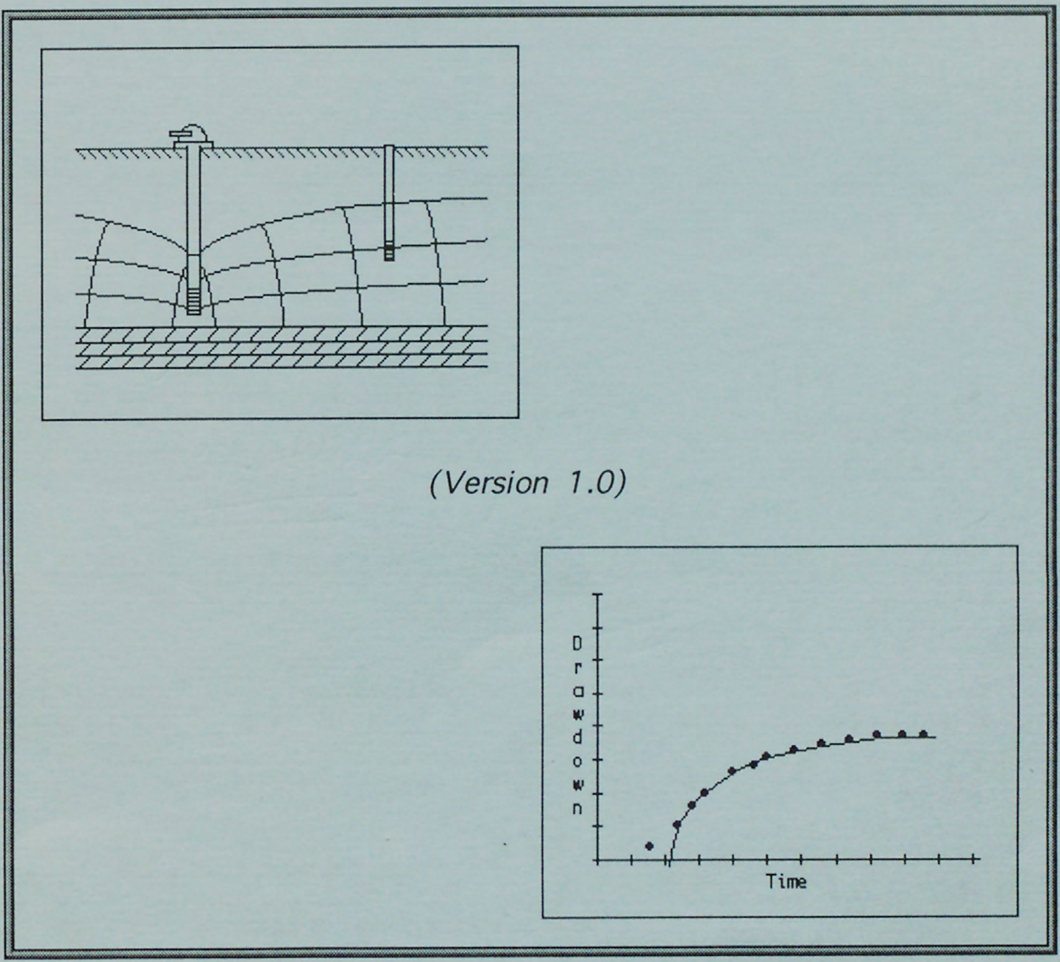
# A COMPUTER PROGRAM (*MACPUMP*) FOR INTERACTIVE AQUIFER-TEST ANALYSIS

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 95-4012



## About the Cover

The figures on the cover of this report illustrate a cross-sectional view of radial ground-water flow to a pumping well (upper left) and the subsequent analysis of time-drawdown data from an adjacent observation well using a curve-matching procedure (lower right), as first introduced by Theis (1935).

