homogeneous, anisotropic unconfined aquifer. Like the Bouwer-Rice and Hvorslev models, the Dagan method employs a quasi-steady-state model that ignores elastic storage in the aquifer.

In cases of noninstantaneous test initiation, apply the translation method of Pandit and Miner (1986) prior to analyzing the data.

For wells screened across the water table, you may apply an optional correction for the effective porosity of the filter pack.

- o Illustration
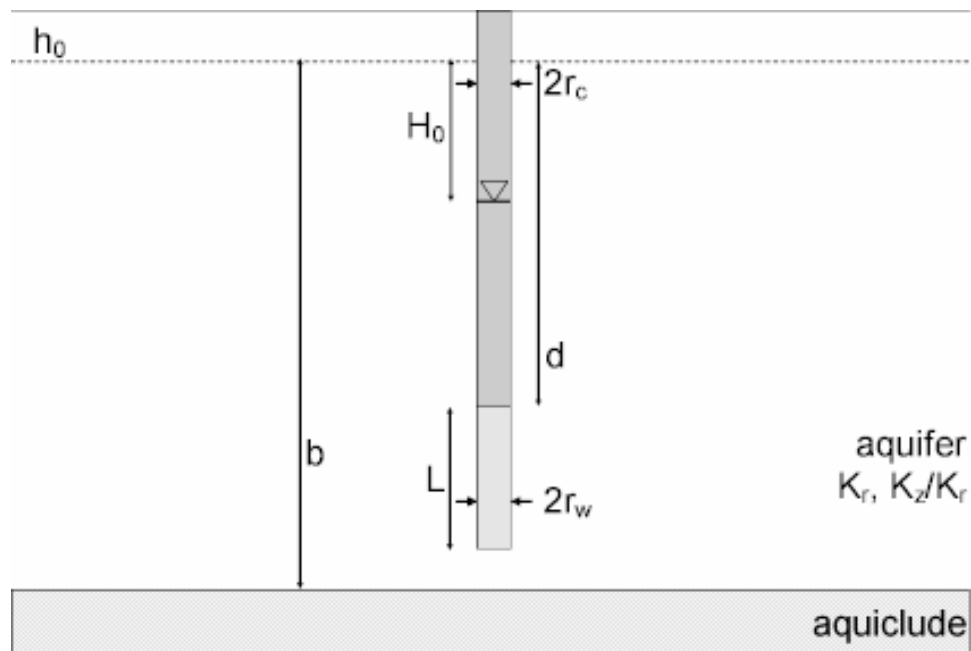
- o Equations

  Dagan (1978) developed semi-analytical method to predict the water-level response due to the instantaneous injection or withdrawal of water from a well screened across the water table in an unconfined aquifer:

  $$\ln\left(\frac{h}{H_0(2L - h/(2L - H_0))}\right) = -\frac{2K_r L t}{r_{ce}^2 / P}$$

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

  where

  - h is displacement at time t [L]

  - H_0 is initial displacement [L]

  - K, K_r is radial hydraulic conductivity [L/T]

- L is screen length [L]

- n_e is filter pack effective porosity [dimensionless]

- P is dimensionless flow parameter

- r_c is casing radius [L]

- r_{ce} is equivalent casing radius [L]

- r_w is well radius including filter pack [L]

- t is time [T]

The term P is a shape factor that depends on well geometry and hydraulic conductivity anisotropy. Values of P are available in Dagan (1978), Boast and Kirkham (1971) and Butler (1998). AQTESOLV uses a table look-up procedure to find appropriate values of P.

- o Assumptions

  - aquifer has infinite areal extent

  - aquifer is homogeneous and of uniform thickness

  - test well is partially penetrating

  - aquifer is unconfined

  - flow to well is quasi-steady-state (storage is negligible)

  - volume of water, V, is injected into or discharged from the well instantaneously

- o Data Requirements

  - test well measurements (time and displacement)

  - initial displacement

  - casing radius and well radius

  - depth to top of well screen and screen length

  - saturated thickness

  - porosity of gravel pack for well screened across water table (optional)

  - hydraulic conductivity anisotropy ratio

- o Estimated Parameters

  - K (hydraulic conductivity)

  - y0 (intercept of line on y axis)

- o Curve Matching Tips

- Follow guidelines developed by Butler (1998) for analyzing slug tests.

- Choose Match>Visual to perform visual curve matching using the procedure for straight-line solutions.

- 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.

- Choose View>Options 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).

o References

- Boast, C.W. and D. Kirkham, 1971. Auger hole seepage theory, Soil Science of America Proceedings, vol. 35, no. 3, pp. 365-373.

- 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.

- Dagan, G., 1978. A note on packer, slug, and recovery tests in unconfined aquifers, Water Resources Research, vol. 14, no. 5. pp. 929-934.

Related Topics

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

(Match > Solution)

Hyder et al. (1994) developed a fully transient model, also known as the **KGS Model**, for an overdamped slug test in an unconfined aquifer for fully and partially penetrating wells. The solution simulates water-level response at the test and observation wells and includes a skin zone of finite thickness enveloping the test well. The KGS Model allows you to analyze data from multiwell slug tests.

When you choose a solution, AQTESOLV provides two configurations for simulating a slug test with the KGS Model. One configuration omits the well skin and the other includes it.

o Illustration

o Equations

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 fully or partially penetrating well in an unconfined aquifer. The equation for the Laplace transform solution for head in the test well is as follows:

$$\overline{h} = \frac{(\gamma/2)\Omega^*}{(1+(\gamma/2)p\Omega^*)}$$
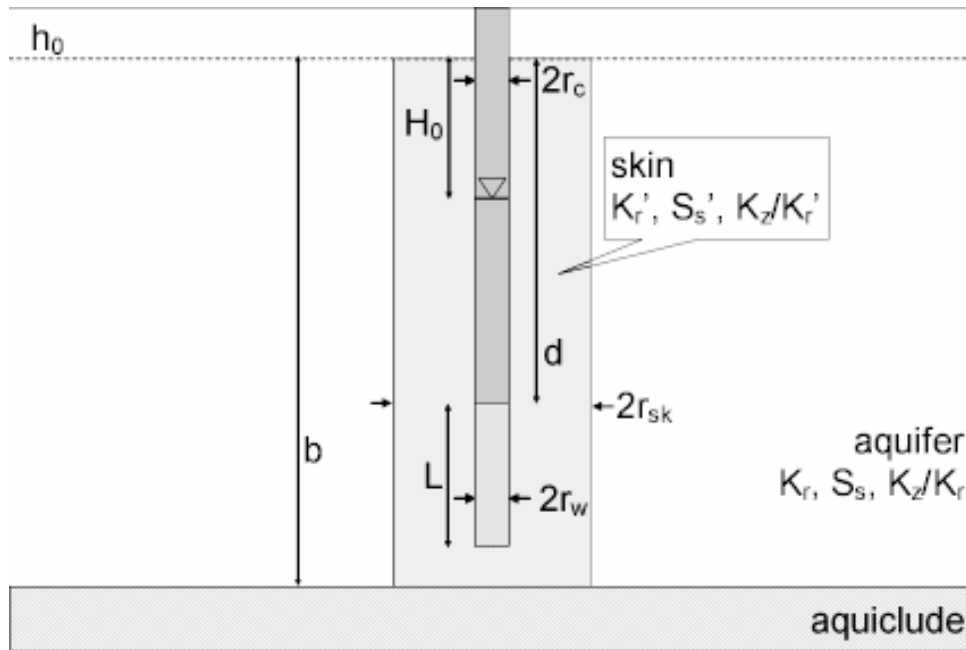
$$\alpha = \frac{2r_2^2 S_{s2} L}{r_c^2}$$

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

$$\Omega^* = \int_{\varsigma}^{\varsigma+1} (F_s^{-1}[F_s(\varpi^*)f_1])d\eta$$

$$f_1 = \frac{[\Delta_2 K_0(\upsilon_1) - \Delta_1 I_0(\upsilon_1)]}{\upsilon_1 [\Delta_2 K_1(\upsilon_1) + \Delta_1 I_1(\upsilon_1)]}$$

$$\eta = z/L$$

$$\varsigma = d/L$$

410

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

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

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

$$a = L / r_w$$

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

$$R_2 = \alpha / 2$$

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

$$\Delta_1 = K_0(\upsilon_1 \xi_{sk}) K_1(\upsilon_2 \xi_{sk}) - \frac{N}{\gamma} K_0(\upsilon_2 \xi_{sk}) K_1(\upsilon_1 \xi_{sk})$$

$$\Delta_2 = I_0(\upsilon_1 \xi_{sk}) K_1(\upsilon_2 \xi_{sk}) + \frac{N}{\gamma} K_0(\upsilon_2 \xi_{sk}) I_1(\upsilon_1 \xi_{sk})$$

$$N = \upsilon_1 / \upsilon_2$$

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

$$F_s(\omega^*) = \text{modified finite fourier sine transform of } B(z)$$

$$F_s^{-1} = \text{inverse modified finite fourier sine transform}$$

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

where

- the subscript i = 1, 2 refers to the aquifer and well skin, respectively
- d is depth to top of well screen [L]
- I_i is modified Bessel function of first kind, order i
- K_r is radial hydraulic conductivity [L/T]
- K_z is vertical hydraulic conductivity [L/T]
- K_i is modified Bessel function of second kind, order i
- L is screen length [L]

- p is the Laplace transform variable

- r is radial distance [L]

- r_c is casing radius [L]

- r_{sk} is well skin radius [L]

- r_w is well radius [L]

- S_s is specific storage [1/L]

- z is depth below top of aquifer [L]

o Assumptions

- aquifer has infinite areal extent

- aquifer is homogeneous and of uniform thickness

- aquifer potentiometric surface is initially horizontal

- test and observation wells are fully or partially penetrating

- aquifer is unconfined

- flow is unsteady

- water is released instantaneously from storage with decline of hydraulic head

- a volume of water, V, is injected into or discharged from the well instantaneously

o Data Requirements

- test and observation well measurements (time and displacement)

- initial displacement

- casing radius, well radius and outer radius of well skin for test well

- saturated thickness

- well depth and screen length

o Estimated Parameters

- Kr (radial hydraulic conductivity in aquifer)

- Ss (specific storage in aquifer)

- Kz/Kr (anisotropy ratio in aquifer)

- Kr' (radial hydraulic conductivity in skin)

- Ss' (specific storage in skin)

- Kz/Kr' (anisotropy ratio in skin)

  o Curve Matching Tips

    - Follow guidelines developed by Butler (1998) for analyzing slug tests.

    - Choose Match>Visual to perform visual curve matching using the procedure for type-curve solutions.

    - Select values of Ss and Kz/Kr from the **Family** and **Curve** drop-down lists on the toolbar.

    - Use parameter tweaking to perform visual curve matching and sensitivity analysis.

  o References

    - 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.

Related Topics

Springer-Gelhar (1991) Solution for a Slug Test in an Unconfined Aquifer

(Match > Solution)

Springer and Gelhar (1991) extended the Bouwer-Rice (1976) solution for a slug test in a homogeneous, anisotropic unconfined aquifer to include inertial effects in the test well. The solution accounts for oscillatory water-level response sometimes observed in aquifers of high hydraulic conductivity. Based on the work of Butler (2002), we also incorporate frictional well loss in small-diameter wells.

The Springer-Gelhar solution predicts the theoretical change in water level in the test well; however, McElwee (2001) and Zurbuchen et al. (2002) have noted that transducer readings vary with depth and thus may not accurately measure the water-level position. Butler et al. (2003) recommend placing the transducer close to the static water surface in the well to avoid this problem.

- o Illustration
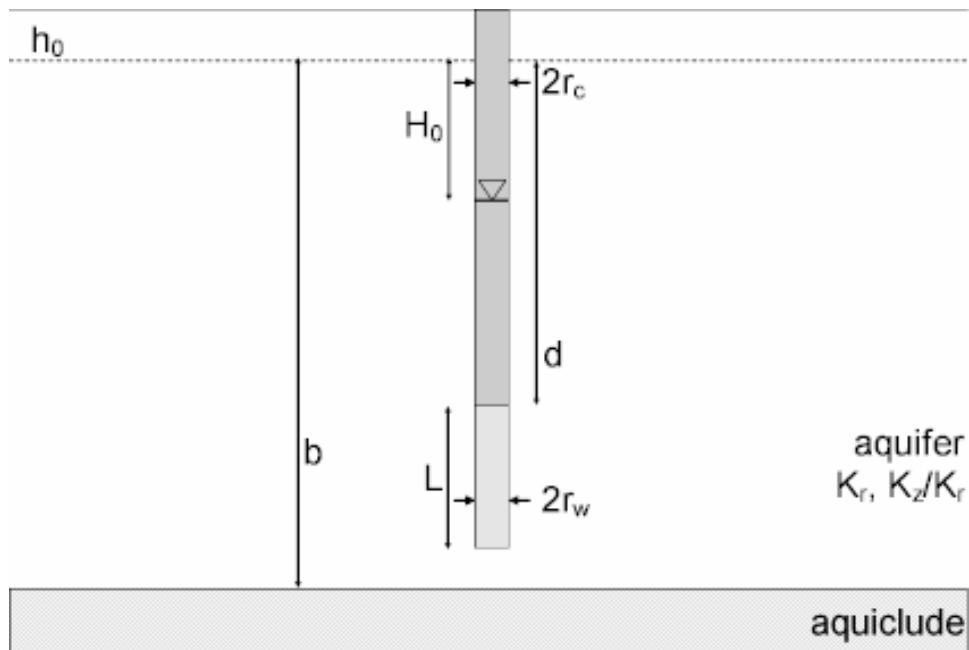
- o Equations

The Springer-Gelhar (1991) solution accounts for underdamped (oscillatory) water-level response sometimes observed in aquifers of high hydraulic conductivity:

$$W_D(t_D) = \begin{cases} e^{-C_D t_D}\left(\cos(\omega_D t_D) + \dfrac{C_D}{\omega_D}\sin(\omega_D t_D)\right), & C_D < 1 \\[2mm] e^{-t_D}(1+t_D), & C_D = 1 \\[2mm] -\left(\dfrac{1}{\omega_D^+ - \omega_D^-}\right)\left(\omega_D^- e^{\omega_D^+ t_D} - \omega_D^+ e^{\omega_D^- t_D}\right), & C_D > 1 \end{cases}$$

$$W_D = s/H_0$$

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

$$C_D = \sqrt{g/L_e}\;\frac{r_c^2 \ln(r_e/r_w)}{4 K_r L}$$

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

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

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

where

- g is gravitational acceleration [L/T^2]

- H$_0$ is initial displacement [L]

- K$_r$ is radial hydraulic conductivity [L/T]

- K$_z$ is vertical hydraulic conductivity [L/T]

- L is screen length [L]

- L$_e$ is effective water column length [L]

- r$_c$ is casing radius [L]

- r$_w$ is well radius [L]

- s is displacement [L]

- t is time [T]

The term ln(r$_e$/r$_w$) is an empirical quantity that accounts for well geometry (Bouwer and Rice 1976).

In the foregoing equations, the dimensionless damping factor, C$_D$, is termed critically damped when its value equals 1. Certain publications (e.g., Butler 1998) use an alternate convention in which the equations are critically damped when C$_D$ equals 2.

Butler (2002) modified the definition of C$_D$ to include frictional well loss:

$$C_D = \sqrt{g / L_e} \left(\frac{r_c^2 \ln(r_e / r_w)}{4 K_r L} + \frac{4\upsilon\left(\ell + \frac{r_c^2}{r_w^2} \frac{L}{2}\right)}{r_c^2 g} \right)$$

where

- ℓ is length of water column above top of well screen [L]

- υ is kinematic viscosity [L^2/T]

o Assumptions

- aquifer has infinite areal extent

- aquifer is homogeneous and of uniform thickness

- test well is fully or partially penetrating

- aquifer is unconfined

- flow is quasi-steady state

- volume of water, V, is injected into or discharged from the well instantaneously

○ Data Requirements

- test well measurements (time and displacement)

- initial displacement

- static water column height

- casing radius and well radius

- depth to top of well screen and screen length

- saturated thickness

- hydraulic conductivity anisotropy ratio

- kinematic viscosity of water (optional)

- gravitational acceleration constant (optional)

○ Estimated Parameters

- K (hydraulic conductivity)

- Le (effective water column length in test well)

For reference, AQTESOLV also displays the parameter L (theoretical effective water column length) determined from well geometry data. One normally expects Le to be close to the value of L.

○ Curve Matching Tips

- Choose Match>Visual to perform visual curve matching using the procedure for type-curve solutions. Move the mouse up and down to adjust the amplitude of the curve. Move the mouse left and right to adjust the period.

- Select values of Le from the **Family** and **Curve** drop-down lists on the toolbar.

- Use parameter tweaking to perform visual curve matching and sensitivity analysis.

- When performing automatic curve matching, save time by setting weights to zero for any observations that have recovered to static near the end of the test.

- Choose View>Options to change the critically damped value of

dimensionless damping factor, C(D) (i.e., 1 or 2).

o References

- 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.

- 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. <u>The Design, Performance, and Analysis of Slug Tests</u>, 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.

- Butler, J.J., Jr., Garnett, E.J. and J.M. Healey, 2003. Analysis of slug tests in formations of high hydraulic conductivity, Ground Water, vol. 41, no. 5, pp. 620-630.

- 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.

- Zurbuchen, B. R., V.A. Zlotnik and J.J. Butler, Jr., 2002. Dynamic interpretation of slug tests in highly permeable aquifers, Water Resources Research, vol. 38, no. 3., 1025, doi:10.1029/2001WRR000354.

Related Topics

Barker-Black (1983) Solution for a Slug Test in a Fractured Aquifer

(Match > Solution)

Barker and Black (1983) derived an analytical solution for a slug test in a well that fully penetrates an isotropic fractured aquifer assuming a double-porosity model with slab-shaped matrix blocks.

- o Illustration
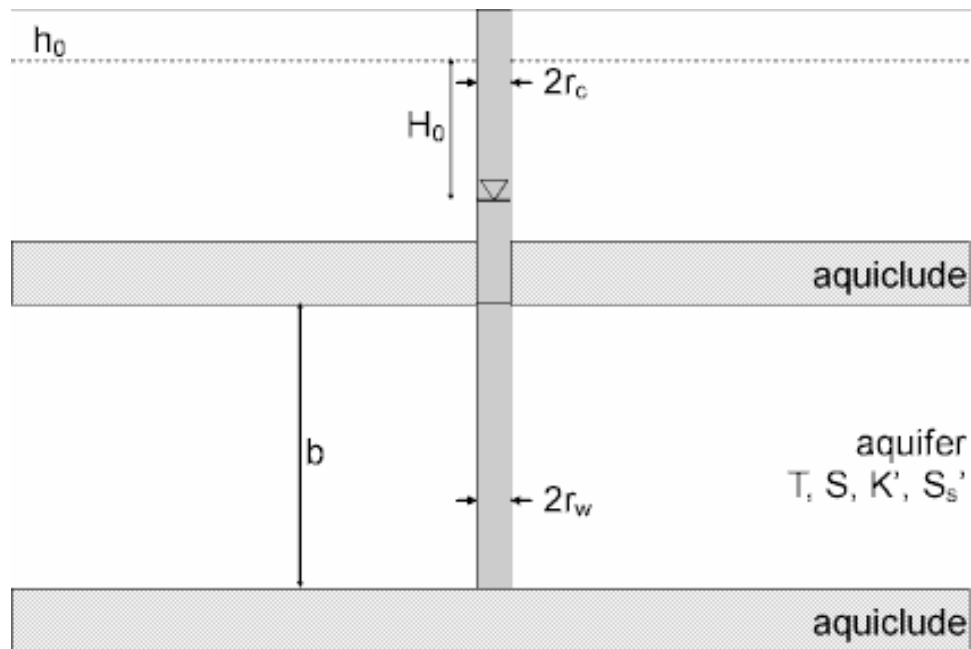
- o Equations

  Barker and Black (1983) derived an analytical solution for a slug test in a well that fully penetrates an isotropic fractured aquifer assuming a double-porosity model with slab-shaped matrix blocks.

  The Laplace transform solution for drawdown as follows:

$$\bar{h} = \frac{H_0 K_0(q r_D)}{p K_0(q) + 2\lambda K_1(q)}$$

$$q = \sqrt{\alpha[p + \beta p^{1/2} \tanh(\gamma p^{1/2})]}$$

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

$$\beta = \frac{2nr_c}{S}\sqrt{\frac{S_s'K'}{T}}$$

$$\gamma = \frac{d}{r_c}\sqrt{\frac{S_s'T}{K'}}$$

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

$$t_D = \frac{Tt}{r_w^2}$$

where

- d is one-half thickness of slab blocks [L]

- H_0 is initial displacement [L]

- K' is matrix hydraulic conductivity [L/T]

- K_i is modified Bessel function of second kind, order i

- n is the number of horizontal fractures in the aquifer

- p is the Laplace transform variable

- r is radial distance [L]

- r_c is casing radius [L]

- r_w is well radius [L]

- S is fracture storativity [dimensionless]

- S_s' is matrix specific storage [1/L]

- t is time [T]

- T is fissure transmissivity [L^2/T]

AQTESOLV computes n = aquifer thickness / slab block thickness.

If you enter a radius for downhole equipment, AQTESOLV uses the effective casing radius instead of the nominal casing radius in the equations for this solution.

- o Assumptions

  - aquifer has infinite areal extent

  - aquifer has uniform thickness

- test well is fully penetrating

- flow to test well is horizontal

- aquifer is confined with double porosity

- matrix blocks are slab shaped

- flow is unsteady

- water is released instantaneously from storage with decline of hydraulic head

- volume of water, V, is injected into or discharged from the well instantaneously

o Data Requirements

- test and observation well locations

- test and observation well measurements (time and displacement)

- casing radius and wellbore radius for test well

- saturated thickness

- thickness of slab blocks

o Estimated Parameters

- T (fracture transmissivity)

- S (fracture storativity)

- K' (matrix hydraulic conductivity)

- Ss' (matrix specific storage)

o Curve Matching Tips

- Follow guidelines developed by Butler (1998) for analyzing slug tests.