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# A COMPUTER PROGRAM (*MACPUMP*) FOR INTERACTIVE AQUIFER-TEST ANALYSIS

By F. D. Day-Lewis, M. A. Person, and L. F. Konikow

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U.S. GEOLOGICAL SURVEY

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Reston, VA

1995

**U.S. DEPARTMENT OF THE INTERIOR**
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**U.S. GEOLOGICAL SURVEY**
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## CONTENTS



## FIGURES

## TABLES



## DISKETTE

# A COMPUTER PROGRAM *(MACPUMP)* FOR INTERACTIVE AQUIFER-TEST ANALYSIS

by

F. D. Day-Lewis[1], M. A. Person[2], and L. F. Konikow[3]

## ABSTRACT

This report introduces ***MACPUMP*** *(Version 1.0)*, an aquifer-test-analysis package for use with Macintosh[4] computers. The report outlines the input-data format, describes the solutions encoded in the program, explains the menu-items, and offers a tutorial illustrating the use of the program. The package reads list-directed aquifer-test data from a file, plots the data to the screen, generates and plots type curves for several different test conditions, and allows mouse-controlled curve matching. ***MACPUMP*** features pull-down menus, a simple text viewer for displaying data-files, and optional on-line help windows. This version includes the analytical solutions for nonleaky and leaky confined aquifers, using both type curves and straight-line methods, and for the analysis of single-well slug tests using type curves. An executable version of the code and sample input data sets are included on an accompanying floppy disk.

## INTRODUCTION

Aquifer tests are used to make field measurements of the hydraulic properties of ground-water systems. Aquifer tests typically involve imposing a change in stress (such as starting or stopping a pump in a well) and monitoring responses in the system (such as changes in hydraulic head over time in one or more observation wells). The data may then be analyzed using nonequilibrium theories, as developed originally by Theis (1935) and expanded on by many others since then (see, for example, Lohman, 1972, or Freeze and Cherry, 1979).

Practical implementation of the theory commonly includes a comparison or overlaying of plots of observed data with type-curve solutions that are available for a variety of conceptual models and boundary conditions of the aquifer system. When a "best-fit" is obtained between the data and the type curve, the coordinates on the four axes at an arbitrary "match point" are used to solve the appropriate equations for calculating the hydraulic properties of the aquifer. This is traditionally a manual exercise and, thus, can be very time consuming. Several attempts to automate the analysis have been described in the literature (for example, Bohling and McElwee, 1992; Earlougher

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[4] The use of brand/firm/trade names, such as Macintosh, AQTESOLV, or DCM, in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey or the University of Minnesota.

and Kersch, 1972; and Madsen, 1985) and several computer packages are available commercially (for example, AQTESOLV by Geraghty and Miller, Inc., Reston, Virginia; Graphical Well Analysis Package by Groundwater Graphics, San Diego, California; WHIP--Well Hydraulics Interpretation Program by HydroGeoChem, Inc., Tucson, Arizona; and SUPRPUMP from the Kansas Geological Survey, Lawrence, Kansas).

***MACPUMP (Version 1.0)*** is an interactive graphics package for the efficient analysis of aquifer-test data that is designed to be used on Macintosh computer systems. The program is menu-driven and features pull-down menus, list-directed data files, and mouse-controlled curve-fitting. Every effort has been made to make the package user-friendly. The program allows the user to generate type curves for various test conditions and to plot test data at the same scale. The user can then overlay the two sets of curves on the monitor and drag one set of curves until a satisfactory match is obtained, just as would be done manually. The program can then calculate the hydraulic properties of the aquifer based on that match. This version of the program includes a limited number of conceptual models for nonleaky and leaky confined aquifers and for the analysis of single-well slug tests. These are based on the analytical solutions of Theis (1935), Hantush and Jacob (1955), Hvorslev (1951), Cooper and Jacob (1946), and Cooper and others (1967). We have included these analytical solutions in ***MACPUMP (Version 1.0)*** because they are frequently used by hydrogeologists and discussed in introductory text books on ground-water hydrology. The program and sample data sets are included on a floppy disk (formatted for a Macintosh computer) at the back of the report.

The curve-matching procedure purposely is not fully automated in this package. Rather, the approach requires users to understand the principles of aquifer hydraulics and well hydraulics so that they may select the appropriate conceptual model and use their scientific judgment in assessing the fit between the data and the type curves. This has the advantages of allowing the user (1) to assess the nature of deviations of data from the type curve, (2) to give more weight to selected parts of the data if desired (perhaps to compensate for known variations in test conditions from those assumed by the analytical model), (3) to disregard spurious data points, and (4) to readily test alternative hypotheses by comparing the data to alternative families of type curves. Interactive packages allow the user to assess the sensitivity of aquifer properties to changes in curve position, curve translation, and the effects of additional sources of water, as in leaky systems.

The program is based on a prototype package documented in 1983 by L.F. Konikow and U.S. Geological Survey colleagues S.M. Fabbri and C.I. Voss[5]. This Macintosh application was written in Fortran and compiled using the MACTRAN PLUS (Version 4.5.3) compiler from DCM Data Products. However, ***MACPUMP*** is a stand-alone application and MACTRAN PLUS is not required in order to run it. The Fortran algorithms for approximating the solutions of Theis (1935), Hantush and Jacob (1955), and Cooper and others (1967) were adapted from Reed (1980).

***MACPUMP*** is intended for use by both students and professionals. We hope that students will find the package to be a useful means of familiarizing themselves with the graphical solutions commonly employed in aquifer-test analysis. Professional or practicing hydrogeologists will find ***MACPUMP*** to be a fast and accurate tool in the determination of aquifer properties.

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[5] This documentation appears in an unpublished article available from author L.F. Konikow (see address on p. *ii*).

This research was supported in part by NSF grant [DUE 9351386], the Gibson Hydrogeology Endowment at the University of Minnesota, and the Undergraduate Research Opportunities Program at the University of New Hampshire. We appreciate the assistance of Ellen Ott, who wrote subroutines used in character manipulation and window creation; Dirk Slawinski, who wrote subroutines used in setting the screen-size, character manipulation, and variable display; and Jim Taylor, Kevin Brewer, J. P. Raffensperger, R. T. Hanson, and J. H. Williams, who reviewed the software and manuscript and offered many helpful suggestions.

# SOLUTIONS

***MACPUMP*** includes the analytical solutions of Theis (1935), Hantush and Jacob (1955), Hvorslev (1951), Cooper and Jacob (1946), and Cooper and others (1967). This section discusses the conceptual models associated with these methods and provides an overview of their applications. Fortran subroutines for calculating the leaky and nonleaky well functions were taken from Reed (1980).

**The Theis Solution:** *Constant Discharge from a Fully Penetrating Well in a Nonleaky Confined Aquifer*

Theis (1935) derived an analytical solution for constant discharge from a fully penetrating well in an areally extensive and nonleaky confined aquifer (fig. 1). The governing ground-water flow equation for radial flow to a well is given by

$$\left(\frac{\partial^2 s}{\partial r^2}\right)+\frac{1}{r}\left(\frac{\partial s}{\partial r}\right)=\frac{S}{T}\left(\frac{\partial s}{\partial t}\right), \quad (1)$$

where $T$ = transmissivity of the aquifer (length$^2$/time),
$S$ = storativity of the aquifer (dimensionless),
$s$ = drawdown (length),
$r$ = distance from the pumped well to the observation well (length), and
$t$ = time of pumping (time).

Theis (1935) made the following assumptions about the aquifer configuration and flow system to solve this differential equation (eq. 1):

1. A nonleaky, confined, horizontal aquifer of infinite lateral extent and constant thickness ($b$) is assumed. (The method may also be used with data for unconfined aquifers if vertical gradients are small--that is, the ratio of drawdown to saturated thickness is much less than 1.)
2. The aquifer is homogeneous and isotropic.
3. Withdrawal is from a single, fully penetrating, pumping well at a constant pumping rate ($Q$), and the well has an infinitesimal diameter. This assumption holds if $t > 2.5 \times 10^2 \, r_c^2/T$, where $r_c$ is the radius of the well casing.