- Choose Match>Visual to perform visual curve matching using the procedure for type curve solutions.

- Use parameter tweaking to perform visual curve matching and sensitivity analysis.

- Perform visual curve matching prior to automatic estimation to obtain reasonable starting values for the aquifer properties.

o References

- Barker, J.A. and J.H. Black, 1983. Slug tests in fissured aquifers, Water Resources Research, vol. 19, no. 6, pp. 1558-1564.

Related Topics

Overview (Constant-Head Test Solutions)

Constant-head tests are sometimes performed as an alternative to constant-rate tests (pumping tests). During a constant-head test, the head or drawdown in the test well is held at a constant level, and discharge (flow rate) is recorded at regular intervals. One can determine aquifer properties by matching analytical solutions to the discharge measurements from a constant-head test.

After a well is shut-in following a constant-head test, special analytical techniques are required for evaluating recovery data because the boundary condition at the test well changes from constant head to constant rate. When you choose a constant-head solution, AQTESOLV also provides an exact method of analyzing the recovery data.

AQTESOLV provides the following solutions for constant-head tests in confined, leaky and fractured aquifers.

Confined	Jacob-Lohman (1952)
Confined	Jacob-Lohman (1952) straight-line method
Confined	Hurst-Clark-Brauer (1969)
Confined	Dougherty-Babu (1984)
Confined	Barker (1988)
Leaky	Hantush (1959)
Leaky	Moench (1985) Case 1: constant head
Fractured	Barker (1988) slab-shaped blocks
Fractured	Barker (1988) spherical blocks
Fractured	Ozkan-Raghavan (1991) uniform-flux vertical fracture
Fractured	Ozkan-Raghavan (1991) infinite-conductivity vertical fracture

- Choose Match>Solution to select a constant-head test solution.

Related Topics

Recovery Solutions (Constant-Head Tests)

AQTESOLV provides two procedures for analyzing recovery data from constant-head tests depending on the type of plot: Agarwal or residual drawdown.

On an **Agarwal plot**, the objective is to match an equivalent constant-rate solution using the approximate method of Uraiet and Raghavan (1980). The Agarwal plot is valuable as a diagnostic tool because the recovery data plot with the same recognizable patterns as constant-rate drawdown tests. For any given constant-head solution, we can find its equivalent constant-rate solution using a general formula. In many cases, however, the equivalent constant-rate and constant-head solutions are

available in the literature. For example, we would use the Jacob-Lohman (1952) solution to analyze a constant-head test in a confined aquifer with a fully penetrating well. The equivalent constant-rate solution for Agarwal recovery analysis is given by Papadopulos-Cooper (1967).

On a **residual drawdown plot**, AQTESOLV computes recovery with an exact solution derived by Ehlig-Economides and Ramey (1981) that rigorously accounts for the change in boundary condition from constant head to constant rate. The exact solution is general and incorporates conditions at the wellbore for different aquifer configurations.

- Use the Solution Expert to identify solutions for recovery analysis.

- Use residual drawdown and Agarwal plots to analyze recovery data from constant-head tests.

Confined Aquifers

Jacob-Lohman (1952) Solution for a Constant-Head Test in a Confined Aquifer

(Match > Solution)

Jacob and Lohman (1952) derived a solution for a constant-head test in a homogeneous, isotropic confined aquifer assuming a fully penetrating well.

Jacob and Lohman (1952) also devised a straight-line method for determining aquifer coefficients from a constant-head test (excluding recovery). The straight-line method is valid for sufficiently large values of time.

When you choose a solution, AQTESOLV provides two options for the Jacob-Lohman solution: type-curve and straight-line methods.

- o Illustration
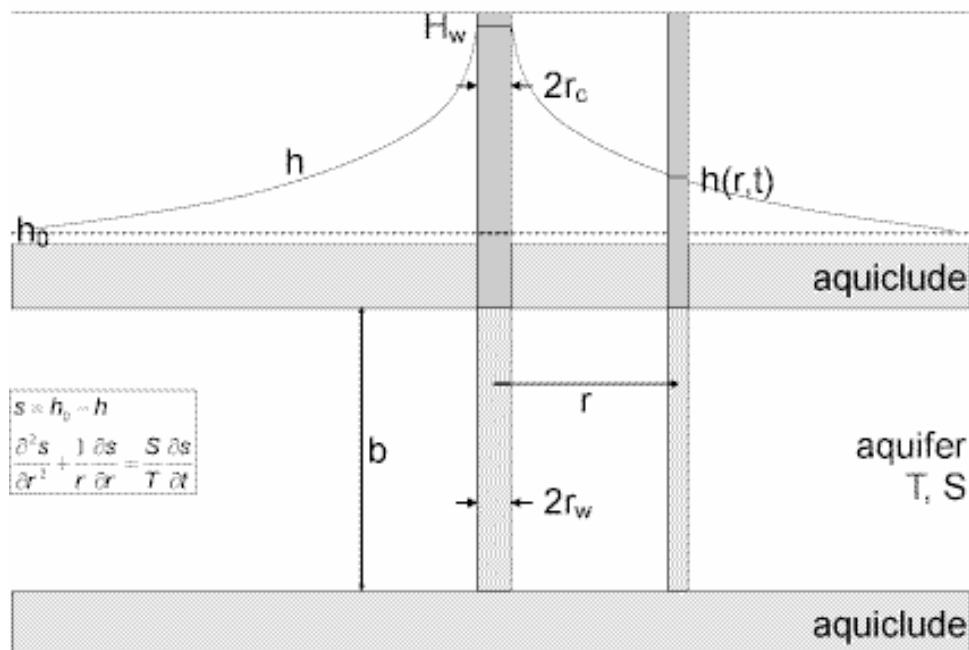
- o Equations

    Jacob and Lohman (1952) derived an analytical solution for a constant-head test in a homogeneous, isotropic confined aquifer assuming a fully penetrating well.

    The Laplace transform solution for dimensionless discharge is as follows:

$$\bar{q}_D = \frac{K_1(\sqrt{p})}{\sqrt{p}K_0(\sqrt{p})}$$

$$q_D = \frac{Q}{2\pi T H_w}$$

$$t_D = \frac{Tt}{Sr_w^2}$$

where

- H_w is the constant head in the test well [L]

- K_i is modified Bessel function of second kind, order i

- p is the Laplace transform variable

- Q is discharge rate [L^3/T]

- r_w is well radius [L]

- S is storativity [dimensionless]

- t is time [T]

- T is transmissivity [L^2/T]

Ehlig-Economides and Ramey (1981) derived an exact solution for recovery following a constant-head test. The calculations use the Papadopulos-Cooper (1967) constant-rate well function to simulate the recovery period. View the exact recovery solution on a residual drawdown plot.

For constant-head tests, casing radius only plays a role during recovery. If you enter a radius for downhole equipment, AQTESOLV uses the effective casing radius instead of the nominal casing radius in the recovery equations for this solution.

Jacob and Lohman (1952) also presented a straight-line method for estimating T and S as follows:

$$\frac{H_w}{Q} = \frac{2.303}{4\pi T} \log \frac{2.25Tt}{Sr_w^2}$$

$$T = \frac{2.303}{4\pi \Delta(H_w/Q)/\Delta \log(t/r_w^2)}$$

$$S = 2.25T\left(\frac{t}{r_w^2}\right)_0$$

The straight-line is matched to a data plot of H_w/Q versus t/r_w^2 on semi-log axes.

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- Assumptions

  - aquifer has infinite areal extent

  - aquifer is homogeneous, isotropic and of uniform thickness

  - aquifer potentiometric surface is initially horizontal

  - well is fully penetrating

  - flow is unsteady

  - aquifer is confined

  - water is released instantaneously from storage with decline of hydraulic head

- Data Requirements

  - test well location

  - constant head maintained in test well

  - observed pumping rate(s)

  - casing radius and well radius

  - downhole equipment radius (optional)

- Solution Options

  - recovery

- Estimated Parameters

  - T (transmissivity)

  - S (storativity)

  - r(w) (well radius)

  - r(c) (nominal casing radius)

- Curve Matching Tips

  - Match the Jacob-Lohman (1952) straight-line solution to late-time data to obtain preliminary estimates of aquifer properties.

  - Choose Match>Visual to perform visual curve matching using the procedure for type curve solutions.

  - Use parameter tweaking to perform visual curve matching and sensitivity analysis.

  - Perform visual curve matching prior to automatic estimation to obtain reasonable starting values for the aquifer properties.

- The exact recovery solution introduces the casing radius, **r(c)**, into the calculations; casing radius has no effect on the solution when the well is flowing.

- If you estimate **r(c)** for the test well, the estimated value replaces the nominal casing radius and AQTESOLV still performs the correction for downhole equipment.

o Recovery

For constant-head tests, the analytical solution displayed with recovery data depends on the type of plot: Agarwal or residual drawdown.

When viewing recovery data from a constant-head test on an **Agarwal plot**, the goal is to match an equivalent constant-rate solution using the approximate method of Uraiet and Raghavan (1980). In the case of the Jacob-Lohman (1952) solution for a constant-head test, the equivalent constant-rate solution is given by Papadopulos-Cooper (1967) assuming a fully penetrating well in a confined aquifer.

On a **residual drawdown plot**, AQTESOLV computes recovery after a constant-head test with an exact solution derived by Ehlig-Economides and Ramey (1981). The exact recovery calculation makes use of the Papadopulos-Cooper (1967) constant-rate solution.

o References

- Jacob, C.E. and S.W. Lohman, 1952. Nonsteady flow to a well of constant drawdown in an extensive aquifer, Trans. Am. Geophys. Union, vol. 33, pp. 559-569.

- Papadopulos, I.S. and H.H. Cooper, 1967. Drawdown in a well of large diameter, Water Resources Research, vol. 3, no. 1, pp. 241-244.

Related Topics

Hurst–Clark–Brauer (1969) Solution for a Constant-Head Test in a Confined Aquifer

(Match > Solution)

Hurst, Clark and Brauer (1969) derived a solution for a constant-head test in a homogeneous, isotropic confined aquifer assuming a fully penetrating well with wellbore skin.

- o Illustration
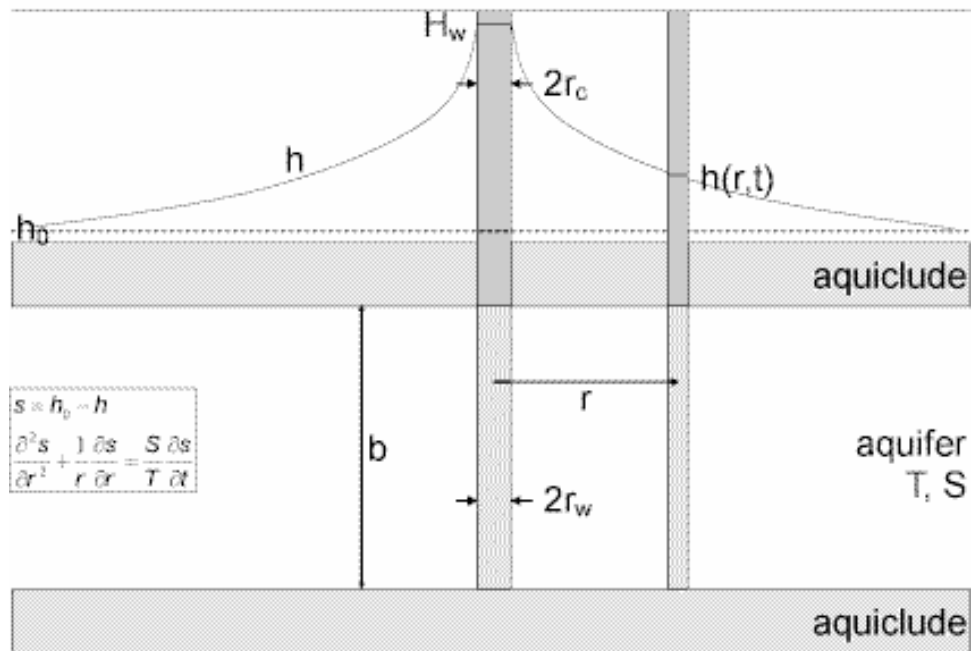
- o Equations

Hurst, Clark and Brauer (1969) derived an analytical solution for a constant-head test in a homogeneous, isotropic confined aquifer assuming a fully penetrating well with wellbore skin.

The Laplace transform solution for dimensionless discharge is as follows:

$$\bar{q}_D = \frac{K_1(\sqrt{p})}{\sqrt{p}\,K_0(\sqrt{p}) + S_w\,p\,K_1(\sqrt{p})}$$

$$q_D = \frac{Q}{2\pi T H_w}$$

$$t_D = \frac{Tt}{Sr_w^2}$$

where

- H_w is the constant head in the test well [L]

- K_i is modified Bessel function of second kind, order i

- p is the Laplace transform variable

- Q is discharge rate [L^3/T]

- r_w is well radius [L]

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- S is storativity [dimensionless]

- S_w is wellbore skin factor [dimensionless]

- t is time [T]

- T is transmissivity [L^2/T]

In the Laplace transform solution, S_w is limited to positive values; however, using the effective well radius concept, we also may simulate a negative skin (Hurst, Clark and Brauer 1969).

Ehlig-Economides and Ramey (1981) derived an exact solution for recovery following a constant-head test. The calculations use the Dougherty-Babu (1984) constant-rate well function to simulate the recovery period. View the exact recovery solution on a residual drawdown plot.

For constant-head tests, casing radius only plays a role during recovery. If you enter a radius for downhole equipment, AQTESOLV uses the effective casing radius instead of the nominal casing radius in the recovery equations for this solution.

- o Assumptions

  - aquifer has infinite areal extent

  - aquifer is homogeneous, isotropic and of uniform thickness

  - aquifer potentiometric surface is initially horizontal

  - well is fully penetrating

  - flow is unsteady

  - aquifer is confined

  - water is released instantaneously from storage with decline of hydraulic head

- o Data Requirements

  - test well location

  - constant head maintained in test well

  - observed pumping rate(s)

  - casing radius and well radius

  - downhole equipment radius (optional)

- o Solution Options

  - recovery

- o Estimated Parameters

  - T (transmissivity)

  - S (storativity)

  - Sw (dimensionless wellbore skin factor)

  - r(w) (well radius)

  - r(c) (nominal casing radius)

- o Curve Matching Tips

  - Match the Jacob-Lohman (1952) straight-line solution to late-time data to obtain preliminary estimates of aquifer properties.

  - Choose Match>Visual to perform visual curve matching using the procedure for type curve solutions.

  - Use parameter tweaking to perform visual curve matching and sensitivity analysis.

  - Perform visual curve matching prior to automatic estimation to obtain reasonable starting values for the aquifer properties.

  - The exact recovery solution introduces the casing radius, **r(c)**, into the calculations; casing radius has no effect on the solution when the well is flowing.

  - If you estimate **r(c)** for the test well, the estimated value replaces the nominal casing radius and AQTESOLV still performs the correction for downhole equipment.

- o Recovery

  For constant-head tests, the analytical solution displayed with recovery data depends on the type of plot: Agarwal or residual drawdown.

  When viewing recovery data from a constant-head test on an **Agarwal plot**, the goal is to match an equivalent constant-rate solution using the approximate method of Uraiet and Raghavan (1980). In the case of the Hurst-Clark-Brauer (1969) solution for a constant-head test, the equivalent constant-rate solution is given by Dougherty-Babu (1984) assuming a fully penetrating well with wellbore skin in a confined aquifer.

  On a **residual drawdown plot**, AQTESOLV computes recovery after a constant-head test with an exact solution derived by Ehlig-Economides and Ramey (1981). The exact recovery calculation makes use of the Dougherty-Babu (1984) constant-rate solution.

- o References

  - Hurst, W., J.D. Clark and E.B. Brauer, 1969. The skin effect in producing wells, Journal of Petroleum Technology, November 1969, pp. 1483-1489.

- Dougherty, D.E and D.K. Babu, 1984. Flow to a partially penetrating well in a double-porosity reservoir, Water Resources Research, vol. 20, no. 8, pp. 1116-1122.

Related Topics

Dougherty-Babu (1984) Solution for a Constant-Head Test in a Confined Aquifer

(Match > Solution)

Dougherty and Babu (1984) derived a Laplace transform solution for a constant-rate test that we can modify to evaluate a constant-head test in a homogeneous, anisotropic confined aquifer assuming a fully or partially penetrating well with wellbore skin.

o   Illustration
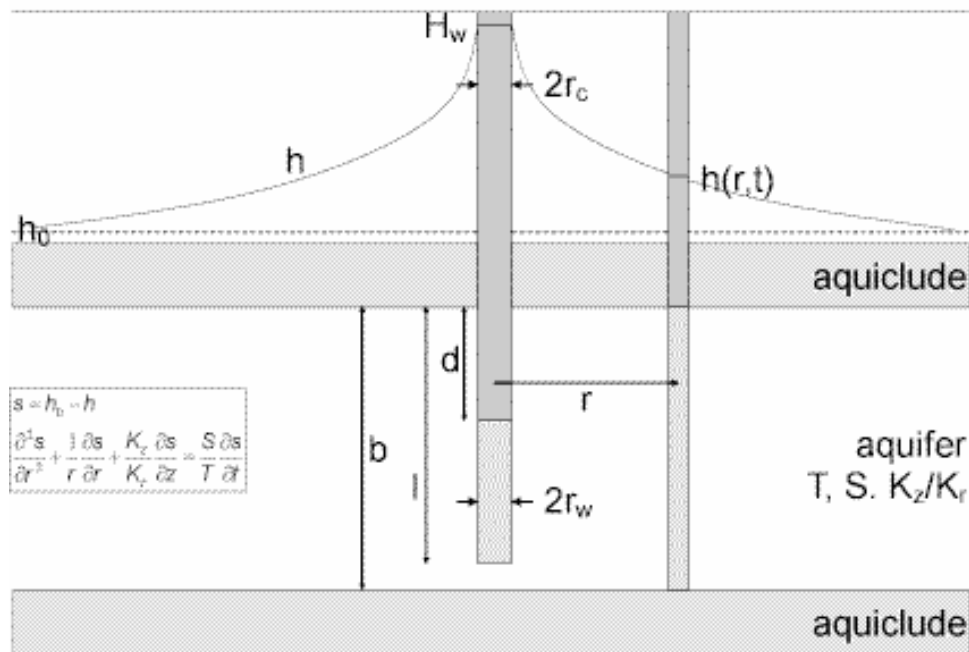
o   Equations

Dougherty and Babu (1984) derived a Laplace transform solution for a constant-rate test in a homogeneous, anisotropic confined aquifer assuming a fully or partially penetrating well with wellbore skin.

We may use the Dougherty-Dabu (1984) constant-rate solution in a general formula to compute dimensionless discharge for a constant-head test:

$$\overline{q}_D = \frac{(l_D - d_D)}{2p(A_0 + A + S_w)}$$

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$$A_0 = \frac{(l_D - d_D)K_0(q_0)}{q_0 K_1(q_0)}$$

$$A = \frac{2}{(l_D - d_D)} \sum_{n=1}^{\infty} \frac{K_0(q_n)[\sin(n\pi l_D) - \sin(n\pi d_D)]^2}{n^2 \pi^2 q_n K_1(q_n)}$$

$$q_n = \sqrt{\frac{r_w^2 n^2 \pi^2}{b^2} \frac{K_z}{K_r} + p}$$

$$q_D = \frac{Q}{2\pi K b H_w}$$

$$t_D = \frac{Kt}{S_s r_w^2}$$

where

- b is aquifer thickness [L]

- d is distance from water table to top of pumping well screen [L]

- d_D is d/b

- H_w is the constant head in the test well [L]

- K is hydraulic conductivity [L/T]

- K_i is modified Bessel function of second kind, order i

- l is distance from water table to bottom of pumping well screen [L]

- l_D is l/b

- p is the Laplace transform variable

- Q is discharge rate [L^3/T]

- r_w is well radius [L]

- S_s is specific storage [1/L]

- S_w is wellbore skin factor [dimensionless]

- t is time [T]

In the Laplace transform solution, S_w is limited to positive values; however, using the effective well radius concept, we also may simulate a negative skin (Hurst, Clark and Brauer 1969).

Ehlig-Economides and Ramey (1981) derived an exact solution for recovery

following a constant-head test. The calculations use the Dougherty-Babu (1984) constant-rate well function to simulate the recovery period. View the exact recovery solution on a residual drawdown plot.

For constant-head tests, casing radius only plays a role during recovery. If you enter a radius for downhole equipment, AQTESOLV uses the effective casing radius instead of the nominal casing radius in the recovery equations for this solution.

o Assumptions

- aquifer has infinite areal extent

- aquifer is homogeneous and of uniform thickness

- aquifer potentiometric surface is initially horizontal

- well is fully or partially penetrating

- flow is unsteady

- aquifer is confined

- water is released instantaneously from storage with decline of hydraulic head

o Data Requirements

- test well location

- constant head maintained in test well

- observed pumping rate(s)

- casing radius and well radius

- downhole equipment radius (optional)

- partial penetration depths

- saturated thickness

- hydraulic conductivity anisotropy ratio

o Solution Options

- partially penetrating well

- recovery

o Estimated Parameters

- T (transmissivity)

- S (storativity)

- Kz/Kr (hydraulic conductivity anisotropy ratio)

- Sw (dimensionless wellbore skin factor)

- r(w) (well radius)

- r(c) (nominal casing radius)

o Curve Matching Tips

  - Match the Jacob-Lohman (1952) straight-line solution to late-time data to obtain preliminary estimates of aquifer properties.

  - Choose Match>Visual to perform visual curve matching using the procedure for type curve solutions.

  - Select values of Kz/Kr from the **Family** and **Curve** drop-down lists on the toolbar.

  - Use parameter tweaking to perform visual curve matching and sensitivity analysis.

  - Perform visual curve matching prior to automatic estimation to obtain reasonable starting values for the aquifer properties.

  - The exact recovery solution introduces the casing radius, **r(c)**, into the calculations; casing radius has no effect on the solution when the well is flowing.

  - If you estimate **r(c)** for the test well, the estimated value replaces the nominal casing radius and AQTESOLV still performs the correction for downhole equipment.

o Recovery

  For constant-head tests, the analytical solution displayed with recovery data depends on the type of plot: Agarwal or residual drawdown.

  When viewing recovery data from a constant-head test on an **Agarwal plot**, the goal is to match an equivalent constant-rate solution using the approximate method of Uraiet and Raghavan (1980). In the case of the Dougherty-Babu (1984) solution for a constant-head test, the equivalent constant-rate solution is given by Dougherty-Babu (1984) assuming a fully or partially penetrating well with wellbore skin in a confined aquifer.

  On a **residual drawdown plot**, AQTESOLV computes recovery after a constant-head test with an exact solution derived by Ehlig-Economides and Ramey (1981). The exact recovery calculation makes use of the Dougherty-Babu (1984) constant-rate solution.

o References

  - Dougherty, D.E and D.K. Babu, 1984. Flow to a partially penetrating well in a double-porosity reservoir, Water Resources Research, vol. 20, no. 8, pp. 1116-1122.

  - Moench, A.F., 1988. The response of partially penetrating wells to pumpage from double-porosity aquifers, Proceedings of the International

Conference on Fluid Flow in Fractured Rocks, Atlanta, GA, May 16-18, 1988.

[Related Topics]

Barker (1988) Solution for a Constant-Head Test in a Confined Aquifer

(Match > Solution)

Barker (1988) derived generalized radial flow model for unsteady, n-dimensional flow to a fully penetrating source in an isotropic, single- or double-porosity fractured aquifer. The single-porosity form of the model describes flow in a confined aquifer. For details, refer to the Barker (1998) solution for a fractured aquifer.

[Related Topics]

Hantush (1959) Solution for a Constant-Head Test in a Leaky Aquifer

(Match > Solution)

Hantush (1959) derived a solution for a constant-head test in a homogeneous, isotropic leaky confined aquifer assuming a fully penetrating well.

- ○ Illustration
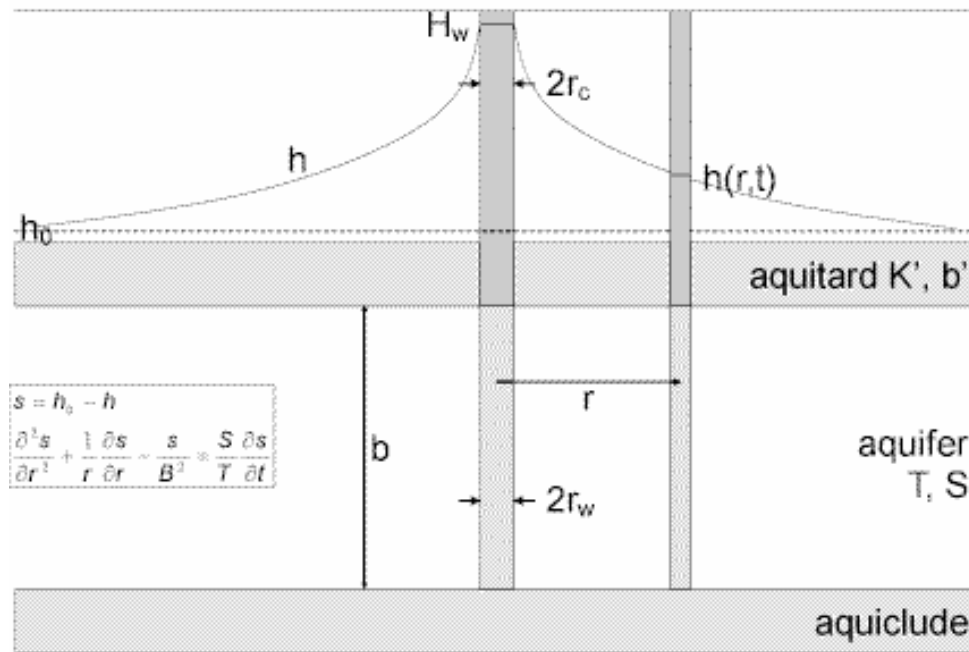
- ○ Equations

  Hantush (1959) derived an analytical solution for a constant-head test in a homogeneous, isotropic leaky confined aquifer assuming a fully penetrating well.

  The Laplace transform solution for dimensionless discharge is as follows:

$$\bar{q}_D = \frac{\sqrt{x} K_1(\sqrt{x})}{p K_0(\sqrt{x})}$$

$$x = \sqrt{p + 1/B_D^2}$$

$$B_D = \frac{B}{r_w} = \frac{\sqrt{Tb'/K'}}{r_w} = \frac{r_D}{(r/B)}$$

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

$$q_D = \frac{Q}{2\pi T H_w}$$

$$t_D = \frac{Tt}{S r_w^2}$$

where

- b' is aquitard thickness [L]

- H_w is the constant head in the test well [L]

- K' is aquitard vertical hydraulic conductivity [L/t]

- K_i is modified Bessel function of second kind, order i

- p is the Laplace transform variable

- Q is discharge rate [L^3/T]

- r_w is well radius [L]

- S is storativity [dimensionless]

- t is time [T]

- T is transmissivity [L^2/T]

Ehlig-Economides and Ramey (1981) derived an exact solution for recovery following a constant-head test. The calculations use the Moench (1985) constant-rate well function for a fully penetrating, finite-diameter well in a leaky confined aquifer without aquitard storage to simulate the recovery period. View the exact recovery solution on a residual drawdown plot.

For constant-head tests, casing radius only plays a role during recovery. If you enter a radius for downhole equipment, AQTESOLV uses the effective casing radius instead of the nominal casing radius in the recovery equations for this solution.

- o Assumptions

  - aquifer has infinite areal extent

  - aquifer is homogeneous, isotropic and of uniform thickness

  - aquifer potentiometric surface is initially horizontal

  - well is fully penetrating

  - flow is unsteady

- aquifer is leaky confined

- water is released instantaneously from storage with decline of hydraulic head

- 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 is vertical in the aquitard(s)

o Data Requirements

- test well location

- constant head maintained in test well

- observed pumping rate(s)

- casing radius and well radius

- downhole equipment radius (optional)

o Solution Options

- recovery

o Estimated Parameters

- T (transmissivity)

- S (storativity)

- r/B (leakage parameter)

- r(w) (well radius)

- r(c) (nominal casing radius)

The Report also shows aquitard properties (K'/b' and K') computed from the leakage parameter (r/B).

o Curve Matching Tips

- Choose Match>Visual to perform visual curve matching using the procedure for type curve solutions.

- Select values of r/B from the **Family** and **Curve** drop-down lists on the toolbar.

- Use parameter tweaking to perform visual curve matching and sensitivity analysis.

- Perform visual curve matching prior to automatic estimation to obtain reasonable starting values for the aquifer properties.

- The exact recovery solution introduces the casing radius, **r(c)**, into the calculations; casing radius has no effect on the solution when the well is flowing.

- If you estimate **r(c)** for the test well, the estimated value replaces the nominal casing radius and AQTESOLV still performs the correction for downhole equipment.

o Recovery

For constant-head tests, the analytical solution displayed with recovery data depends on the type of plot: Agarwal or residual drawdown.

On an **Agarwal plot**, the goal is to match an equivalent constant-rate solution using the approximate method of Uraiet and Raghavan (1980). In the case of the Hantush (1959) solution for a constant-head test, the equivalent constant-rate solution is given by Moench (1985) assuming a constant-head boundary and no storage in the aquitard.

On a **residual drawdown plot**, AQTESOLV computes recovery after a constant-head test with an exact solution derived by Ehlig-Economides and Ramey (1981). The exact recovery calculation makes use of the Moench (1985) constant-rate solution.

o References

- Hantush, M.S., 1959. Nonsteady flow to flow wells in leaky aquifers, Journal of Geophysical Research, vol. 64, no. 5, pp. 1043-1052.

- 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.

Related Topics

Moench (1985) Solution for a Constant-Head Test in a Leaky Aquifer

(Match > Solution)

Moench (1985) derived a Laplace transform solution for a constant-rate test that we can modify to evaluate a constant-head test in a homogeneous, isotropic confined aquifer assuming a fully penetrating well with wellbore skin.

- Illustration
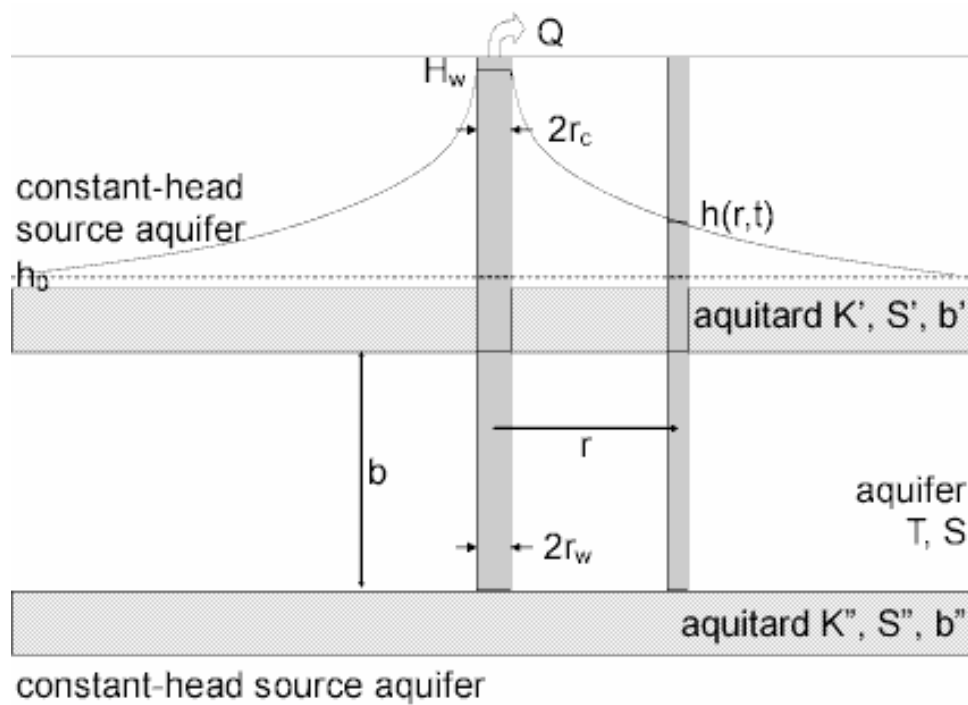
constant-head source aquifer

- Equations

Moench (1985) derived a Laplace transform solution for a constant-rate test that we can modify to evaluate a constant-head test in a homogeneous, isotropic confined aquifer assuming a fully penetrating well with wellbore skin.

We may use the Moench (1985) constant-rate solution in a general formula to compute dimensionless discharge for a constant-head test:

$$\overline{q}_D = \frac{xK_1(x)}{p[K_0(x) + xS_wK_1(x)]}$$

$$x = (p + \overline{q}_{lD})^{1/2}$$

$$\overline{q}_{lD} = \gamma'^2 m' \coth(m') + \gamma''^2 m'' \coth(m'') \quad (Case\ 1)$$

$$m' = \frac{(\sigma'p)^{1/2}}{\gamma'}$$

$$m'' = \frac{(\sigma''p)^{1/2}}{\gamma''}$$

$$\gamma' = r_w \left(\frac{K'}{Kbb'} \right)^{1/2}$$

$$\gamma'' = r_w \left(\frac{K''}{Kbb''} \right)^{1/2}$$

$$\sigma' = \frac{S'_s b'}{S_s b}$$

$$\sigma'' = \frac{S''_s b''}{S_s b}$$

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

$$q_D = \frac{Q}{2\pi T H_w}$$

$$t_D = \frac{Tt}{Sr_w^2}$$

where

- b is aquifer thickness [L]
- b' is thickness of first aquitard [L]
- b" is thickness of second aquitard [L]
- H_w is constant head in test well [L]
- K is aquifer hydraulic conductivity [L/T]
- K' is vertical hydraulic conductivity of first aquitard [L/T]
- K" is vertical hydraulic conductivity of second aquitard [L/T]
- K_i is modified Bessel function of second kind, order i
- p is the Laplace transform variable
- Q is pumping rate [L^3/T]
- r is radial distance [L]
- r_c is casing radius [L]

- r_w is well radius [L]

- S_s is aquifer specific storage [1/L]

- S_s' is specific storage of first aquitard [1/L]

- S_s'' is specific storage of second aquitard [1/L]

- S_w is wellbore skin factor [dimensionless]

- t is time [T]

AQTESOLV reports the aquitard properties in terms of the more familiar parameters from the Hantush (1960) solution, which one can readily compute from Moench's parameters as follows:

$$r/B = \gamma r_D$$

$$\beta = \frac{\gamma}{4}\sigma^{1/2}r_D$$

Ehlig-Economides and Ramey (1981) derived an exact solution for recovery following a constant-head test. The calculations use the Moench (1985) constant-rate well function for a fully penetrating, finite-diameter well in a leaky confined aquifer to simulate the recovery period. View the exact recovery solution on a residual drawdown plot.

For constant-head tests, casing radius only plays a role during recovery. If you enter a radius for downhole equipment, AQTESOLV uses the effective casing radius instead of the nominal casing radius in the recovery equations for this solution.

- o Assumptions

    - aquifer has infinite areal extent

    - aquifer is homogeneous, isotropic and of uniform thickness

    - aquifer potentiometric surface is initially horizontal

    - well is fully penetrating

    - flow is unsteady

    - aquifer is leaky confined

    - 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 is vertical in the aquitard(s)

o Data Requirements

- test well location

- constant head maintained in test well

- observed pumping rate(s)

- casing radius and well radius

- downhole equipment radius (optional)

o Solution Options

- recovery

o Estimated Parameters

- T (transmissivity)

- S (storativity)

- r/B' (dimensionless leakage parameter, aquitard 1)

- β' (dimensionless leakage parameter, aquitard 1)

- r/B" (dimensionless leakage parameter, aquitard 2)

- $\beta"$ (dimensionless leakage parameter, aquitard 2)

- Sw (wellbore skin factor)

- r(w) (well radius)

- r(c) (nominal casing radius)

The Report also shows aquitard properties (K'/b' and K'; K"/b" and K")
computed from the leakage parameter (r/B' and r/B").

o Curve Matching Tips

- Match the Jacob-Lohman (1952) straight-line solution to late-time data to obtain preliminary estimates of aquifer properties.

- Choose Match>Visual to perform visual curve matching using the procedure for type curve solutions.

- Select values of r/B' and β' from the **Family** and **Curve** drop-down lists on the toolbar.

- Use parameter tweaking to perform visual curve matching and sensitivity analysis.

- Perform visual curve matching prior to automatic estimation to obtain reasonable starting values for the aquifer properties.

- The exact recovery solution introduces the casing radius, **r(c)**, into the calculations; casing radius has no effect on the solution when the well is flowing.

- If you estimate **r(c)** for the test well, the estimated value replaces the nominal casing radius and AQTESOLV still performs the correction for downhole equipment.

o Recovery

For constant-head tests, the analytical solution displayed with recovery data depends on the type of plot: Agarwal or residual drawdown.

When viewing recovery data from a constant-head test on an **Agarwal plot**, the goal is to match an equivalent constant-rate solution using the approximate method of Uraiet and Raghavan (1980). In the case of the Moench (1985) solution for a constant-head test, the equivalent constant-rate solution is given by Moench (1985) assuming a fully penetrating well with wellbore skin in a leaky confined aquifer.

On a **residual drawdown plot**, AQTESOLV computes recovery after a constant-head test with an exact solution derived by Ehlig-Economides and Ramey (1981). The exact recovery calculation makes use of the Moench (1985) constant-rate solution.

o References

- 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.

Related Topics

Barker (1988) Solution for a Constant-Head Test in a Fractured Aquifer

(Match > Solution)

Barker (1988) derived a generalized radial flow model for unsteady, n-dimensional flow to a fully penetrating source in an isotropic, single- or double-porosity fractured aquifer. The source is an n-dimensional sphere (projected through three-dimensional space) of finite radius (r_w), storage capacity (β) and skin factor (S_w).

As described by Doe (1990), the spatial dimension (n) determines the change in conduit area with distance from the source. In a two-dimensional system (n=2), the source is a finite cylinder, the typical configuration for analyzing cylindrical flow to a well.

AQTESOLV uses the principle of superposition in time to simulate variable-rate tests including recovery with the Barker solution. Use this solution to analyze both pumping and recovery data from constant- or variable-rate pumping tests.

When you choose a solution, AQTESOLV provides three configurations for the Barker generalized radial flow model:

- single-porosity (confined/fractured aquifer)

- double-porosity with slab-shaped blocks (fractured aquifer)

- double-porosity with spherical blocks (fractured aquifer)
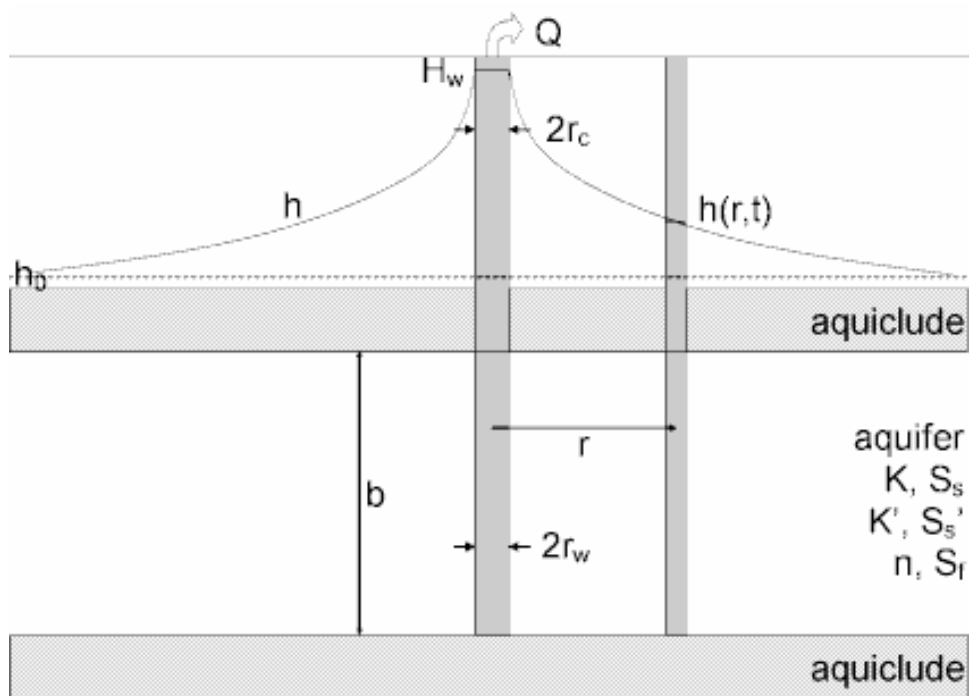
o Illustration

o Equations

Barker (1988) derived a generalized radial flow model for unsteady, n-dimensional flow to a fully penetrating source in an isotropic, single- or double-porosity fractured aquifer.

The Laplace transform solution for discharge is as follows:

$$\bar{q} = \frac{H_w K b^{3-n} \alpha_n r_w^{n-2} \Phi_v(x)}{p[1 + S_w \Phi_v(x)]}$$

$$v = 1 - n/2$$

$$\lambda^2 = p S_s / K$$

$$\mu = \lambda r_w$$

$$r_D = r / r_w$$

$$\Phi_v(z) = z K_{v-1}(z) / K_v(z)$$

$$\alpha_n = 2\pi^{n/2} / \Gamma(n/2)$$

For single-porosity models, we have:

$$X = \mu$$

For double-porosity models, we use the functions of Moench (1984) for slab and spherical blocks including fracture skin.

$$X = (\mu^2 + \bar{q}_{rD})^{1/2}$$

slab blocks:

$$\bar{q}_{rD} = \frac{\gamma^2 m \tanh(m)}{1 + S_r m \tanh(m)}$$

spherical blocks:

$$\bar{q}_{rD} = \frac{3\gamma^2 [m \coth(m) - 1]}{1 + S_r [m \coth(m) - 1]}$$

$$m = \frac{(\sigma \mu^2)^{1/2}}{\gamma}$$

$$\gamma = \frac{r_w}{b_f} \left(\frac{K'}{K}\right)^{1/2}$$

$$\sigma = \frac{S_s{}'}{S_s}$$

$$S_f = \frac{K' b_s}{K_s b'}$$

where

- b is extent of flow region [L]

- b' is block thickness [L]

- b_s is fracture skin thickness [L]

- H_w is head maintained in the well [L]

- K is aquifer/fracture hydraulic conductivity [L/T]

- K' is matrix hydraulic conductivity [L/T]

- K_s is fracture skin hydraulic conductivity [L/T]

- K_v is modified Bessel function of second kind, order v

- n is flow dimension [dimensionless]

- p is the Laplace transform variable

- r is radial distance [L]

- r_w is well radius [L]

- S_f is fracture skin factor [dimensionless]

- S_s is aquifer/fracture specific storage [1/L]

- S_s' is matrix specific storage [1/L]

- S_w is wellbore skin factor [dimensionless]

- t is time [T]

The parameter b, the flow region extent, has a simple interpretation for integral flow dimensions. For one-dimensional flow (n=1), it is the square root of the conduit flow area (normal to the flow direction). For n=2 (two-dimensional radial flow), b is the thickness of the aquifer. For spherical flow (n=3), the parameter b, which is raised to the power of 3-n, has no significance. For nonintegral flow dimensions, b has no simple interpretation (Barker 1988).

Ehlig-Economides and Ramey (1981) derived an exact solution for recovery following a constant-head test. The calculations use the Barker (1988) constant-rate solution to simulate the recovery period. View the exact recovery solution on a residual drawdown plot.