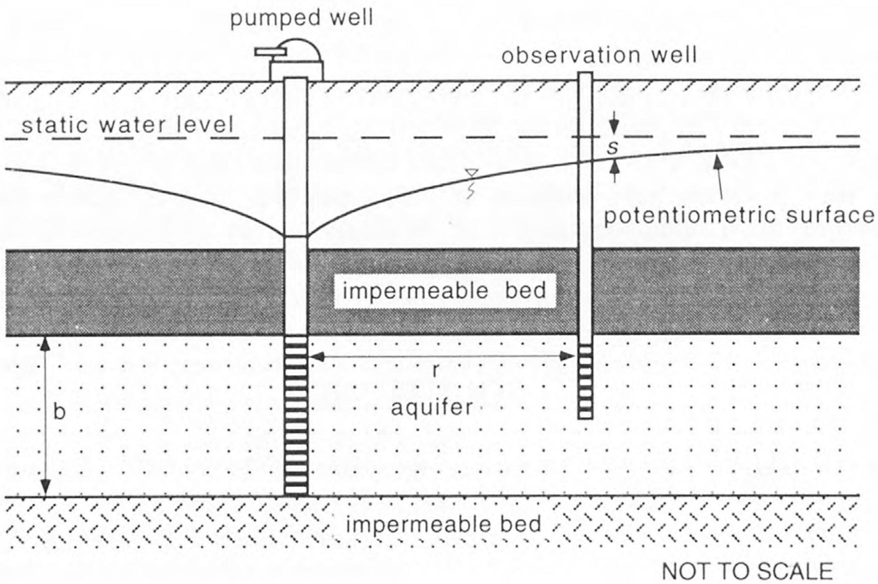


Figure 1. Schematic diagram illustrating radial flow to a well in a nonleaky artesian-aquifer system.

The boundary and initial conditions for this problem are given by

$$s(r,0) = 0, \; r \geq 0 \tag{2}$$

$$s(\infty, t) = 0, \; t \geq 0 \tag{3}$$

$$\begin{cases} Q = 0, \; t < 0 \\ Q = constant > 0, \; t \geq 0 \end{cases} \tag{4}$$

$$\lim_{r \to 0} r \frac{\partial s}{\partial r} = -\frac{Q}{2\pi T}, \; t \geq 0. \tag{5}$$

Theis (1935) found that the exact solution to the above equation and imposed boundary conditions was

$$s = \frac{Q}{4\pi T} \int_u^\infty \frac{e^{-y}}{y} dy, \tag{6}$$

where

$$u = \frac{r^2 S}{4Tt}. \tag{7}$$

The exponential integral, termed the well function, $W(u)$, in this equation, can be solved using the following series expansion:

$$\int_u^\infty \frac{e^{-y}}{y} dy = W(u) = -.577216 - \log_e u + u - \frac{u^2}{2!2} + \frac{u^3}{3!3} - \frac{u^4}{4!4} + \cdots, \tag{8}$$

yielding

$$s = \frac{Q}{4\pi T} W(u). \tag{9}$$

If the aquifer parameters are the unknowns, then the inverse problem must be solved. That is, transmissivity and storativity are calculated from observed changes in head by a graphical procedure, as described by Walton (1962), Lohman (1972), and Fetter (1988).

The equations for $u$ and $s$ show that $s$ is related to $W(u)$ by a constant factor, $Q/(4\pi T)$, just as $1/u$ is related to $t$ by the constant $r^2S/4T$. Embedded in these constants are the hydraulic parameters of interest. Theis' analytical solution is plotted as $1/u$ as a function of $W(u)$ on a log-log scale, thus generating a curve--the Theis or Nonequilibrium Type Curve; the data are plotted as $t$ as a function of $s$ at the same log-log scale. Alternatively, for multiple-well tests, the data may be plotted as $t/r^2$ as a function of $s$, producing a composite plot. Analysis of data for multiple wells may provide more insight in choosing the appropriate conceptual model and will result in values for hydraulic properties that are more representative of the entire test area (Stallman, 1983).

The solution is manually overlain on the data and fit to the data points. After obtaining the best possible fit, an arbitrary matchpoint is chosen, relating the position of the solution to the data. The matchpoint coordinates ($t/r^2$ or $t$, $s$, $1/u$, and $W(u)$) are used to calculate $T$ and $S$ by rearranging equations (6) and (7) as follows:

$$T = QW(u)/(4\pi s) \tag{10}$$

$$S = (Tut)/r^2 . \tag{11}$$

***MACPUMP*** performs a procedure similar to the manual one described above. First it plots the data, using scaling factors to fit it in the window. Once the solution is chosen, the program calculates a new set of $x$- and $y$-scaling factors for the type curve. It selects the smaller of the two $x$-scaling factors, and the smaller of the two $y$-scaling factors, to yield a common scale that will fit both the data and curve in the window. Next it plots the data and stores the image in one integer array; and the curve is plotted and stored in another array. ***MACPUMP*** tracks the movement of the mouse, updates the location of the type-curve origin, and redraws the curve image, centering it around the pointer. When the matchpoint is chosen, the program calculates the distance from the matchpoint to the two origins, and, going backward through the scaling process, it computes $1/u$, $W(u)$, $t/r^2$, and $s$. These values are then used in calculating $T$ and $S$. By automating the plotting, curve-dragging procedure, and all calculations, ***MACPUMP*** is intended to reduce potential for human error, and to serve as a fast and accurate method for aquifer-test analysis.

**Hantush and Jacob's Leaky Artesian Method:** Constant Discharge from a Fully Penetrating Well in a Semiconfined (Leaky) Aquifer

If the confining layer (above or below the aquifer) is semipervious (fig. 2), it may act as a source of recharge to the aquifer. Cooper (1963) developed a curve-matching method for determination of hydraulic properties in leaky aquifers and their confining layers using the leaky well function, $W(u,r/B)$, of Hantush and Jacob (1955). The governing ground-water flow equation for such a system is given by

$$\left(\frac{\partial^2 s}{\partial r^2}\right) + \frac{1}{r}\left(\frac{\partial s}{\partial r}\right) - \frac{sK'}{Tb'} = \frac{S}{T}\left(\frac{\partial s}{\partial t}\right) , \tag{12}$$

where $K'$ = vertical hydraulic conductivity of the confining layer (length/time),
$b'$ = thickness of the confining layer (length), and
$K'/b'$ = leakance coefficient (time$^{-1}$).

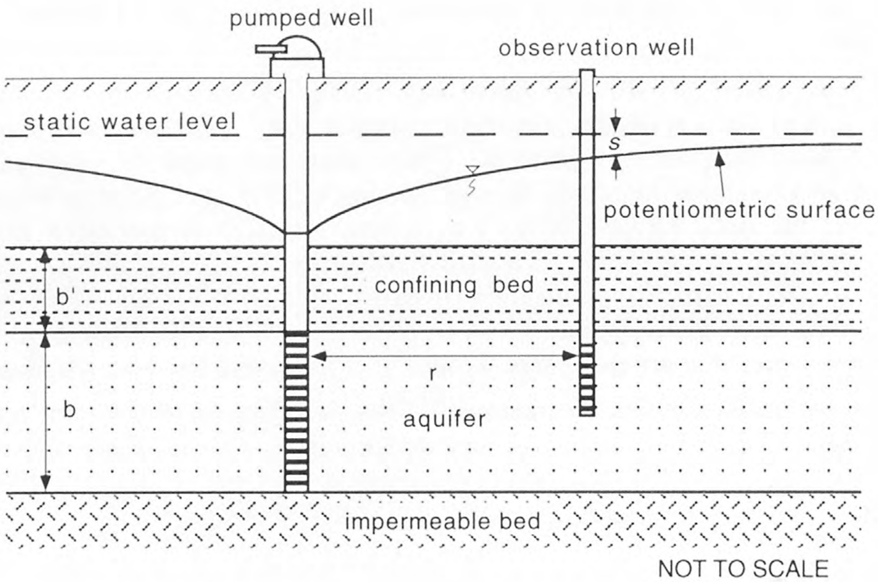


Figure 2. Schematic diagram illustrating radial flow to a well in a leaky artesian-aquifer system.

Hantush and Jacob (1955) made the following assumptions about the aquifer system and pumping conditions to develop an analytical solution to this problem:

1. The aquifer is semiconfined, horizontal, infinite in lateral extent, and has a constant thickness $b$.
2. The aquifer is homogeneous and isotropic.
3. Withdrawal is from a single, fully penetrating, pumped well at a constant pumping rate ($Q$), and the well has an infinitely small diameter.
4. The overlying or underlying confining layer has a hydraulic conductivity ($K'$) and uniform thickness ($b'$) and acts as a source of recharge to the aquifer.
5. No water is released from storage in the confining layer.
6. Flow is horizontal in the aquifer and vertical in the confining layer. This assumption holds if $K >> K'$.