For constant-head tests, casing radius only plays a role during recovery. If you enter a radius for downhole equipment, AQTESOLV uses the effective casing radius instead of the nominal casing radius in the recovery equations for this solution.

- o Assumptions

  - aquifer has infinite extent

  - aquifer has uniform extent of flow region

  - pumping and observation wells are fully penetrating

  - aquifer is confined with single or double porosity

  - matrix blocks in double-porosity models are slab shaped or spherical

  - flow is unsteady

  - water is released instantaneously from storage with decline of hydraulic head

- o Data Requirements

  - test well location

- constant head maintained in test well

- observed pumping rate(s)

- casing radius and well radius

- downhole equipment radius (optional)

- extent of flow region

- thickness of slab blocks or diameter of spherical blocks (double-porosity models)

o Solution Options

- recovery

o Estimated Parameters

- K (fracture hydraulic conductivity)

- Ss (fracture specific storage)

- K' (matrix hydraulic conductivity)

- Ss' (matrix specific storage)

- n (flow dimension)

- b (extent of flow region)

- Sf (fracture skin factor)

- Sw (wellbore skin factor)

- r(w) (well radius)

- r(c) (nominal casing radius)

o Curve Matching Tips

- Match the Jacob-Lohman (1952) straight-line solution to late-time data to obtain preliminary estimates of aquifer properties.

- Choose Match>Visual to perform visual curve matching using the procedure for type curve solutions.

- Select values of n, Sf and Sw from the **Family** and **Curve** drop-down lists on the toolbar.

- Use parameter tweaking to perform visual curve matching and sensitivity analysis.

- Perform visual curve matching prior to automatic estimation to obtain reasonable starting values for the aquifer properties.

- The exact recovery solution introduces the casing radius, **r(c)**, into the

calculations; casing radius has no effect on the solution when the well is flowing.

- If you estimate **r(c)** for the test well, the estimated value replaces the nominal casing radius and AQTESOLV still performs the correction for downhole equipment.

○ Recovery

For constant-head tests, the analytical solution displayed with recovery data depends on the type of plot: Agarwal or residual drawdown.

When viewing recovery data from a constant-head test on an **Agarwal plot**, the goal is to match an equivalent constant-rate solution using the approximate method of Uraiet and Raghavan (1980). In the case of the Barker (1988) solution for a constant-head test, the equivalent constant-rate solution is given by Barker (1988) assuming a fully penetrating well with wellbore skin in a fractured aquifer.

On a **residual drawdown plot**, AQTESOLV computes recovery after a constant-head test with an exact solution derived by Ehlig-Economides and Ramey (1981). The exact recovery calculation makes use of the Barker (1988) constant-rate solution.

○ References

- Barker, J.A., 1988. A generalized radial flow model for hydraulic tests in fractured rock, Water Resources Research, vol. 24, no. 10, pp. 1796-1804.

- 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.

Related Topics

Ozkan-Raghavan (1991) Solution for a Constant-Head Test in a Fractured Aquifer

(Match > Solution)

Ozkan and Raghavan (1991) derived a Laplace transform solution for a constant-rate test that we can modify for a constant-head test assuming a fully penetrating well which intersects a single vertical fracture in an anisotropic confined aquifer. The test well bisects the fracture which is represented in the solution by a fully penetrating vertical plane source oriented parallel to the x axis.

When you choose a solution, AQTESOLV provides two options for the Ozkan-Raghavan solution: uniform-flux and infinite-conductivity vertical fracture models.

- o Illustration
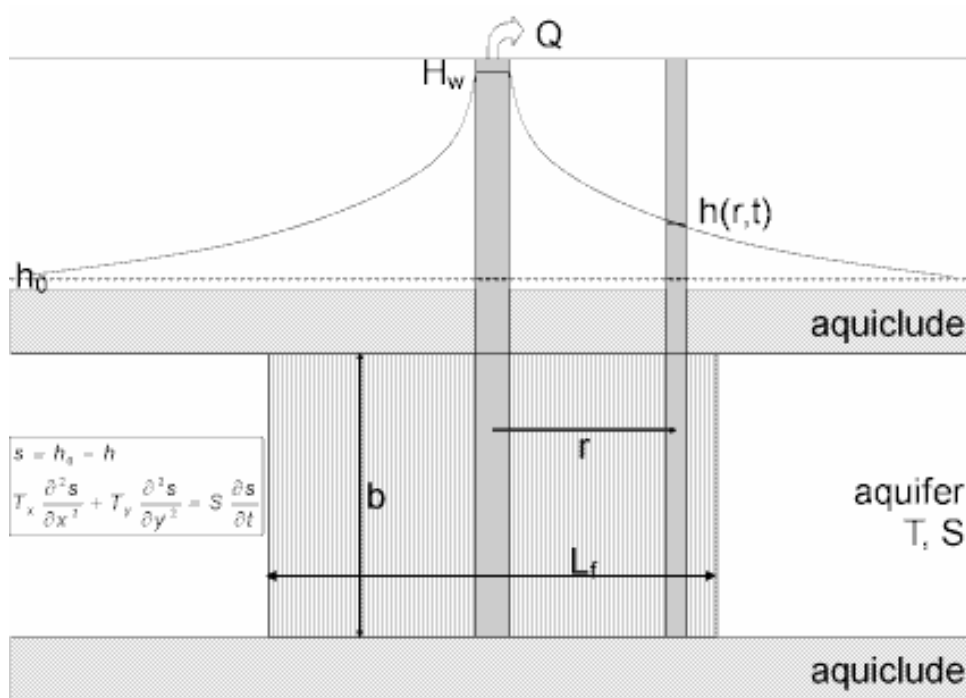
- o Equations

Ozkan and Raghavan (1991) derived the following Laplace transform solution for dimensionless head in a fully penetrating, uniform-flux vertical fracture in a confined aquifer assuming constant-rate flow (y=0):

$$\overline{h}_D = \frac{1}{2p} \int_{-1}^{+1} K_0 \left(\sqrt{p} \sqrt{(x_D - \alpha \sqrt{K_y/K_x})^2} \right) d\alpha$$

$$t_D = \frac{T_x t}{S x_f^2}$$

$$x_D = \frac{x}{x_f}$$

where

- K_y/K_x is hydraulic conductivity anisotropy ratio [L^2/T]

- K_0 is modified Bessel function of second kind, zero order

- p is Laplace transform variable

- Q is pumping rate [L^3/T]

- s is drawdown [L]

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- S is storativity [dimensionless]

- t is time [T]

- T_x is transmissivity in x direction [L^2/T]

- T_y is transmissivity in y direction [L^2/T]

- x and y are coordinate distances [L]

- x_f is half-length of fracture in x direction [L]

For a constant-head test, we use the constant-rate solution to compute the Laplace transform of dimensionless discharge using a general relationship given by van Everdingen and Hurst (1949).

Ehlig-Economides and Ramey (1981) derived an exact solution for recovery following a constant-head test. The calculations use the Ozkan-Raghavan (1991) constant-rate solution to simulate the recovery period. View the exact recovery solution on a residual drawdown plot.

Gringarten, Ramey and Raghavan (1974) found that the uniform-flux solution could be used to predict the drawdown in an infinite-conductivity fracture by simply using $x_D = 0.732$ to compute head in the test well.

o Assumptions

- aquifer has infinite areal extent

- aquifer has uniform thickness

- aquifer potentiometric surface is initially horizontal

- test well is 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

o Data Requirements

- test well location

- constant head maintained in test well

- observed pumping rate(s)

- length of vertical fracture

- o Solution Options

  - recovery

- o Estimated Parameters

  - Kx (hydraulic conductivity in x direction)

  - Ss (specific storage)

  - Ky/Kx (hydraulic conductivity anisotropy ratio)

  - Lf (length of fracture)

- o Curve Matching Tips

  - Match the Jacob-Lohman (1952) straight-line solution to late-time data to obtain preliminary estimates of aquifer properties.

  - Choose Match>Visual to perform visual curve matching using the procedure for type curve solutions.

  - Use active type curves for more effective visual matching with variable-rate pumping tests.

  - Select values of Ky/Kx from the **Family** and **Curve** drop-down lists on the toolbar.

  - Use parameter tweaking to perform visual curve matching and sensitivity analysis.

  - Perform visual curve matching prior to automatic estimation to obtain reasonable starting values for the aquifer properties.

- o Recovery

  For constant-head tests, the analytical solution displayed with recovery data depends on the type of plot: Agarwal or residual drawdown.

  When viewing recovery data from a constant-head test on an **Agarwal plot**, the goal is to match an equivalent constant-rate solution using the approximate method of Uraiet and Raghavan (1980). In the case of the Ozkan-Raghavan (1991) solution for a constant-head test, the equivalent constant-rate solution is given by Ozkan-Raghavan (1991) assuming a fully penetrating vertical fracture in a confined aquifer.

  On a **residual drawdown plot**, AQTESOLV computes recovery after a constant-head test with an exact solution derived by Ehlig-Economides and Ramey (1981). The exact calculation makes use of the Ozkan-Raghavan (1991) constant-rate solution.

- o References

  - Ozkan, E. and R. Raghavan, 1991. New solutions for well-test analysis problems: Part I-analytical considerations, SPE Formation Evaluation, Sept. 1991, pp. 359-368.

- Gringarten, A.C., Ramey, H.J., Jr. and R. Raghavan, 1974. Unsteady-state pressure distributions created by a well with single infinite-conductivity vertical fracture, Soc. Petrol. Engrs. J., pp. 347-360.

Related Topics

Curve Matching

Overview (Curve Matching)

Use the following strategy to perform more effective curve matching with AQTESOLV.

1. Develop a **conceptual model** for the system under study based on site-specific hydrogeologic data. Enter these data into a new data set.

   TIPS

   - To help you identify reasonable values for aquifer properties, use representative data from the literature for hydraulic conductivity, porosity, specific yield and storativity.

2. Use diagnostic flow plots and derivative analysis to help identify appropriate solution methods for the data.

   TIPS

   - Use diagnostic methods to identify wellbore storage effects, linear flow, bilinear flow, infinite-acting radial flow and boundary effects.

3. Perform visual curve matching or parameter tweaking to obtain estimates of aquifer properties.

   TIPS

   - Use visual curve matching to obtain preliminary estimates of aquifer properties prior to performing automatic curve matching.

   - For pumping tests, use the Cooper-Jacob straight-line method to obtain preliminary estimates of aquifer parameters before applying more complicated solution methods.

   - Use active type curves to perform more effective visual curve matching for a variety of analyses.

4. Perform automatic curve matching to refine aquifer property estimates using a nonlinear least-squares fitting procedure.

   TIPS

   - The efficiency of automatic curve matching is often sensitive to initial estimates of aquifer properties. Use visual curve matching to obtain reasonable starting values prior to performing automatic curve matching.

5. Use parameter tweaking to perform **sensitivity analysis** for specified aquifer properties.

Related Topics

Curve Matching Tips for Pumping Tests

- Use the Cooper-Jacob (1946) straight-line method to obtain preliminary estimates of aquifer properties before proceeding to more complicated type curve solutions.

- Obtain preliminary estimates of aquifer properties with visual curve matching prior to performing automatic curve matching.

- Use active type curves for more effective visual curve matching with variable-rate tests.

- Match recovery data with residual-drawdown and Agarwal plots.

- Use derivative and diagnostic flow plots to evaluate special conditions such as wellbore storage, radial flow, linear flow and more.

- Superimpose the derivative on plots to match derivative and displacement data simultaneously.

- Apply the slope checking tool to evaluate conditions including wellbore storage, linear flow and boundary effects.

- Adjust curve resolution settings to optimize curve plotting performance.

Curve Matching Tips for Slug Tests

- Use guidelines developed by Butler (1998, Chapter 12) to assist in the analysis of slug tests.

- When using straight-line methods (e.g., Bouwer-Rice, Hvorslev), use the recommended head ranges (Butler 1998) for more effective visual curve matching.

- For straight-line methods (e.g., Bouwer-Rice, Hvorslev), where curve matching relies on your judgement to position the line over the data, visual curve matching is often preferable to automatic curve matching.

- Obtain preliminary estimates of aquifer properties with visual curve matching prior to performing automatic curve matching.

- Control the range of data used in automatic curve matching by defining a match window or by assigning observation weights.

- Use active type curves to match underdamped slug test solutions.

- For type curve solutions (e.g., Cooper et al., KGS Model), you can plot data and curves on either linear-log or log-linear axes.

- If you prefer, you may analyze slug tests using normalized head.

Curve Matching Tips for Constant-Head Tests

- Use the Jacob-Lohman (1952) straight-line method to obtain preliminary

estimates of aquifer properties before proceeding to more complicated type curve solutions.

- Obtain preliminary estimates of aquifer properties with visual curve matching prior to performing automatic curve matching.

- Match recovery data with residual-drawdown and Agarwal plots.

- Limit the number of parameters estimated with automatic curve matching to avoid parameter correlation.

- Superimpose the derivative on plots to match derivative and displacement data simultaneously.

Diagnostic Methods

Derivative Analysis

Derivative analysis, a technique introduced in the petroleum industry (Bourdet et al. 1983; Bourdet et al. 1989), provides a valuable diagnostic tool for aquifer test analysis. In performing derivative analysis, it is common practice to plot drawdown and derivative data on the same graph.

➡ Example: Pumping Test in Confined Aquifer

Obs. Wells
  ▫ Well 1

Aquifer Model
  Confined

Solution
  Theis

Parameters
  T   = 1.014E+4 gal/day/ft
  S   = 2.042E-5
  Kz/Kr = 1.
  b   = 18. ft
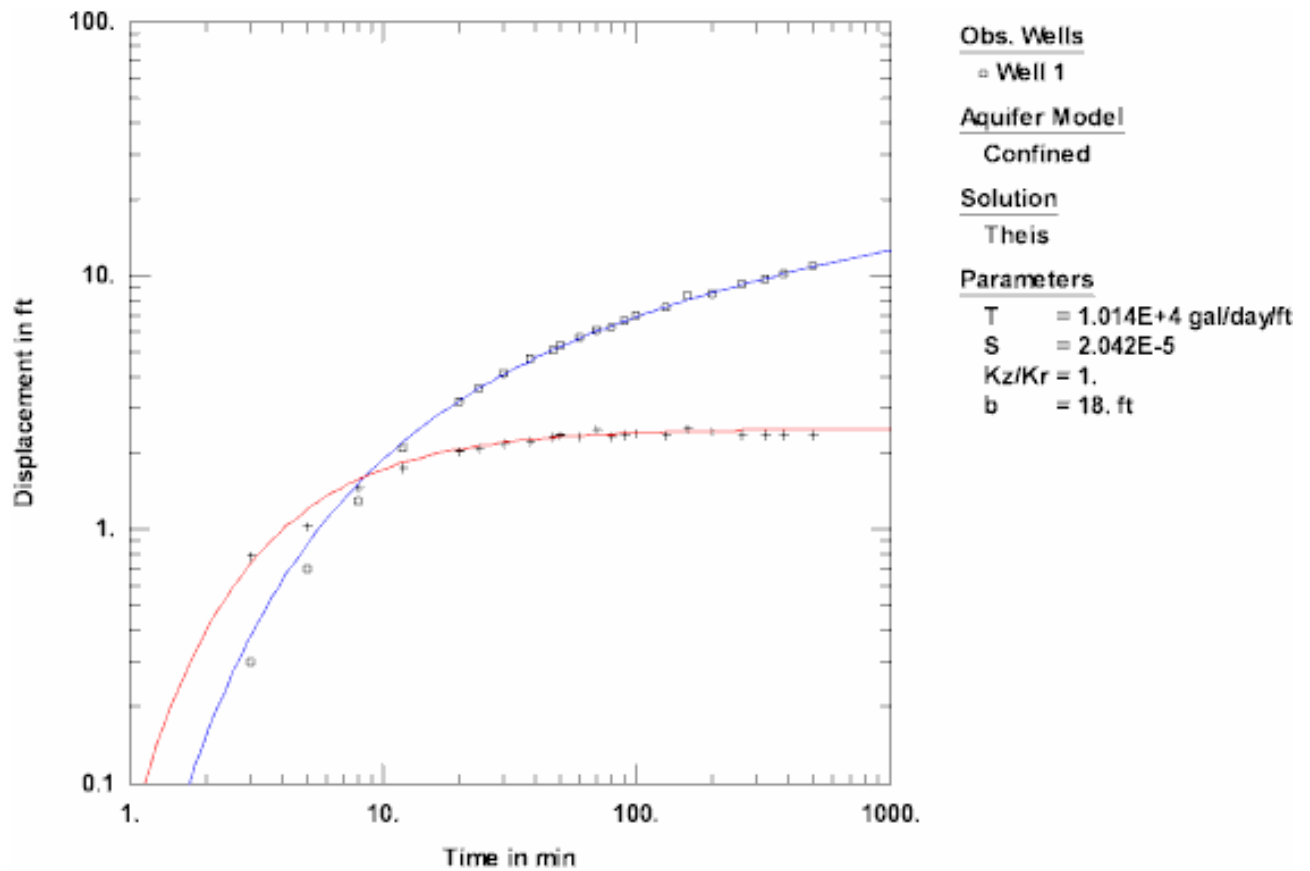
➡ Example: Pumping Test in Leaky Confined Aquifer
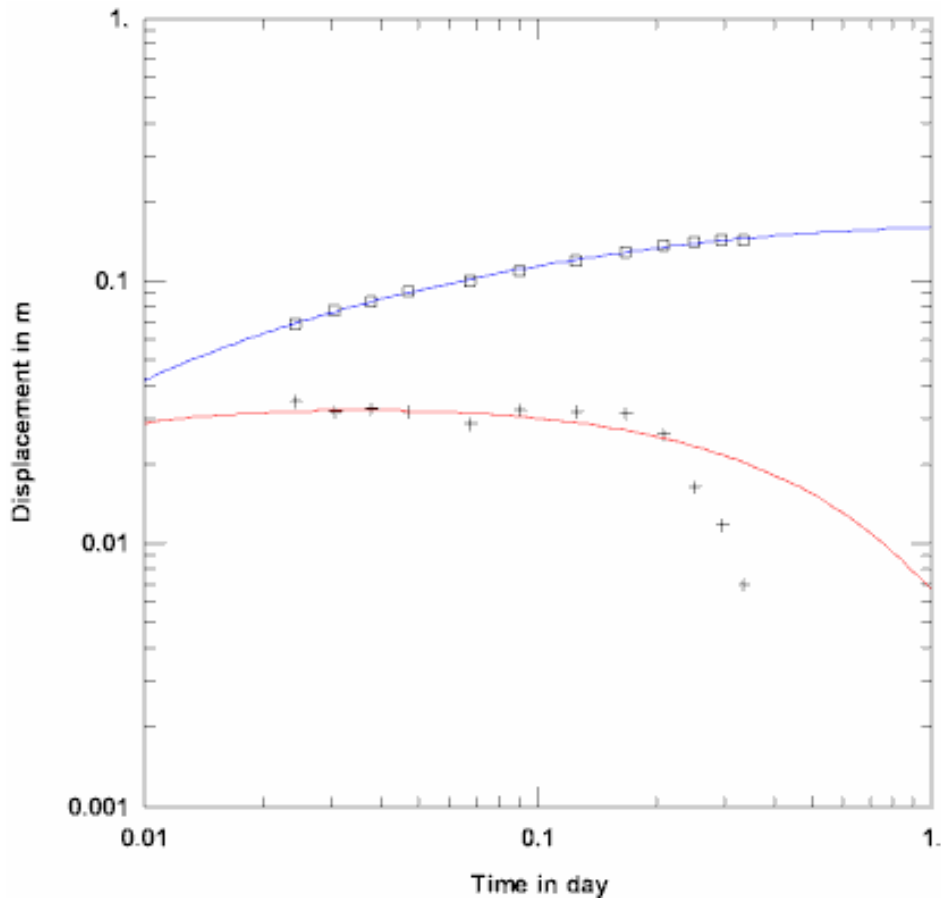
Obs. Wells
□ r=90

Aquifer Model
Leaky

Solution
Hantush-Jacob

Parameters
T   = 1662.3 m^2/day
S   = 0.001785
r/B   = 0.1219
Kz/Kr = 1.
b   = 40. m
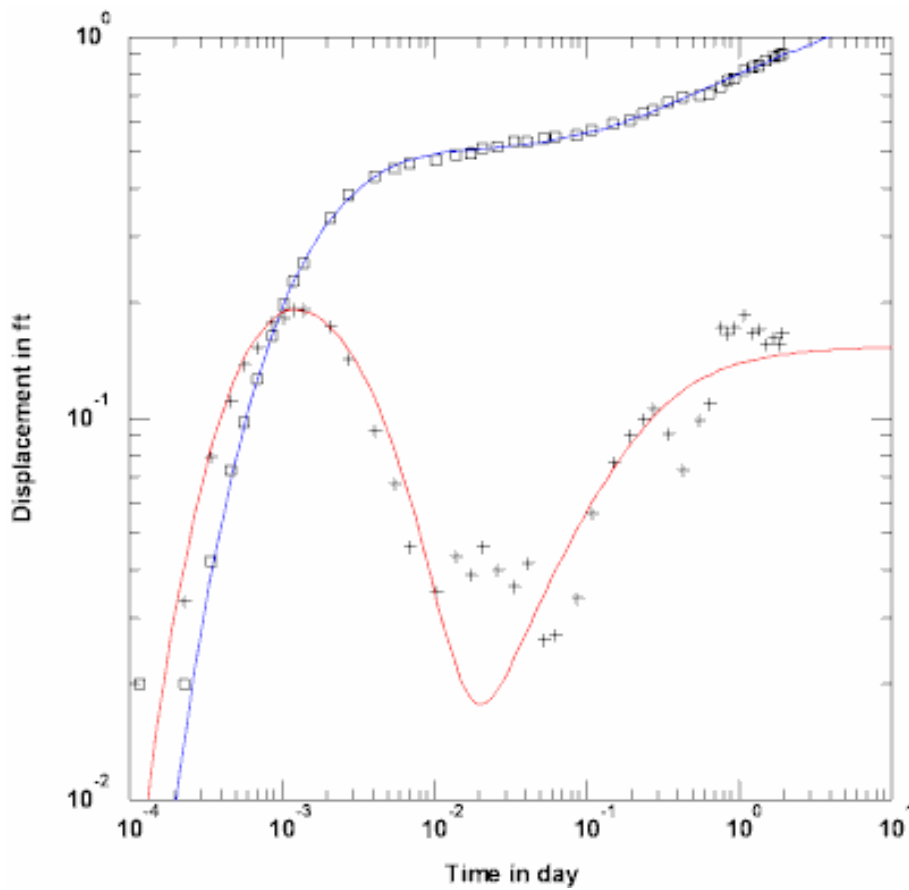
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Example: Pumping Test in Unconfined Aquifer

Obs. Wells
  SA 1072

Aquifer Model
  Unconfined

Solution
  Moench

Parameters
  T   = 1.276E+4 gal/day/ft
  S   = 0.008449
  Sy   = 0.2374
  ß   = 0.1089
  Sw   = 0.
  r(w)   = 0.5 ft
  r(c)   = 0.333 ft
  alpha = 1.0E+30 day^{-1}

Example: Pumping Test in Double-Porosity Aquifer (Multiwell)
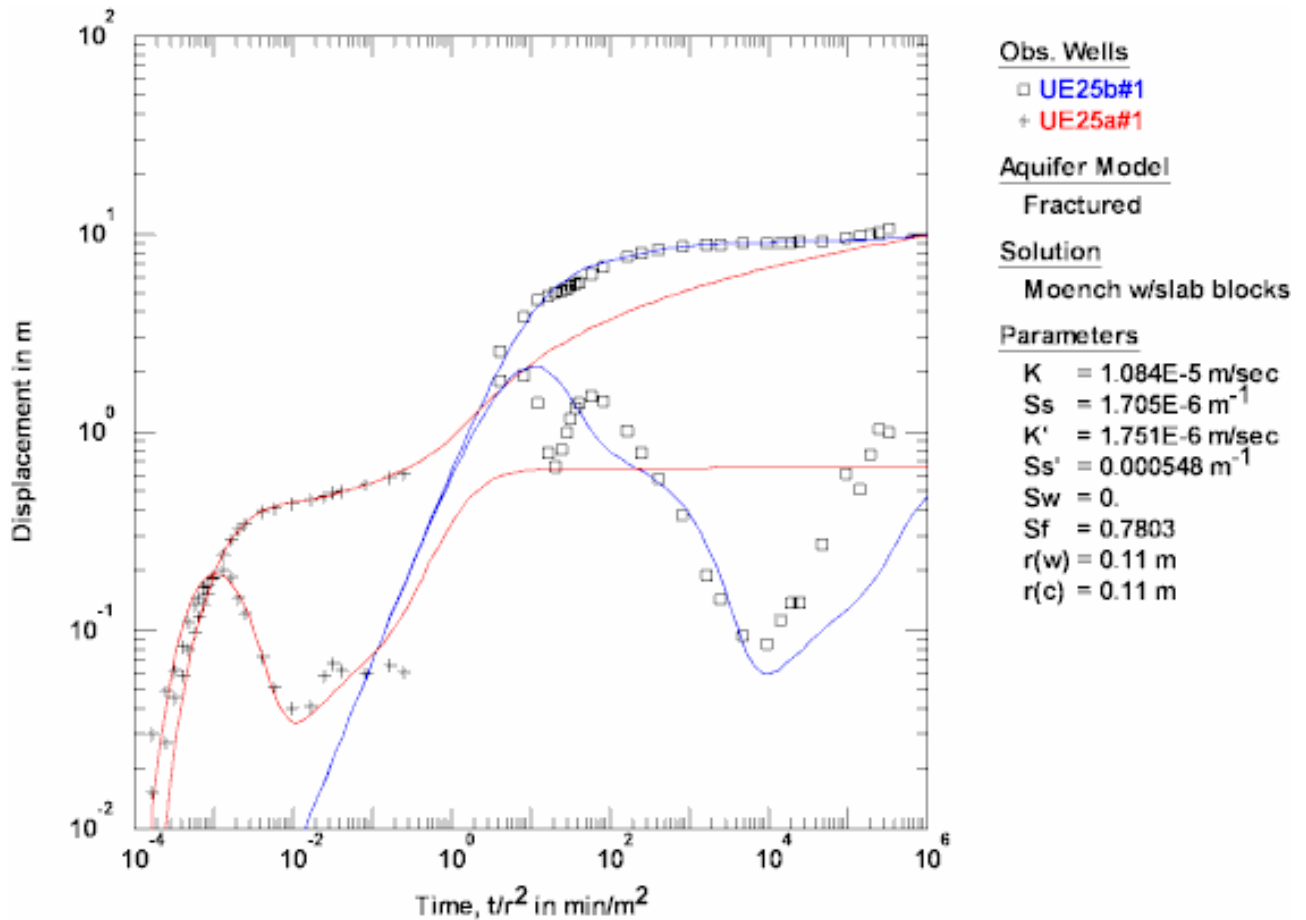
The following simple formula is used to compute the derivative:

$$\left(\frac{\partial s}{\partial \ln T}\right)_i = \frac{(\Delta s_{i-1}/\Delta \ln T_{i-1})\Delta \ln T_{i+1} + (\Delta s_{i+1}/\Delta \ln T_{i+1})\Delta \ln T_{i-1}}{\Delta \ln T_{i-1} + \Delta \ln T_{i+1}}$$

where T is an appropriate time function (e.g., elapsed time or Agarwal equivalent time). Essentially, this formula is a weighted average of slopes computed from data points on either side of data point *i*. In the above formula, the two slopes are

$$\Delta s_{i-1}/\Delta \ln T_{i-1}$$

and

$$\Delta s_{i+1}/\Delta \ln T_{i+1}$$

An important aspect of performing derivative analysis is the selection of an appropriate calculation method. AQTESOLV provides four methods for calculating derivatives from observed data. The default **Nearest Neighbor** option, recommended by Bourdet (2002) for preliminary analysis, often results in noisy derivatives. To remove noise from the calculated derivatives, apply the **Bourdet**,

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Spane or **Smoothing** options as needed.

- o Nearest Neighbor

    - The nearest neighbor option computes the derivative for data point *i* using adjacent data points.

    - Bourdet (2002) recommends using the nearest neighbor option for preliminary derivative analysis.

    - For noise-free, logarithmically spaced data, this method introduces the least amount of smoothing; however, noise in the data often makes this method impractical.

- o Bourdet

    - The **Bourdet method** implements the "preferred" method of Bourdet et al. (1989).

    - This method of calculating the derivative at data point *i* uses data points separated logarithmically in time by a **differentiation interval** "L" that normally ranges between 0.1 and 0.5 log cycles of time (Horne 1995).

    - A smaller differentiation interval is preferred to reduce distortion of the derivative data.

- o Spane

    - The **Spane method** implements the method of Spane and Wurstner (1993).

    - The Spane method of calculating the derivative at data point *i* uses linear regression to compute slopes from all data points falling within a **differentiation interval** "L" that normally ranges between 0.1 and 0.5 log cycles of time.

    - A smaller differentiation interval is preferred to reduce distortion of the derivative data.

- o Smoothing

    - The smoothing method of computing the derivative at data point *i* uses linear regression to compute slopes from a fixed number of data points.

    - This method works well with data spaced geometrically in time (e.g., logarithmic spacing).

    - A smaller number of points (i.e., smaller smoothing factor) is preferred to reduce distortion of the derivative data.

➡ Example: Use of Smoothing

The following figures show the use of AQTESOLV's derivative options for a single-well pumping test (data from the pumped well). Drawdown data are shown in **blue** and derivative data are shown in **red**.

Bourdet (2002) recommends using the **nearest neighbor option** (below) at the outset of derivative analysis. If the derivative appears too noisy, as it often does with high frequency data, apply higher levels of smoothing to clarify the derivative signal.

Nearest Neighbor Option (No Smoothing)
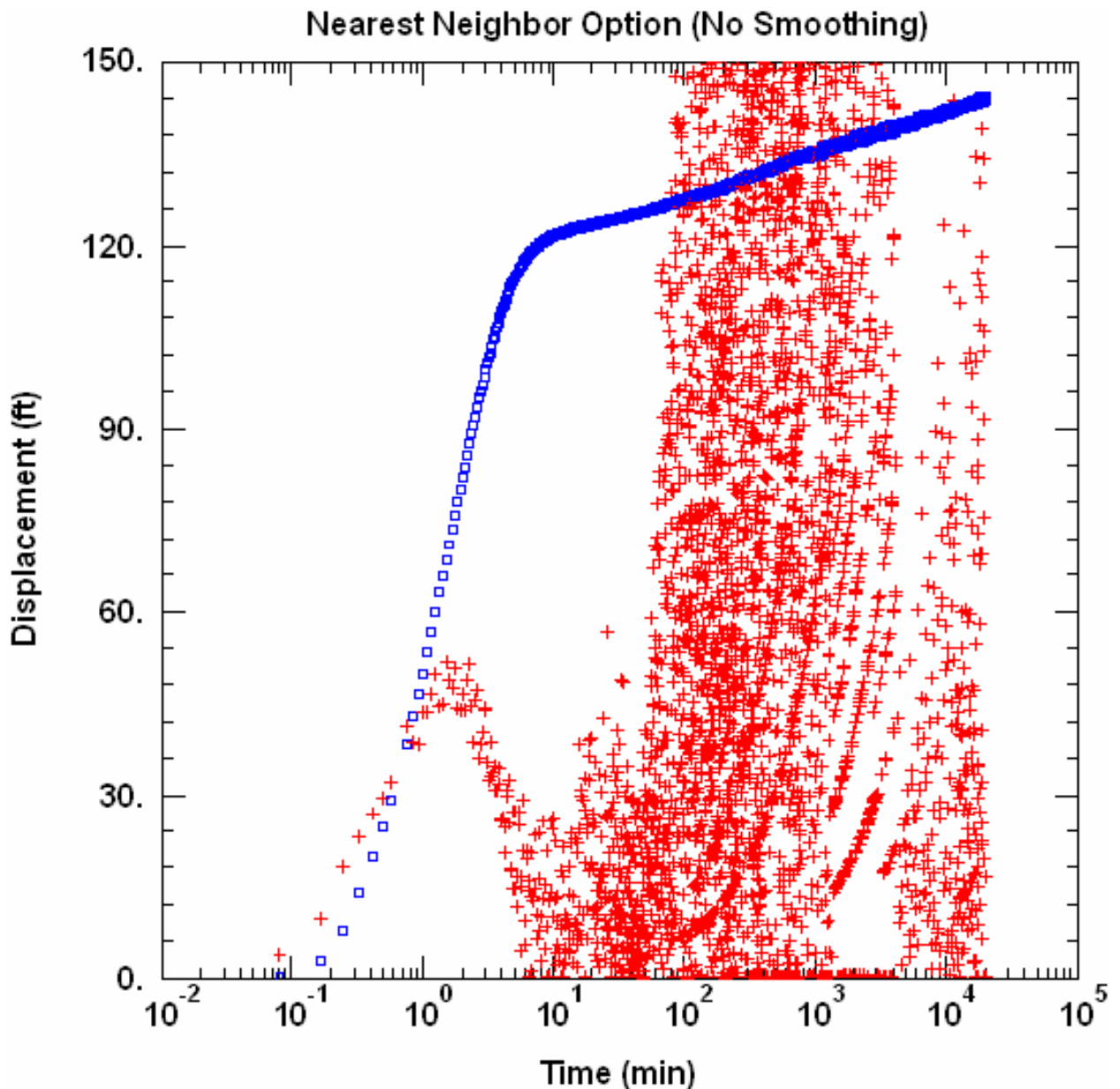
For this data set, one may smooth the derivative data with either the **Bourdet** or **Spane** option to obtain a clear view of the derivative signal (below). The differentiation interval "L" for this example is 0.2; however, a smaller or larger value may be required for some data sets. For this particular data set, the **Smoothing** option is not very effective because the data are spaced linearly rather than logarithmically in time.

Bourdet Option (L = 0.2)

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Spane Option (L = 0.2)
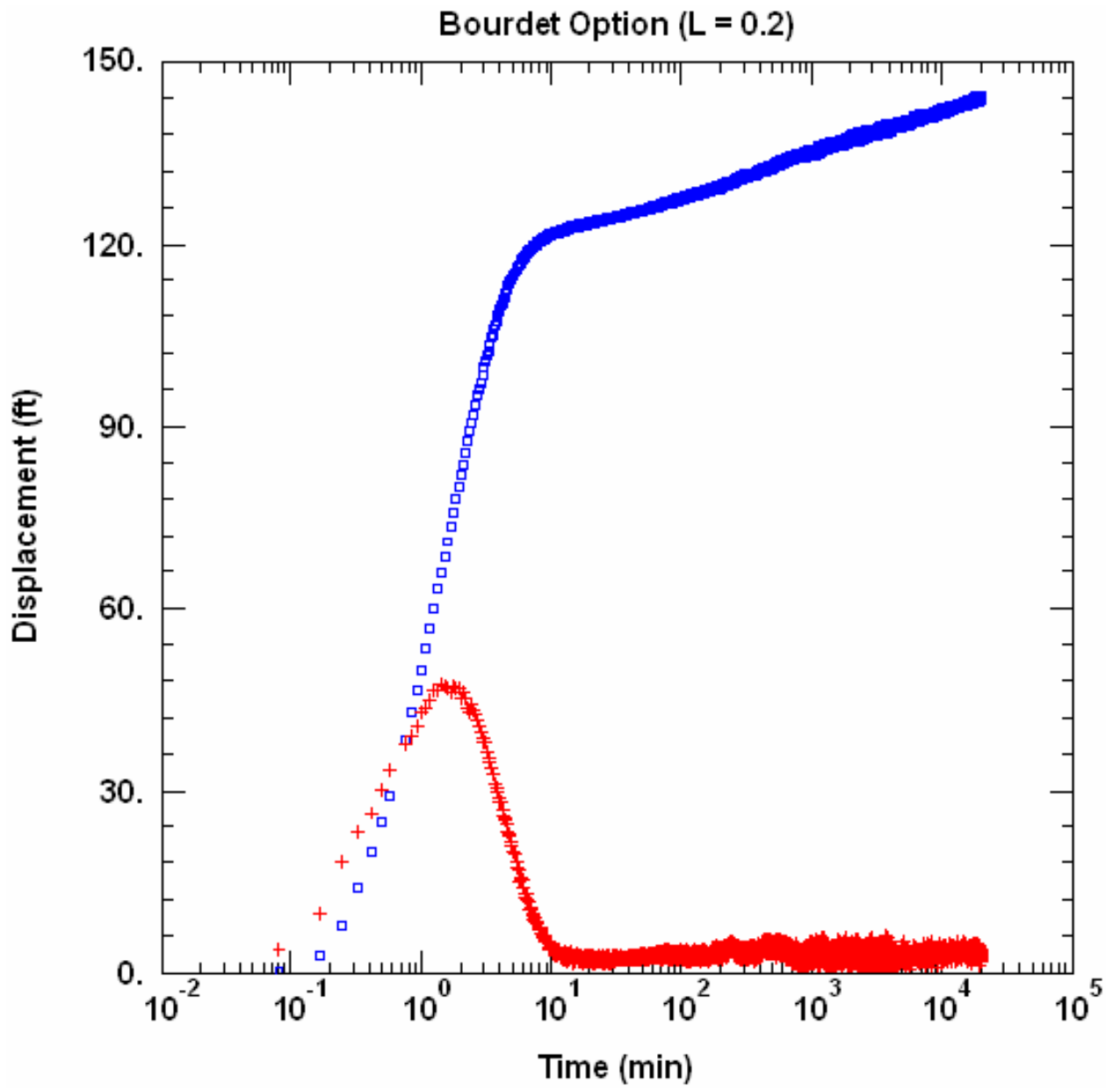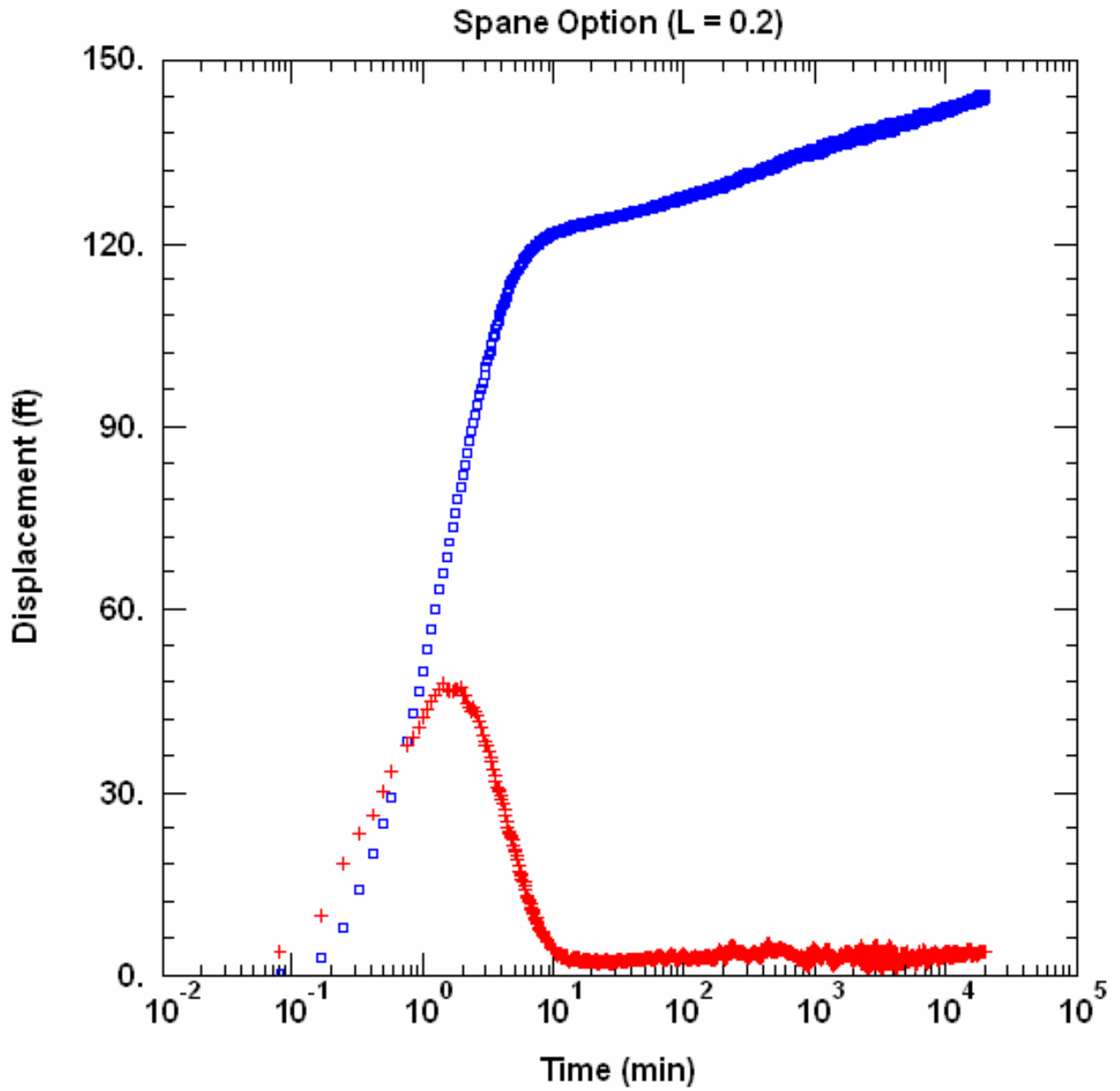
On a plot with log-log axes, more smoothing may be necessary because of the exaggeration of noise on a log scale. For this data set, the **Bourdet** option with L = 0.5 (below) produces a satisfactory plot of the derivative data.