This results in the following set of boundary and initial conditions:

$$s(\infty, t) = 0, \ \ t \geq 0 \tag{13}$$

$$Q = \begin{cases} 0, \ \ t < 0 \\ constant > 0, \ \ t \geq 0 \end{cases} \tag{14}$$

$$\lim_{r \to 0} r \frac{\partial s}{\partial r} = -\frac{Q}{2\pi T} \ . \tag{15}$$

The solution derived by Hantush and Jacob (1955) and presented by Cooper (1963) is

$$s = \frac{Q}{4\pi T}\int_u^\infty \frac{e^{-z-\frac{r^2}{4B^2 z}}}{z}dz \;, \tag{16}$$

where

$$u = \frac{r^2 S}{4Tt} \tag{17}$$

$$B = \sqrt{\frac{Tb'}{K'}} \;. \tag{18}$$

Cooper recast the equation as

$$L(u,v) = \int_u^\infty \frac{e^{-y-\frac{v^2}{y}}}{y}dy \tag{19}$$

where

$$v = \frac{r}{2}\sqrt{\frac{K'}{Tb'}} = \frac{r}{2B} \;. \tag{20}$$

Tabulated values of *L(u,v)* can be found in Reed (1980). Applying Theis' graphical curve-matching procedure described in the last section (but replacing *W(u)* with *L(u,v)* on the *y*-axis), a matchpoint is found, giving values for $1/u$, *L(u,v)*, $t,/r^2$ and *s*. Once these matchpoint values are obtained, values of *T*, *S*, and *K'/b'* can be calculated from

$$T = \frac{Q}{4\pi}\frac{L(u,v)}{s} \tag{21}$$

$$S = 4T\frac{t/r^2}{1/u} \tag{22}$$

$$\frac{K'}{b'} = 4T\frac{v^2}{r^2} \;. \tag{23}$$

In the idealized case, the ratio of the curve parameter *v* (or *r/B*) to *r* is constant, so that *K'/b'* will be the same for different observation wells in a multiple-well test. Scientific discretion must be used when applying this method and fitting curves to data from observation wells at different distances.

Note that ***MACPUMP*** prompts the user for *r/B* values as defined by Hantush and Jacob, which should not be confused with the *v* parameter as defined by Cooper *(v=r/2B)*. The program converts the *r/B* values to the corresponding values of *v*, which are then sent to the subroutines from Reed (1980).

**The Cooper and Jacob Straight-Line Methods:** Constant Discharge from a Fully Penetrating Well in a Fully-Confined Nonleaky Aquifer

If $u$ is small, the higher order terms of the well function (eq. 8) become negligible, and

$$W(u) \cong -.577216 - \ln u \ . \tag{24}$$

By neglecting terms beyond $\ln(u)$, Cooper and Jacob (1946) devised an approximation for the Theis formula that can be represented as a straight line on a semi-log plot:

$$s = \frac{Q}{4\pi T}(-.5772 - \ln u) = \frac{2.3Q}{4\pi T}\log_{10}\left(2.25Tt/Sr^2\right). \tag{25}$$

This method can be applied to either time-drawdown data for one or more observation wells, or to distance-drawdown data collected from multiple wells at a fixed time (fig. 3). In the former case, data are interpreted by plotting $t$ (or $t/r^2$) as a function of drawdown on a semi-log plot. A line is then fit to the data points, representing the solution. The drawdown over one log cycle ($\Delta s$), and the value for time corresponding to $s = 0$ ($t_0$) are found from the straight-line fit. Using these values in the approximation, $T$ and $S$ can be determined from