Bourdet Option (L = 0.5)
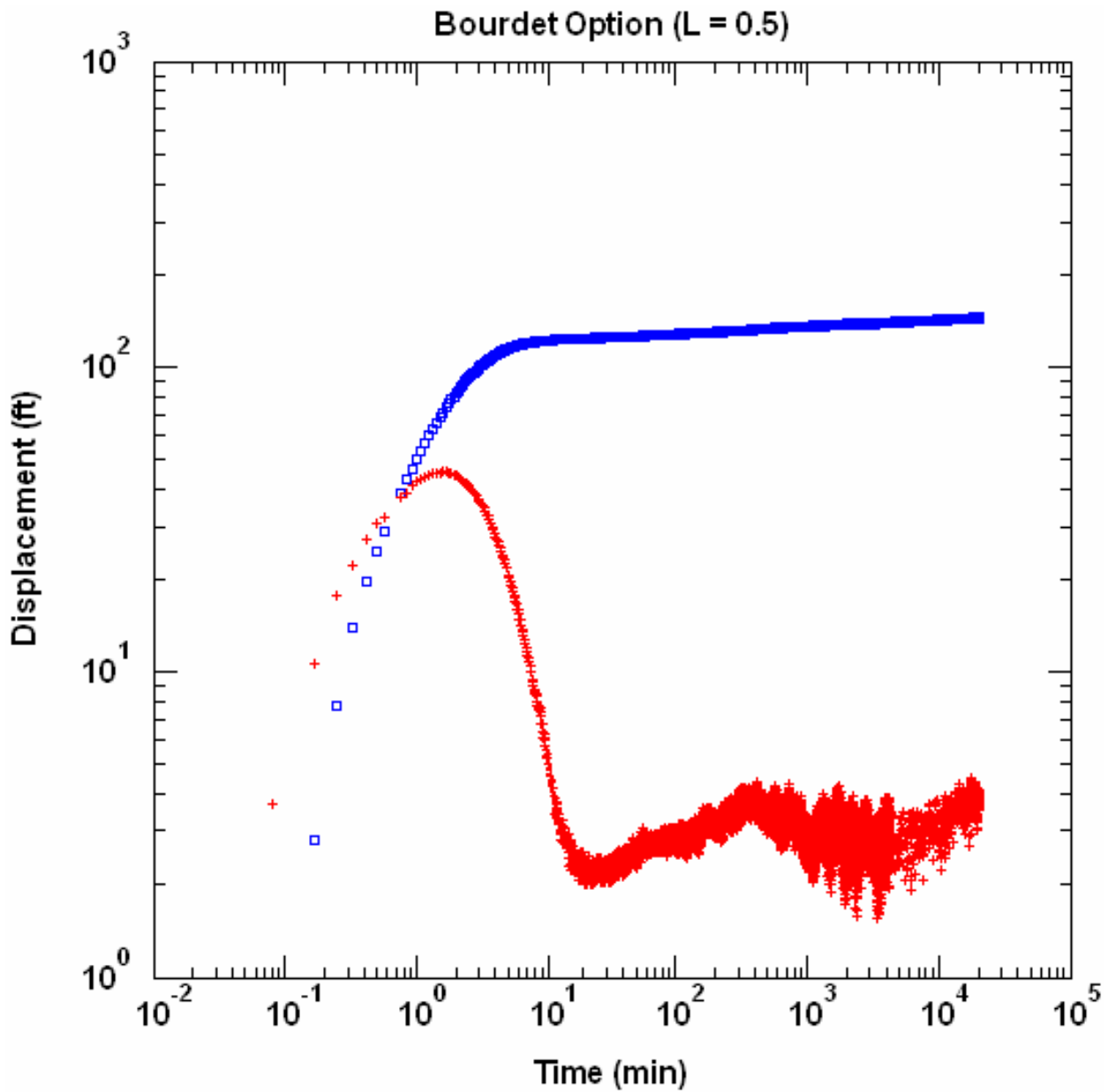
In many cases, an effective strategy for speeding up computations and performing derivative analysis is to filter the number of observations. For example, if 20 points per log cycle time are retained from the original data, we can use the **Bourdet** option with L = 0.5 to observe the same derivative response as the full data set.

Bourdet Option (L = 0.5)
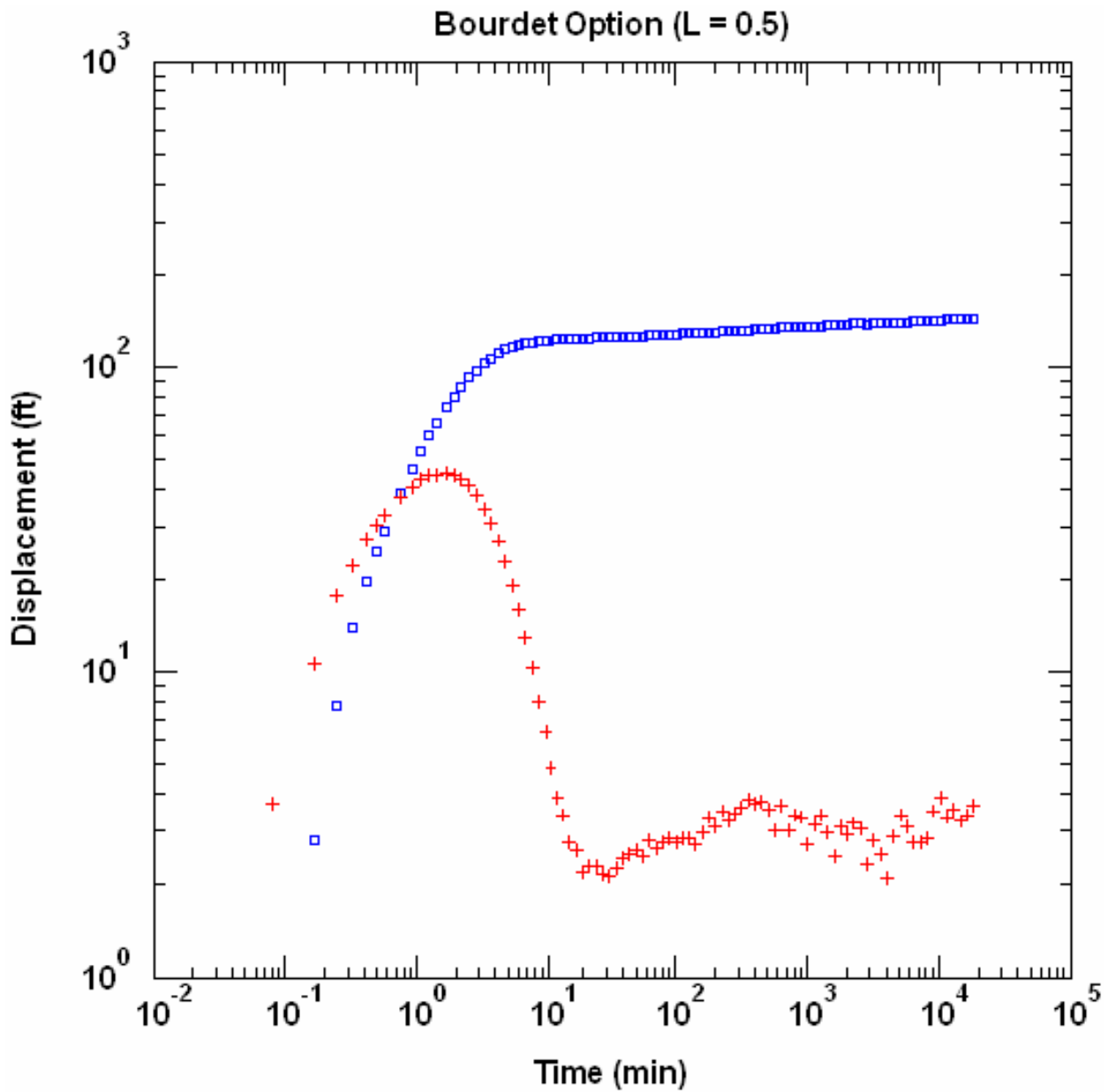
- Choose Options from the **View** menu to select the calculation method for the derivatives.

- Select the **nearest neighbor** method to view the derivative with no smoothing.

- To reduce noise in the computed derivative, choose the **Bourdet**, **Spane** or **smoothing** method.

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- Choose Derivative-Time from the **View** menu to display the derivative as a function of time. Perform visual curve matching using parameter tweaking.

- Select Options from the **View** menu to superimpose the derivative on displacement-time, composite or Agarwal plots. Choose Visual from the **Match** menu to perform visual curve matching.

- Choose Wells from the **Edit** menu to modify derivative symbol and curve properties.

- Find examples of derivative plots in the Quick Start chapter.

Related Topics

Check Slope

(Match > Check Slope)

Choose **Check Slope** from the **Match** menu to test the slope of pumping test or constant-head test data on a semi-log or log-log plot.

Use this option to test the slope of data on plots with semi-log or log axes.

- o Checking the Slope

    1. Click and hold the left mouse button down.

    2. While holding the mouse button down, move the mouse to draw a line over a range of data on the plot.

    3. The slope of the line is displayed in the message pane of the status bar.

- When wellbore storage is present, early-time data on a log-log displacement-time or radial flow plot have a unit slope.

- Assuming a constant-rate test, the slope of data on a log-log displacement-time or radial flow plot approaches the flow dimension when n < 2 (Barker 1988).

- For constant-rate conditions, a single no-flow boundary doubles the slope of data on a semi-log displacement-time or radial flow plot.

- Tracking is disabled when you perform slope checking.

Related Topics

Visual Curve Matching

Overview (Visual Curve Matching)

AQTESOLV provides a suite of tools for interactive visual curve matching that you may use to obtain estimates of aquifer properties.

Visual Curve Matching Procedures

➡️ Type Curve Methods

1. Choose Visual from the **Match** menu.

2. Click and hold the left mouse button down over a point within the plot area.

3. Move the mouse to match the type curve to your data. As you move the type curve, AQTESOLV 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.

   Examples of type curve methods include Theis (1935), Hantush-Jacob (1955) and Neuman (1974) for pumping tests; Cooper et al. (1967), Hyder et al. (1994) and Springer-Gelhar (1991) for slug tests; and Jacob-Lohman (1952), Hantush (1959) and Barker (1988) for constant-head tests.

➡️ Straight-Line Methods

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 draws 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 automatically updates the plot legend to reflect changes in parameter values.

   Examples of straight-line methods include Cooper-Jacob (1946) and Theis (1935) residual drawdown for pumping tests; Bouwer-Rice (1976) and Hvorslev (1951) for slug tests; and Jacob-Lohman (1952) for constant-head tests.

- Use visual curve matching to obtain preliminary estimates of aquifer

properties prior to performing automatic curve matching.

- For pumping tests, use the Cooper-Jacob straight-line method to obtain preliminary estimates of aquifer parameters before applying more complicated solution methods.

- Use active type curves to perform more effective visual curve matching for variable-rate pumping tests, recovery tests, multi-well pumping and slug tests, and slug tests with oscillatory response.

- Quickly select type curve families on the toolbar.

- Adjust individual aquifer properties using parameter tweaking.

Related Topics

Active Type Curves

Choose **Active Curves** from the **Match** menu or click 🐾 on the toolbar to toggle the active type curves feature and simultaneously initiate visual curve matching.

The **Active Type Curves** feature is an enhanced method of performing visual curve matching introduced by AQTESOLV. With active type curves, the program automatically refreshes the complete type curve as you perform visual curve matching.

Apply **Active Type Curves** for effective visual curve matching in the following situations:

- **pumping tests** with variable pumping rates

- **pumping tests** with early- and late-time response such as delayed gravity response or double porosity effects (see Matching Early/Late Data)

- **slug tests** with oscillatory response (i.e., solutions with inertial effects in high-K aquifers)

Related Topics

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.
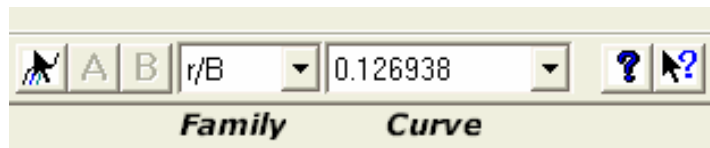
1. Select an aquifer parameter for a type curve family from those available in the **Family** list on the toolbar.

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. To format curve families, select Format from the **View** menu and click the **Family** tab.

5. The controls for the **Family** and **Curve** lists on the toolbar appear inactive when type curve families are not available for the active solution.

Related Topics

Matching Early/Late Data

Certain aquifer test solutions involve aquifer parameters that affect early- or late-time response.

For example, visual curve matching with the Neuman (1974) solution for a pumping test in an unconfined aquifer involves matching **Type A** curves to early-time data and **Type B** curves to late-time data. The final match of the **Type A** curve determines the values of **T**, **S** and β; the **Type B** curve determines **T**, **S$_y$** and β.

How To Match Early- or Late-Time Data

1. Click **Match Early Data** A on the toolbar to toggle the Type A option and simultaneously initiate visual curve matching.

2. Click **Match Late Data** B on the toolbar to toggle the Type B option and simultaneously initiate visual curve matching.

➡ Solutions Using Early/Late Visual Matching

1. Neuman (1974) pumping test solution for unconfined aquifers

2. Neuman-Witherspoon (1969) pumping test solution for leaky aquifers

3. Moench (1984) pumping test solution for fractured aquifers with slab-shaped blocks

4. Moench (1984) pumping test solution for fractured aquifers with spherical blocks

- Use active type curves in conjunction with Type A and Type B visual curve matching.

- You also may choose Match>Toolbox>Options to set the Type A and Type B options.

[Related Topics]

Parameter Tweaking

(Match > Toolbox > Tweak)

Choose Toolbox from the **Match** menu and click the **Tweak** tab to adjust the values of individual aquifer parameters. Use this tool for visual curve matching and sensitivity analysis.

Tweaking Parameters

1. Select an aquifer parameter to adjust from the **Parameter** list.

2. Tweak the value of the selected aquifer parameter using the scroll bar control.

3. Click **Apply** to refresh all plots.

4. Check **Apply changes automatically** so you don't have to click the **Apply** button when you tweak a parameter value.
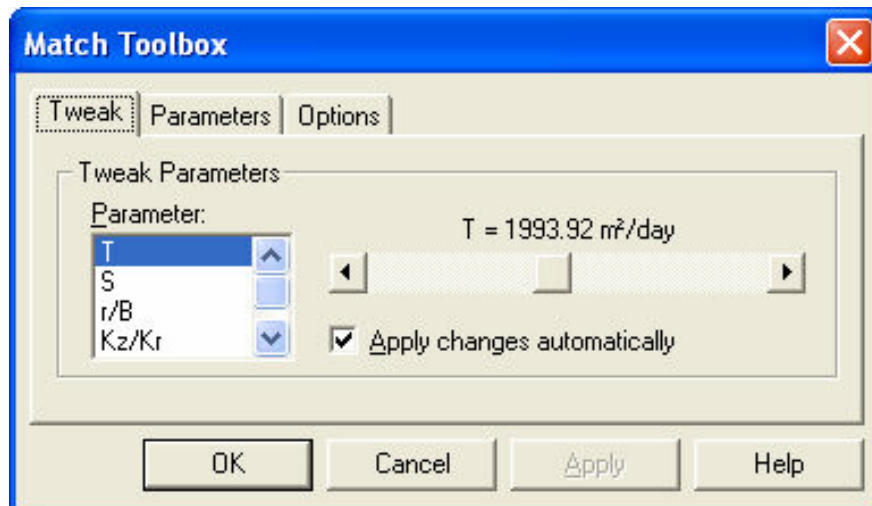
- Click the Parameters tab to adjust the range (minimum and maximum) of the parameter that you are tweaking. Enter a smaller range to make finer tweaking adjustments.

[Related Topics]

Overview (Automatic Curve Matching)

AQTESOLV's automatic curve matching feature uses a nonlinear least squares procedure to match solutions (type curves and straight lines) to data from an aquifer test. Through a sequence of iterations, the program systematically adjusts the values of hydraulic properties to achieve the best statistical match between a solution and your test data. Each iteration seeks to minimize the sum of squared residuals. By defining convergence tolerances, you control when iterations terminate.

- To control the iterative automatic curve matching procedure, you can define the maximum number of iterations and convergence criteria.

- To hold parameter values constant during automatic estimation, you may declare a set of inactive parameters.

- Choose a set of active wells to limit automatic curve matching to selected observation wells.

- Define a time window for automatic estimation to match a type curve or straight line to a desired range of data.

- Assign weights to individual observations or select a weighting method to control automatic curve matching.

- Use visual matching to improve starting guesses for the automatic curve fitting procedure.

Related Topics

How Automatic Curve Matching Works

AQTESOLV 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 includes the Marquardt damping parameter (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:

$$y_i = \hat{y}_i + \frac{\partial y}{\partial b}\Delta b + \frac{\partial^2 y}{2!\partial^2 b}(\Delta b)^2 + \frac{\partial^3 y}{3!\partial^3 b}(\Delta b)^3 \ldots$$

where:

y_i = ith observed value of response variable

$\hat{y}_i$ = estimate of y_i

Δb = parameter correction, $\hat{b}^1 - \hat{b}^0$

$\hat{b}^1$ = updated estimate of unknown parameter

$\hat{b}^0$ = previous estimate of unknown parameter

The previous equation can be linearized by truncating the Taylor series after the first derivative as follows:

$$y_i \cong \hat{y}_i + \frac{\partial y}{\partial b} \Delta b$$

Thus, for p unknown parameters, the general linearized equation for computing parameter corrections is written as follows:

$$y_i \cong \hat{y}_i + \sum_{k=1}^{p} \frac{\partial y_i}{\partial b_k} \Delta b_k$$

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**. When a parameter is insensitive, its sensitivity coefficients will approach zero. You can choose a method for calculating the sensitivity coefficients in the advanced options for automatic estimation.

The resulting system of linearized equations is solved iteratively until convergence is obtained. The objective function for this minimization problem is the residual sum squares (RSS) 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:

ΔB = p x 1 vector of parameter corrections

X = n x p matrix of sensitivity coefficients

X^T = p x n transpose of X

$X^T X$ = p x p variance-covariance matrix

ΔY = n x 1 vector of residuals $(y_i - \hat{y}_i)$

To improve the conditioning of the $X^T X$ variance-covariance matrix, AQTESOLV adds the Marquardt damping parameter to the previous equation:

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$$\Delta B = (X^T X + \lambda \cdot I)^{-1} X^T \Delta Y$$

where:

λ = Marquardt correction factor

I = identity matrix

AQTESOLV also uses scaling of the variance-covariance matrix to improve the conditioning of the procedure (Bard 1970).

A well-conditioned variance-covariance matrix has a small condition number. Large condition numbers can result from poor starting guesses and lead to slow convergence, or even divergence, of the iterative parameter updating procedure; in these situations, **singular value decomposition**, an advanced estimation option, can improve convergence of the procedure.

AQTESOLV adds the Marquardt damping parameter when parameter corrections computed by the Gauss-Newton method fail to reduce the RSS. Iterations performed with the Marquardt damping parameter start with a sufficiently small value of lambda; larger values of lambda are applied until the RSS is reduced. As iterations continue and the objective function approaches a minimum, AQTESOLV reduces lambda for faster convergence. You can control the lambda updating method in the advanced options for automatic estimation. The parameter estimation algorithm terminates when user-defined convergence criteria are met.

Weighted least-squares estimation is accomplished as follows:

$$\Delta B = (X^T W X)^{-1} X^T W \Delta Y$$

where:

W = n x n nonsingular symmetric matrix of weights obtained from $\omega^T \omega$

ω = n x n diagonal matrix of weights

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.

AQTESOLV determines variances of the estimated parameters as follows:

$$Var(\hat{b}) = (X^T \omega X)^{-1} \sigma_e^2$$

The standard errors of the estimated parameters are given by the square root of the main diagonal elements of the $(X^T \omega X)^{-1} \sigma_e^2$ matrix.

Correlations between the individual parameters are determined from the following equation:

$$r_{ij} = \frac{Cov(\hat{b}_i, \hat{b}_j)}{\sqrt{Var(\hat{b}_i)Var(\hat{b}_j)}}$$

where the variance and covariance terms are components of $(X^T \omega X)^{-1} \sigma_e^2$.

Related Topics

Parameter Statistics

Confidence Interval

Using the results from automatic curve matching, one can construct an approximate confidence interval under the assumptions that the model is linear in the neighborhood of the minimum of the objective function and the errors are normally distributed:

$$\hat{b}_i \pm t(\alpha/2, n-p) s.e.(\hat{b}_i)$$

where

- $\hat{b}_i$ is the estimate of ith parameter

- $t(\alpha/2, n-p)$ is the probability points of the Student t distribution with α level of significance and n-p degrees of freedom

- $s.e.(\hat{b}_i)$ is the standard error of the ith estimated parameter

AQTESOLV uses the above formula to report 95% confidence interval for parameters.

When the degrees of freedom (n-p) is large, the 95% (1-α) confidence interval may be conveniently approximated as follows (Draper and Smith 1981):

$$\hat{b}_i \pm 2 s.e.(\hat{b}_i)$$

Significance Test

One can perform an approximate test of whether the true value of a parameter is equal to a specific value β_* by comparing the following quantity (t-ratio):

$$t = \frac{\hat{b} - \beta_*}{s.e.(\hat{b})}$$

to a table of Student's t distribution with n-p degrees of freedom.

For example, if n-p is large and one wishes to test whether b is different from zero at the $\alpha = 0.05$ level of significance, one would reject the null hypothesis (i.e., b = 0) when the t-ratio 2, where 2 is the approximate critical t-value when the degrees of

Residual Statistics

A **residual**, e, is the difference between an observed value and its estimated (simulated) value:

$$e_i = y_i - \hat{y}_i$$
$$y_i = \text{ith observation}$$
$$\hat{y}_i = \text{estimate of } y_i$$

The objective function that is minimized during automatic curve matching is the **sum of the squared residuals** (RSS) given by the following expression:

$$RSS = \sum_{i=1}^{n} e_i^2$$

where n is the total number of observations.

The **residual variance** and **standard deviation** are defined as follows:

$$\sigma_e^2 = \frac{RSS}{n - p}$$

$$\sigma_e = \sqrt{\frac{RSS}{n - p}}$$

where p is the number of estimated parameters.

Finally, we compute the **residual mean** using the following formula:

$$\bar{e} = \frac{\sum_{i=1}^{n} y_i - \hat{y}_i}{n}$$

Automatic curve matching seeks to minimize the residual sum of squares, residual variance and standard deviation and obtain a residual mean close to zero.

Related Topics

Tips for Automatic Curve Matching

Starting Guesses

Improve the performance of automatic parameter estimation by developing

reasonable preliminary estimates of aquifer properties from site-specific data and literature values (e.g., hydraulic conductivity). Refine the starting guesses using visual matching before proceeding to automatic curve matching.

Windows and Weights

You may control automatic curve matching using the match window and observation weighting features in AQTESOLV.

A match window defines a range of time for automatic curve matching. With the window active, AQTESOLV matches the solution to observations within the window; observations outside the time range of the window are excluded from the fitting procedure. For example, you could assign a match window to exclude recovery data and match only pumping data.

Two weighting options are available in AQTESOLV.

1. You may assign weights to individual observations. A weight of zero excludes the observation from automatic curve matching; a larger weight increases the importance of the observation in the fitting process. For example, you could assign a weight of zero to observations known to have large measurement error.

2. Alternatively, you may select a weighting method that applies to all active observations in all active wells. For example, the weighting schemes are useful for multiwell tests when the response data differ markedly in magnitude between observation wells.

Conditioning

Automatic parameter estimation performs better when the covariance matrix (X^TX) formulated for the nonlinear least-squares algorithm is well conditioned (i.e., has a small condition number). Convergence difficulties often are the result of a covariance matrix having a large condition number.

In many cases, you can reduce the condition number of the covariance matrix and improve automatic estimation performance by employing the strategies outlined below.

1. Determine if the model (solution) is appropriate. Trying to match an inappropriate model can lead to convergence problems. A model with fewer parameters may be more appropriate.

2. Use visual matching to improve the starting guesses of model parameters (hydraulic properties) as much as possible. Even a crude visual match that moves the solution curve over the data may be sufficient to overcome difficulties associated with ill conditioning.

3. Match a subset of the solution parameters by fixing (holding constant) the values of insensitive parameters. During automatic estimation, the values of insensitive parameters tend to fluctuate greatly between iterations.

    For example, if you matching the Neuman solution to pumping test data that do not exhibit the expected late-time behavior of an unconfined aquifer with delayed gravity response, you will not be able to match specific yield (Sy)

with any precision. In this case, you could fix the value of Sy at an appropriate value (e.g., 0.1 or 0.2) and match the remaining hydraulic properties in the solution with automatic estimation.

In some instances, the sensitivity of certain parameters may increase as the objective function is minimized. After performing a sequence of iterations with a set of fixed parameter values, you may choose to attempt additional iterations with all parameters active to improve the fit of the solution.

As an alternative to manually holding parameters constant, you can employ singular value decomposition to improve conditioning (see below).

4. Try a different updating method for the Marquardt lambda parameter. A more conservative scheme may take more iterations to converge, but avoid problems sometimes caused by overshoot (parameter corrections that are too large) during the iterative automatic estimation procedure.

5. Apply SVD (singular value decomposition) to improve convergence from poor starting guesses.

SVD dampens the corrections of parameters with small eigenvalues in the parameter updating equations, thereby decreasing the condition number of the covariance matrix. AQTESOLV performs this procedure when a parameter's eigenvalue, π_i, meets the following test:

$\pi_i \quad |\pi_{max}|/CTOL$
where CTOL is the condition number threshold criterion set in the advanced options for automatic estimation.

Obtaining Output

Printing

Overview (Printing)

Choose options from the File menu to send the active plot or report to a printing device connected to your computer.

Print	Print the plot or report in the active window
Print Preview	Preview the plot or report before printing
Print Setup	Configure printer options
Page Setup	Format the page for printing
Batch Print	Batch print a group of data sets

- To customize the appearance of a plot or report for printing, choose View>Format.

- You can change to font size for a plot legend to fit more information on one page.

- As an alternative to printing, you may copy a plot or report and paste it into another Windows application.

Print

(File > Print)

Choose **Print** from the **File** menu or click on the toolbar to open a dialog for printing the plot or report in the active window.

- Click **Setup** or **Properties** to configure the selected printer.

- If the legend of a plot does not fit on one page, choose View>Format>Legend tab to decrease the font size.

Print Preview

(File > Print Preview)

Choose **Print Preview** from the **File** menu or click 📄 on the toolbar to preview the appearance of a plot or report prior to printing.

- While previewing, click **Print** to print the plot/report or **Close** to end print preview without printing.

- If the legend of a plot does not fit on one page, choose View>Format>Legend tab to decrease the font size.

Related Topics

Print Setup

(File > Print Setup)

Choose **Print Setup** from the **File** menu to open a dialog for selecting and configuring a printer connected to your computer.

Related Topics

Page Setup

(File > Page Setup)

Choose **Page Setup** from the **File** menu to configure page options for report headers and footers and other page customization features.

- o Margins Tab

    1. Enter values (in inches) for the margins of printed pages of plots and reports.

- o Print Tab

    1. Select options to customize the printing of plots and reports.

    2. If the y-axis label is not rotated when you print a plot, check **Force font rotation of y-axis label on plots**. If the font is still not rotated after selecting this option, your printer does not support font rotation.

Related Topics

Batch Print

(File > Batch Print)

Choose **Batch Print** from the **File** menu to launch the **Batch Print Wizard** for printing a group of AQTESOLV data sets at one time.

Batch Print Wizard

➡️ Step 1
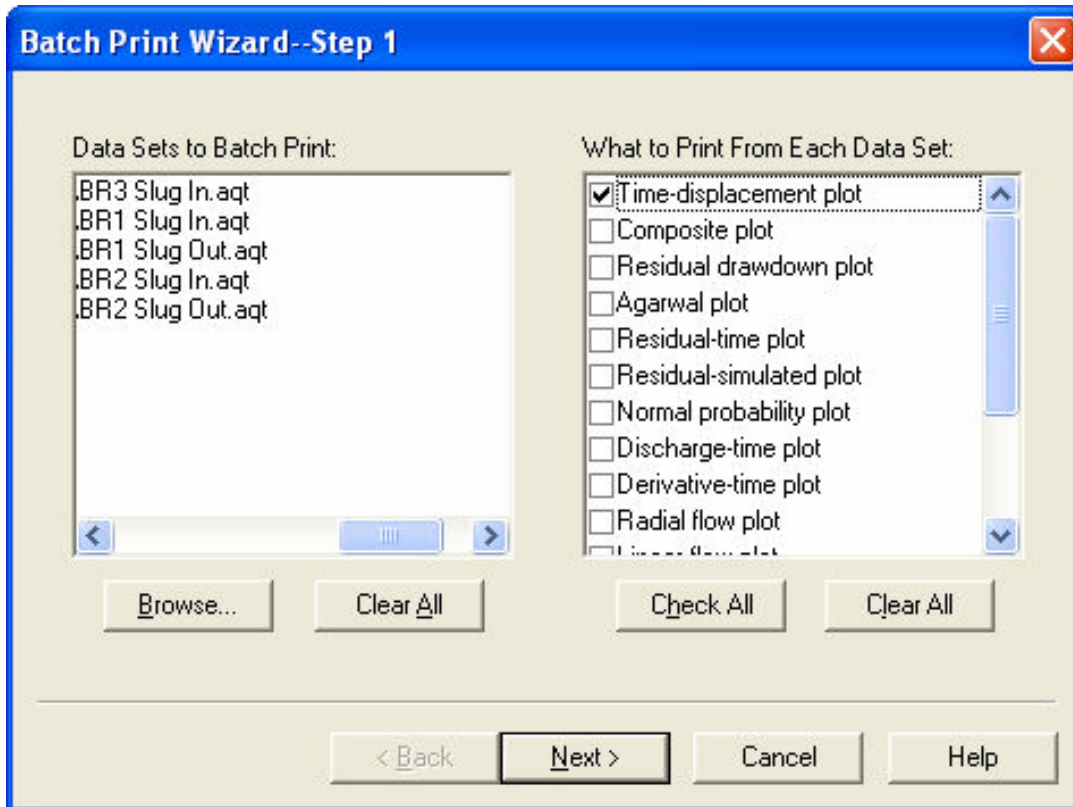
1. In Step 1 of the wizard, click **Browse** to select a group of AQTESOLV data sets to batch print.

2. Place a check next to each plot or report that you want to print from each data set.

3. Click **Next**.

Step 2
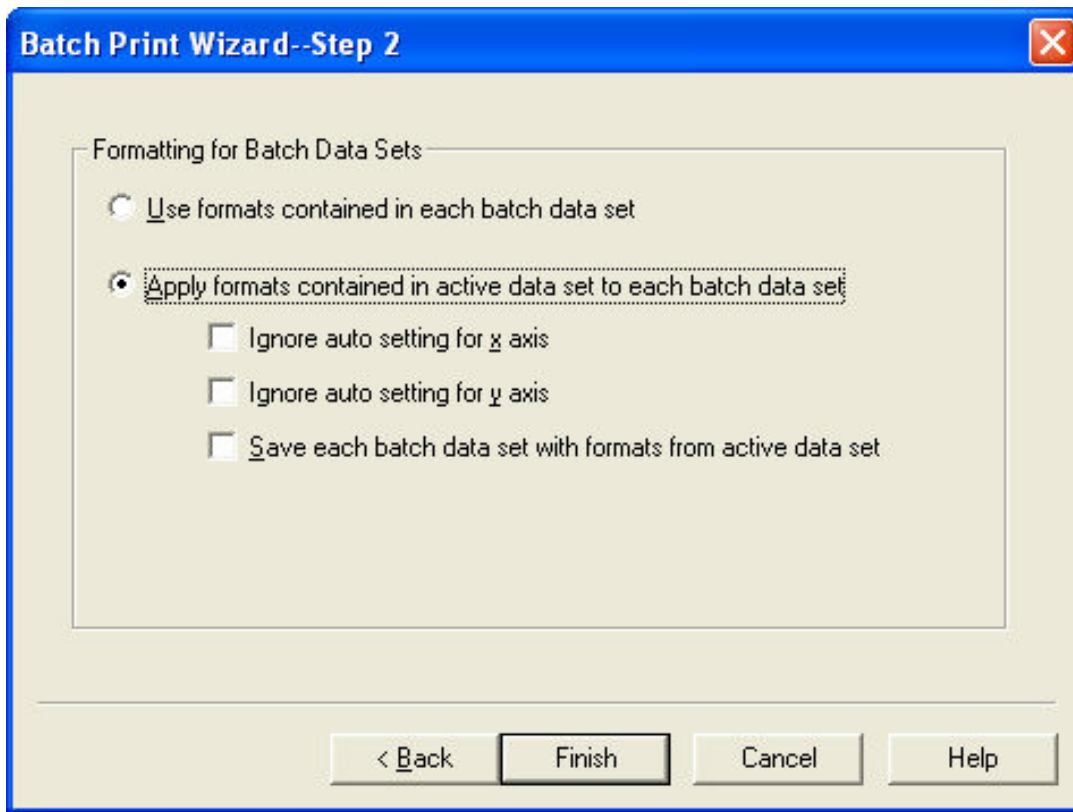
1. In Step 2 of the wizard, choose a formatting option for the data sets that you are batch printing. You may use (a) formats contained in the individual data sets without changes or (b) formats from a "master" data set to reformat all of the data sets.

2. You can use the active data set (the data set in the active window) to apply a consistent set of formats to each printed plot or report.

3. Check **Save each batch data set with formats from active data set** if you would like to save a *copy* of each batch data set with the consistent formats. The formats in original files are not changed.

4. Click **Finish**.

- If you would like to print a group of data sets with a consistent set of formats, first open a "master" data set from the group. Make any formatting changes in the master data set before selecting **Batch Print** (do not close the master data set).

Related Topics

Tips for Printing

- Decrease the font size of the legend text to fit more information on one page when printing a plot.

- Use Print Preview to inspect the layout of a plot before printing.

- Set page orientation (portrait or landscape) with Print Setup.

Contouring

Overview (Contouring)

Use AQTESOLV to create contour plots of observed and simulated drawdown from an aquifer test.

- To create a contour plot of simulated drawdown, choose View>Contour to launch the Grid Wizard. AQTESOLV provides a seamless link for automatically generating contour plots with Surfer.

- To export data for generating a contour plot of observed data, choose File>Export and select the option to export well data. You may imported the exported file into contouring packages such as **Surfer**.

Contour

(View > Contour)

Choose **Contour** from the **View** menu or click 🔲 on the toolbar to launch the Grid Wizard which prepares a grid file for contouring and optionally creates a contour plot using Surfer (version 6 or higher).

🔲 TIPS

- Right-click over a plot to select **Grid/Contour**.

- For bounded aquifers, enter grid dimensions within the specified boundaries.

Related Topics

Grid Wizard

Use the **Grid Wizard** to prepare a grid file for contouring. If you have **Surfer** (version 6 or higher) installed on your computer, AQTESOLV can automatically display a contour plot for you.

Using the Grid Wizard

1. Choose **Contour** from the **View** menu or click 🔲 on the toolbar to launch the **Grid Wizard**.

2. Follow the steps in the wizard: open the grid file, specify the grid dimensions and display the contour plot.

🔲 TIPS

- You can use the **Grid Wizard** to create a grid file without having **Surfer**

installed on your computer. Use grid files to prepare plots with contouring applications such as Surfer, Tecplot and RockWorks.

- The **Grid Wizard** requires that you enter values greater than zero for casing radius and wellbore radius for each pumping well.

Related Topics

Exporting and Sharing Data

Overview (Exporting and Sharing Data)

Choose options from the File menu to export and share data.

Export	Export data to files
Send Mail	Send the active data set as an email attachment

- You can print a plot or report or you may copy it to the Windows clipboard and paste it into another Windows application.

- Use AQTESOLV to contour simulated drawdown with the automated link to Surfer.

Export

(File > Export)

Choose **Export** from the **File** menu to export data in file formats suitable for use in other programs.

X-Y Plot Data	Export data shown on a plot (e.g., time and drawdown) into a tab-delimited text file.
Well Data	Export well coordinates, observed drawdown and simulated drawdown data for a specified time into a text file. • Data are exported as comma-separated values (CSV). • Four values are exported for each observation well: X coordinate; Y coordinate; observed drawdown; simulated drawdown. AQTESOLV automatically interpolates or extrapolates observed drawdown for the specified time as required.
Type Curve (dimensional)	Export type curve data (e.g., time and simulated drawdown) into a tab-delimited text file. Values are dimensional (e.g., seconds and meters).
Type Curve (dimensionless)	Export dimensionless type curve data (e.g., time and simulated drawdown) into a tab-delimited text file.
Windows Metafile	Export a plot or report as a placeable

	Windows metafile (.wmf).
Enhanced Windows Metafile	Export a plot or report as an enhanced Windows metafile (.emf).

- You can import a **Windows metafile** created with AQTESOLV into other applications such as Microsoft Office (Word, Excel, PowerPoint, etc.).

- You also may use AQTESOLV to copy a plot or report to the clipboard and paste it into another Windows application.

Send Mail

(File > Send Mail)

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

Related Topics

Tools

Overview (Tools)

The Tools menu provides options for performing special tasks such as groundwater mounding calculations and running related Windows applications such as ModelCad for Windows, TWODAN and WinSitu.

Mounding

(Tools > Mounding)

Choose **Mounding** from the **Tools** menu to select options for predicting the transient water table rise beneath circular and rectangular recharge areas.

- Open a new or existing data set to access this tool.

Related Topics

ModelCad

(Tools > ModelCad)

Choose **ModelCad** from the **Tools** menu to launch the ModelCad for Windows application, if installed on your computer. ModelCad for Windows is a modeling environment for groundwater flow and solute transport simulator such as MODFLOW/MT3D.

- To configure this application, select Tools>Customize.

- Find out more about the ModelCad for Windows software at our web site.

TWODAN

(Tools > TWODAN)

Choose **TWODAN** from the **Tools** menu to launch the TWODAN application, if installed on your computer. TWODAN is a two-dimensional analytic element groundwater flow model.

- To configure this application, select Tools>Customize.

- Find out more about the TWODAN software at our web site.

WinSitu

(Tools > WinSitu)

Choose **WinSitu** from the **Tools** menu to launch the WinSitu application, if installed on your computer. The WinSitu software works in concert with In-Situ data logger products.

- To configure this application, select Tools>Customize.

- Find out more about the WinSitu software at the In-Situ web site.

- Use the Observation Data Import Wizard to import In-Situ data logger files.

Support

Q & A

When looking for answers to questions, remember that you can click the **Help** button in any data entry window to get context-sensitive help about that window.

The following are answers to questions that occasionally arise with regard to the use of AQTESOLV.

Aquifer Data

I don't have any information on aquifer thickness. What should I enter into AQTESOLV?

We have prepared some tips to help you estimate the thickness of an aquifer.

Well Data

How do I enter well depths?

Enter depths for partially penetrating wells measured from the top of the aquifer (confined, leaky or fractured aquifers) or from the water table (unconfined aquifers). Refer to well construction data for more information.

When should I correct for gravel pack porosity?

The optional correction for gravel pack porosity recommended by Bouwer and Rice (1976) is only required for slug tests in wells screened across the water table.

What is the well skin radius?

The skin radius only applies to certain slug test solutions (e.g., KGS Model). Refer to the well radius data for more information.

The total depth of my well extends into a confining unit or my well is open above the water table. What screen length should I enter?

The total depth of the well should not exceed the thickness of the aquifer.

For a **pumping test** or **constant-head test**, refer to the well construction data.

For a **slug test**, refer to the well screen data.

Importing Data

What files can AQTESOLV import from In-Situ data loggers?

Remember that you must use the Win-Situ software to convert the native In-Situ data logger file (.wsl or .bin) into a file type that AQTESOLV can import.

Using Win-Situ, export a file that is compatible with AQTESOLV:

1. **text (.txt) files**

2. **comma-separated values (.csv) files**

Why won't AQTESOLV import data from an In-Situ Level TROLL text file?

1. Download and install the latest version of the Win-Situ software from the In-Situ we site.

2. Before exporting a text file from Win-Situ, choose **General Settings** from the **Preferences** menu.

3. Select the **Custom** option for the Time Format.

4. Enter **H:mm:ss** in the Time input box.

   Note the "H" is capitalized in the format string.

   This custom format displays and records the time stamp with a 24-hour (military) clock format.

5. Click the "check" button to save your changes to the settings.

6. Export a text file from Win-Situ and import it into AQTESOLV.

Recovery Tests

How do I enter recovery data from a pumping test?

Entering data for a recovery test is no different than a pumping test.

For a recovery test, the pumping well data must include all pumping rates leading up to and including the time when pump was shut off. Thus, for the final pumping period in the rate data, enter the elapsed time since the start of the test when the pump was shut off and a rate of zero. In the following example, pumping stopped after 800 minutes.
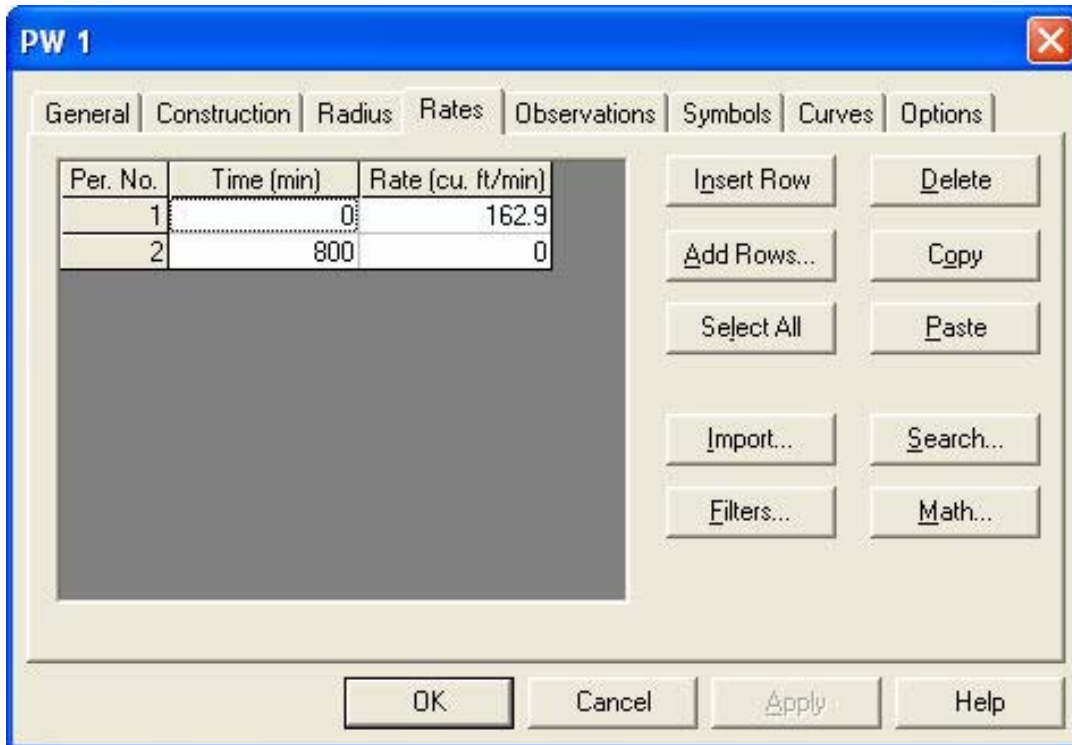
When you enter observation data for a recovery test, enter residual drawdown data (not recovery). Each value of time during the recovery period should be greater than the time when pumping stopped. In the following example, recovery starts after 800 minutes.
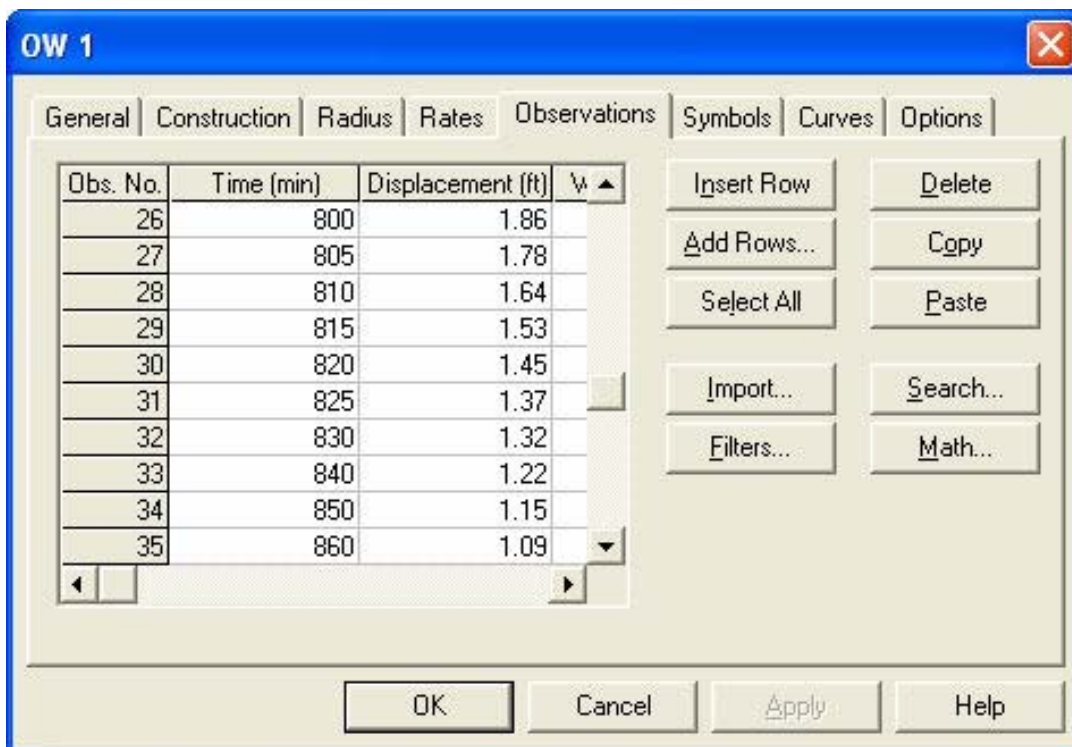
Curve Matching

Why doesn't a straight-line solution fit the trend of my test data when I perform automatic curve matching?

Matching a straight-line solution (e.g., Cooper-Jacob, Theis residual drawdown, Bouwer-Rice, Hvorslev and Jacob-Lohman) to test data requires your judgment to define the appropriate range of data for matching the solution.

With automatic curve matching, you can define this range using a match window; however, it is usually more efficient to perform visual curve matching with these solutions.

Why can't I see the simulated displacement curve (type curve) when I choose a solution?

The curve for the simulated displacement may be plotting outside the plot window. You can format the plot to expand the axes or you can use visual curve matching to reposition the curve.

Can I match data from multiple observation wells?

Yes. You may add more than one observation well to a data set. When you perform visual or automatic curve matching, AQTESOLV matches one set of aquifer properties to **all** of the observation wells in the data set.

Here is a strategy that you may follow in analyzing multiple observation wells:

1. Create a master data containing all of the observation wells from your test. Perform curve matching using all of the wells.

2. Due to heterogeneity or horizontal anisotropy, you may find that matching one set of aquifer properties to all of the wells produces a poor fit. In this situation, you may delete observation wells from the master data set that behave differently and save the wells that behave in similar fashion in a separate data set.

3. You may analyze wells singly by deleting the other wells from the master data set and saving them in individual data sets.

Plots, Reports and Printing

Why don't the data plotted on my graph match the observed data?

There are two cases where this may occur.

1. If you are using the Theis or Cooper-Jacob solution for a pumping test in an unconfined aquifer, the drawdown data are adjusted using Jacob's correction for partial dewatering of the aquifer.

2. If you are using the Cooper-Jacob solution for a pumping test in a confined or unconfined aquifer and the pumping rate is variable, the program transforms the time and drawdown to allow you to match a straight line.

How do I place the origin in the upper-left corner of a plot?

Choose Format from the **View** menu and click the **Graph** tab to change the origin of the plot to the upper-left corner.

When I print a graph, why aren't the characters in the y-axis label rotated as they appear on the screen?

Your printer may not support font rotation; however, on most newer printers, you can force font rotation to remedy this issue.

How do I print the plot legend on a single page?

To fit more legend information on a page when you print a plot, change formatting options such as the font size or the number of items displayed.

How do I display axis tick labels as 10^2 instead of 1.E2?

Choose Format from the **View** menu. In the **Graph** tab, check **Use Base10 Label Format on Log Axes**.

Why don't I see any data when I select the option for an Agarwal plot?

To use an Agarwal plot to analyze data from a recovery test, make sure that your observation well data include a drawdown value measured at time t_p when the pump was shut off.

Let us suppose that you pump a well for 1440 minutes and monitor recovery after turning off the pump. Your observation data must include a drawdown measurement at 1440 minutes (t_p) if you intend to use the Agarwal method.

Contouring

Why does the Grid Wizard ask for a depth interval when I contour drawdown in plan view?

If the solution that you are contouring supports partially penetrating wells, you can contour drawdown in plan view over a specific depth interval in the aquifer.

For example, assume the thickness of the aquifer under study is 10 feet. To contour the drawdown in observation wells screened between 9 and 10 feet, enter minimum and maximum z values in the Grid Wizard of 9 and 10, respectively.

Error Messages

What should I do when I see "Check Errors" at the bottom of the AQTESOLV window?

When you see **Check Errors** on the status bar, you should view the Error Log to identify and correct errors that AQTESOLV has detected in the data set.

What does the "Maximum displacement > initial displacement" warning in the Error Log mean?

In a slug test, the initial displacement is generally the maximum displacement measured during the test. If you get this warning, it indicates that a displacement measured after the initial reading exceeds the initial displacement value. Inspect the observation data to find the displacement measurement that is greater than the initial displacement and correct if necessary. Otherwise you may ignore the warning.

Why do I get a warning about "Initial Displacement > saturated thickness" in the Error Log?

This warning applies to a slug test in an unconfined aquifer. It alerts you to a possible error in the case of the initial displacement due to slug removal exceeding the saturated thickness of the aquifer.

For confined aquifers or slug injection, you may ignore this warning.

Why do I get a warning about "Maximum Displacement > saturated thickness" in the Error Log?

This warning applies to a pumping test in an unconfined aquifer. It alerts you to a possible error in the case of the maximum drawdown in the observation data exceeding the saturated thickness of the aquifer.

For confined aquifers or injection tests, you may ignore this warning.

How do I correct errors shown in the Error Log?

Choose options from the Edit menu to modify the data set.

Miscellaneous

How do you pronounce AQTESOLV anyway?

Click here to find out!

Find answers to other support questions in the **Knowledge Base** at the AQTESOLV web site.

Technical Support

Software Registration

Please use our on-line form to register your copy of AQTESOLV.

Web Resources

Visit the support section of our web site to join the **AQTESOLV Users' Group**, find answers to technical questions in the **Knowledge Base**, and download helpful **examples and tutorials**.

Telephone Support

For other questions, contact HydroSOLVE, Inc. by telephone, fax or e-mail. Please have your **serial number** available.

<div align="center">

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Please be prepared to provide as full a description of your problem as possible.

To assist us in answering your question, it is very helpful to send a copy of your AQTESOLV data set (.aqt file) as an e-mail attachment.

Special Services Available

If you or your company would like specialized instruction on the analysis of aquifer tests using AQTESOLV, feel free to contact HydroSOLVE, Inc. or visit our web site for information on short courses, seminars and professional consulting services.

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General

Pumping Tests

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Slug Tests

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General

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Additional Sources

You may find additional resources relating to aquifer testing on the web. The Aquifer Test Forum, maintained by HydroSOLVE, Inc., includes a bookstore and reference list.

Appendices

Conversions

Use the following tables to convert units of length, area, volume and volumetric flow rate.

Length

To Convert	Multiply By	To Obtain
ft	0.3048	m
ft	30.48	cm
cm	2.54	in
m	3.2808	ft
mile	5280	ft
mile	1.6093	km

Area

To Convert	Multiply By	To Obtain
acres	43560	ft^2
ft^2	0.092903	m^2

Volume

To Convert	Multiply By	To Obtain
ft^3	7.4805	U.S. gallons
ft^3	62.38	pounds of water
liters	0.26417	U.S. gallons
liters	0.03531	ft^3
m^3	35.3145	ft^3
m^3	1000	liters
m^3	264.17	U.S. gallons
U.S. gallons	0.8327	Imperial gallons

Volumetric Flow Rate

To Convert	Multiply By	To Obtain
ft^3/sec	2.832×10^{-2}	m^3/sec
gpd	4.381×10^{-5}	liters/sec
gpm	0.06309	liters/sec

Permeability

To Convert	Multiply By	To Obtain
darcy	9.870×10^{-13}	m^2
ft^2	0.092903	m^2

Pressure

To Convert	Multiply By	To Obtain
psi	2.3067196	ft of water @ 4°C
kPa	0.101974	m of water @ 4°C

Abbreviations

cm = centimeter

ft = foot

gpd = U.S. gallons/day

gpm = U.S. gallons/minute

in = inch

km = kilometer

kPa = kilopascal

m = meter

min = minute

psi = pound-force/in^2

sec = second

Examples

1. Convert 25 U.S. gallons to liters.

   (25 U.S. gallons)(liters/0.26417 U.S. gallons) = 94.6 liters

2. Convert 2 inches to meters.

   (2 in)(2.54 cm/in)(m/100 cm) = 0.051 m

3. Convert 1 ft/min to cm/sec.

   (1 ft/min)(12 in/ft)(2.54 cm/in)(min/60 sec) = 0.51 cm/sec

4. Convert 100,000 gpd/ft to m^2/sec.

   (100,000 gal/day/ft)(ft^3/7.4805 gal)(0.092903 ft^2/m^2)(day/86400 sec) = 0.0144 m^2/sec

5. Convert 1 darcy (permeability) to m/sec (hydraulic conductivity).

   The relationship between the permeability of a porous medium and hydraulic conductivity is $K = k\rho g/\mu$ where K is hydraulic conductivity [L/T], k is permeability [L^2], ρ is density of water [M/L^3], g is gravitational acceleration [L/T^2], and μ is dynamic viscosity of water [M/LT].

   If we assume ρ = 998.8 kg/m^3, g = 9.8 m/sec^2 and μ = 0.00111 Nsec/m^2 @ 15° and 1 atm, the conversion is as follows:

   (1 darcy)(9.870x10^{-13} m^2/darcy)(998.8 kg/m^3)(9.8 m/sec^2)/(0.00111 Nsec/m^2) = 8.70x10^{-6} m/sec

   Note that dynamic viscosity and density are dependent on temperature and pressure. If we assume ρ = 1000 kg/m^3 and μ = 0.001 Nsec/m^2, we find that 1 darcy = 9.67x10^{-6} m/sec.

Hydraulic Conductivity

Hydraulic conductivity is defined as a constant of proportionality relating the specific discharge of a porous medium under a unit hydraulic gradient in Darcy's law:

$\nu = -Ki$

where ν is specific discharge [L/T], K is hydraulic conductivity [L/T] and i is hydraulic gradient [dimensionless].

The transmissivity of an aquifer is related to hydraulic conductivity as follows:

$T = Kb$

where T is transmissivity [L^2/T] and b is aquifer thickness [L].

The following tables show representative values of hydraulic conductivity for various unconsolidated sedimentary materials, sedimentary rocks and crystalline rocks (from Domenico and Schwartz 1990):

Unconsolidated Sedimentary Materials	
Material	Hydraulic Conductivity (m/sec)
Gravel	3×10^{-4} to 3×10^{-2}
Coarse sand	9×10^{-7} to 6×10^{-3}
Medium sand	9×10^{-7} to 5×10^{-4}
Fine sand	2×10^{-7} to 2×10^{-4}
Silt, loess	1×10^{-9} to 2×10^{-5}
Till	1×10^{-12} to 2×10^{-6}
Clay	1×10^{-11} to 4.7×10^{-9}
Unweathered marine clay	8×10^{-13} to 2×10^{-9}

Sedimentary Rocks	
Rock Type	Hydraulic Conductivity (m/sec)
Karst and reef limestone	1×10^{-6} to 2×10^{-2}
Limestone, dolomite	1×10^{-9} to 6×10^{-6}
Sandstone	3×10^{-10} to 6×10^{-6}
Siltstone	1×10^{-11} to 1.4×10^{-8}
Salt	1×10^{-12} to 1×10^{-10}
Anhydrite	4×10^{-13} to 2×10^{-8}
Shale	1×10^{-13} to 2×10^{-9}

Crystalline Rocks	
Material	Hydraulic Conductivity (m/sec)
Permeable basalt	4×10^{-7} to 2×10^{-2}
Fractured igneous and metamorphic rock	8×10^{-9} to 3×10^{-4}
Weathered granite	3.3×10^{-6} to 5.2×10^{-5}
Weathered gabbro	5.5×10^{-7} to 3.8×10^{-6}

Basalt	2×10^{-11} to 4.2×10^{-7}
Unfractured igneous and metamorphic rock	3×10^{-14} to 2×10^{-10}

To Convert	Multiply By	To Obtain
m/sec	100	cm/sec
m/sec	2.12×10^6	gal/day/ft^2
m/sec	3.2808	ft/sec

Related Topics

Anisotropy Ratio

An anisotropy ratio relates hydraulic conductivities in different directions. For example, vertical-to-horizontal hydraulic conductivity anisotropy ratio is given by K_z/K_r where K_z is vertical hydraulic conductivity and K_r is radial (horizontal) hydraulic conductivity. Anisotropy in a horizontal plane is given by K_y/K_x where K_x and K_y are horizontal hydraulic conductivities in the x and y directions, respectively.

Todd (1980) reports values of K_z/K_r ranging between 0.1 and 0.5 for alluvium and possibly as low as 0.01 when clay layers are present.

The following table shows representative values of horizontal and vertical hydraulic conductivities for selected rock types (from Domenico and Schwartz 1990):

Material	Horizontal Hydraulic Conductivity (m/sec)	Vertical Hydraulic Conductivity (m/sec)
Anhydrite	10^{-14} to 10^{-12}	10^{-15} to 10^{-13}
Chalk	10^{-10} to 10^{-8}	5×10^{-11} to 5×10^{-9}
Limestone, dolomite	10^{-9} to 10^{-7}	5×10^{-10} to 5×10^{-8}
Sandstone	5×10^{-13} to 10^{-10}	2.5×10^{-13} to 5×10^{-11}
Shale	10^{-14} to 10^{-12}	10^{-15} to 10^{-13}
Salt	10^{-14}	10^{-14}

Related Topics

Porosity

Porosity (n) is defined as the void space of a rock or unconsolidated material:

$$n = V_v/V_T$$

where V_v is void volume and V_T is total volume.

The following tables show representative porosity values for various unconsolidated sedimentary materials, sedimentary rocks and crystalline rocks (from Morris and Johnson 1967):

Unconsolidated Sedimentary Materials	
Material	Porosity (%)
Gravel, coarse	24 - 37

Gravel, medium	24 - 44
Gravel, fine	25 - 39
Sand, coarse	31 - 46
Sand, medium	29 - 49
Sand, fine	26 - 53
Silt	34 - 61
Clay	34 - 57

Sedimentary Rocks	
Rock Type	**Porosity (%)**
Sandstone	14 - 49
Siltstone	21 - 41
Claystone	41 - 45
Shale	1 - 10
Limestone	7 - 56
Dolomite	19 - 33

Crystalline Rocks	
Rock Type	**Porosity (%)**
Basalt	3 - 35
Weathered granite	34 - 57
Weathered gabbro	42 - 45

Related Topics

Specific Yield

Specific yield (S_y) is defined as the volume of water released from storage by an unconfined aquifer per unit surface area of aquifer per unit decline of the water table.

Bear (1979) relates specific yield to total porosity (n) as follows:

$n = S_y + S_r$

where S_r is specific retention, the amount of water retained by capillary forces during gravity drainage of an unconfined aquifer. Thus, specific yield, which is sometimes called effective porosity, is less than the total porosity of an unconfined aquifer (Bear 1979).

The following table shows representative values of specific yield for various geologic materials (from Morris and Johnson 1967):

Material	**Specific Yield (%)**
Gravel, coarse	21
Gravel, medium	24
Gravel, fine	28
Sand, coarse	30
Sand, medium	32
Sand, fine	33

Silt	20
Clay	6
Sandstone, fine grained	21
Sandstone, medium grained	27
Limestone	14
Dune sand	38
Loess	18
Peat	44
Schist	26
Siltstone	12
Till, predominantly silt	6
Till, predominantly sand	16
Till, predominantly gravel	16
Tuff	21

Related Topics

Storativity

The storativity (S) of a confined aquifer (or aquitard) is defined as the volume of water released from storage per unit surface area of a confined aquifer (or aquitard) per unit decline in hydraulic head. Storativity is also known by the terms *coefficient of storage* and *storage coefficient*.

In a confined aquifer (or aquitard), storativity is defined as

$S = S_s b$

where S_s is specific storage and b is aquifer (or aquitard) thickness [L]. Specific storage is the volume of water that a unit volume of aquifer (or aquitard) releases from storage under a unit decline in head by the expansion of water and compression of the soil or rock skeleton. Storativity generally ranges between 0.00005 and 0.005 in confined aquifers.

Specific storage is related to the compressibilities of the aquifer (or aquitard) and water as follows:

$S_s = \rho g(\alpha + n_e \beta)$

where ρ is mass density of water [M/L^3], g is gravitational acceleration (= 9.8 m/sec^2) [L/T^2], α is aquifer (or aquitard) compressibility [$T^2 L/M$], n_e is effective porosity [dimensionless], and β is compressibility of water (= 4.4×10^{-10} m sec^2/kg or [$T^2 L/M$].

In an unconfined aquifer (or aquitard), storativity is given by

$S = S_y + S_s b$

where S_y is specific yield. Because $S_s b$ is typically small in comparison to S_y, storativity in an unconfined aquifer is essentially equal to specific yield.

The following table shows representative values of specific storage for various geologic materials (from Batu 1998):

Material	S_s (ft^{-1})
Plastic clay	7.8×10^{-4} to 6.2×10^{-3}
Stiff clay	3.9×10^{-4} to 7.8×10^{-4}
Medium hard clay	2.8×10^{-4} to 3.9×10^{-4}
Loose sand	1.5×10^{-4} to 3.1×10^{-4}
Dense sand	3.9×10^{-5} to 6.2×10^{-5}
Dense sandy gravel	1.5×10^{-5} to 3.1×10^{-5}
Rock, fissured	1×10^{-6} to 2.1×10^{-5}
Rock, sound	$< 1 \times 10^{-6}$

To Convert	Divide By	To Obtain
ft^{-1}	0.3048	m^{-1}

Freeze and Cherry (1979) provided the following representative values of compressibility for various aquifer materials:

Material	Compressibility, α (m^2/N or Pa^{-1})
Clay	10^{-8} to 10^{-6}
Sand	10^{-9} to 10^{-7}
Gravel	10^{-10} to 10^{-8}
Jointed rock	10^{-10} to 10^{-8}
Sound rock	10^{-11} to 10^{-9}

$$Pa^{-1} = m^2/N = m \ sec^2/kg$$

Examples

1. Use compressibility data to estimate the storativity of a 35-ft thick confined sand aquifer (assume ρ = 1000 kg/m^3 and n_e = 0.3).

   $S = S_s b = \rho g(\alpha + n_e\beta)b$ = (1000 kg/m^3)(9.8 m/sec^2) m^2/N + (0.3) m^2/N)](35 ft)(0.3048 m/ft) =

2. Use specific storage data to estimate storativity for the same aquifer given in the preceding example.

   $S = S_s b$ = (35 ft) =

Related Topics

Specific Capacity

A specific capacity of a pumping well is defined as follows:

$$specific\ capacity = \frac{Q}{s_w}$$

where

- Q is pumping rate [L^3/T]

- s_w is drawdown in pumped well at a specified time since pumping began [L]

> For example, if a well in a confined aquifer is pumped at a rate of 77 gpm and the drawdown at the end of 24 hours is 25.4 ft, one computes the specific capacity as follows:
>
> Q/s_w = 77 gpm/25.4 ft = 3.03 gpm/ft of drawdown at 24 hours
>
> Using appropriate conversions, we compute the specific capacity in units of meters and days as follows:
>
> (3.03 gal/min/ft)(m^3/264.17 gal)(1440 min/day)(3.2808 ft/m) = 54.2 m^3/day/m of drawdown at 24 hours

Estimating Transmissivity from Specific Capacity

In lieu of aquifer testing results, you may estimate the transmissivity of an aquifer from specific capacity data.

Based on the Cooper-Jacob (1946) formula for drawdown in a confined aquifer, we can compute specific capacity using the following equation:

$$\frac{Q}{s_w} = \frac{T}{0.183 \log\left(\frac{2.25Tt}{r_w^2 S}\right)}$$

where

- r_w is radius of the pumped well [L]

- S is storativity [dimensionless]

- t is time since pumping began [T]

- T is transmissivity [L^2/T]

Using the above equation for specific capacity, Driscoll (1986) assumed the following "typical" conditions

- r_w = 0.5 ft

- S = 0.0001 (confined aquifer) or 0.075 (unconfined aquifer)

- T = 30,000 gpd/ft

- t = 1 day

- the pumped well is 100% efficient

and proposed the following approximate relationships for estimating transmissivity from specific capacity data in confined and unconfined aquifers:

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Q/s$_w$ = T/2000 (confined aquifer)

Q/s$_w$ = T/1500 (unconfined aquifer)

where

- Q is pumping rate [gpm]

- s$_w$ is drawdown in pumped well [ft]

- T is transmissivity [gpd/ft]

Given the limiting assumptions, these two relationships for predicting transmissivity are only approximate.

Using the above example for specific capacity, estimate transmissivity as follows:

T = (2000)(3.03 gpm/ft) = 6060 gpd/ft = 75.3 m^2/day

Various authors have used regression methods to develop equations relating specific capacity and transmissivity. For example, Razack and Huntley (1991) reported the following prediction equation for 215 wells in a large heterogeneous alluvial aquifer in Morocco:

$$T = 15.3 \left(\frac{Q}{s_w} \right)^{0.67}$$

where

- T is transmissivity [m^2/day]

- Q is pumping rate [m^3/day]

- s$_w$ is drawdown in pumped well [m]

For units of ft instead of m, change the coefficient from 15.3 to 33.6 in the foregoing equation.

Let us estimate the value of T with the relationship developed by Razack and Huntley:

T = (15.3)(54.2 m^3/day/m)$^{0.67}$ = 222.1 m^2/day

Mace (1997) developed a similar regression equation for 71 wells completed in a confined karst aquifer located in central Texas (the Edwards aquifer):

$$T = 0.76 \left(\frac{Q}{s_w} \right)^{1.08}$$

where

- T is transmissivity [m^2/day]

- Q is pumping rate [m^3/day]

- s_w is drawdown in pumped well [m]

Using the same example as above, let's estimate T with the Mace equation:

T = (0.76)(54.2 m^3/day/m)$^{1.08}$ = 56.7 m^2/day

Huntley et al. (1992) devised another predictive equation for estimating transmissivity from specific capacity data in fractured aquifers:

$$T = 0.12\left(\frac{Q}{s_w}\right)^{1.18}$$

where

- T is transmissivity [m^2/day]

- Q is pumping rate [m^3/day]

- s_w is drawdown in pumped well [m]

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