$$S = \frac{2.25Tt_0}{r^2} \tag{26}$$

$$T = \frac{2.30Q}{4\pi\Delta s} \ . \tag{27}$$

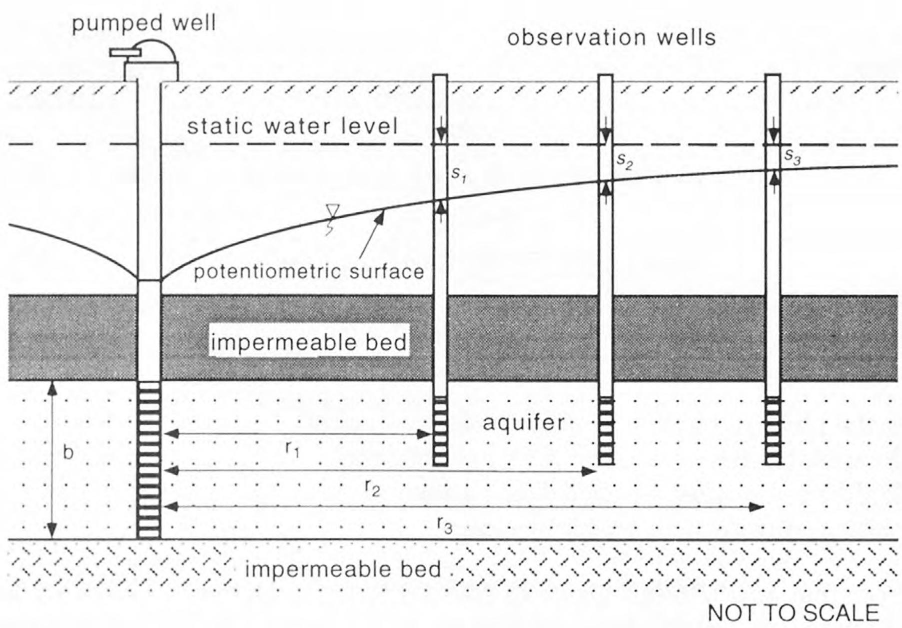


Figure 3. Schematic diagram illustrating radial flow to a well in a nonleaky artesian-aquifer system in an aquifer test using multiple observation wells.

The analysis of distance-drawdown data involves a similar procedure. Data are plotted as distance as a function of drawdown using semi-log scaling, and a line is fit to the data as before. Values are found for $r$ at $s = 0$ ($r_o$), and the drawdown over one log cycle ($\Delta s$), allowing us to solve for $T$ and $S$ using Cooper and Jacob's approximation,

$$S = \frac{2.25Tt}{r_0^2} \tag{28}$$

$$T = \frac{2.30Q}{2\pi\Delta s} \ . \tag{29}$$

Because the straight-line method is based on the Theis Equation, all of the assumptions associated with that method must be met. In addition, $u$ must be small ($u < 0.05$) for the approximation to be accurate. To insure that only data corresponding to negligible $u$-values are used in fitting the line, a $t_{critical}$ or $r_{critical}$ is calculated after $T$ and $S$ are computed. For time-drawdown analysis, only drawdown data for times exceeding $t_{critical}$ should have been used in determining the placement of the best-fit line. For distance-drawdown analysis, only data for observation well distances less than $r_{critical}$ from the pumping well should have been used. The formulas used to calculate the critical time and radius are given by

$$t_{critical} = \frac{r^2 S}{4Tu} \qquad \text{(time-drawdown analysis)} \tag{30}$$

or

$$r_{critical} = \sqrt{\frac{4uTt}{S}} \qquad \text{(distance-drawdown analysis).} \tag{31}$$

An iterative procedure should be employed with the straight-line methods. If the line is fit to data before time $t_{critical}$ or less than distance $r_{critical}$, then a new fit must be made using less of the data and producing new values of $T$, $S$, and $t_{critical}$ or $r_{critical}$. Using $u = 0.05$, the associated error will be less than two percent; for $u = 0.10$ the error will be less than 5 percent (Kruseman and de Ridder, 1991). When using these methods, ***MACPUMP*** calculates and displays $t_{critical}$ or $r_{critical}$ for $u = 0.05$ after the line has been placed and the hydraulic parameters calculated.

**The Hvorslev Slug-Test Method:** Instantaneous Change in Water Level in a Partially Penetrating Piezometer

Hvorslev (1951) presented a graphical method for assessing hydraulic conductivity using a single partially-penetrating piezometer (fig. 4). Making a series of simplifying assumptions regarding the aquifer geometry and well configuration, he derived a formula for ground-water flow to the piezometer tip during a bail test (or flow from it during a slug test; Freeze and Cherry, 1979). The assumptions include--

1. The aquifer is homogeneous, isotropic, and areally extensive, and
2. soil and water are incompressible.

Boundary and initial conditions for this problem are given by

$$h = \begin{cases} H, t < 0, & t = \infty \\ H_0, & t = 0 \end{cases} . \tag{32}$$

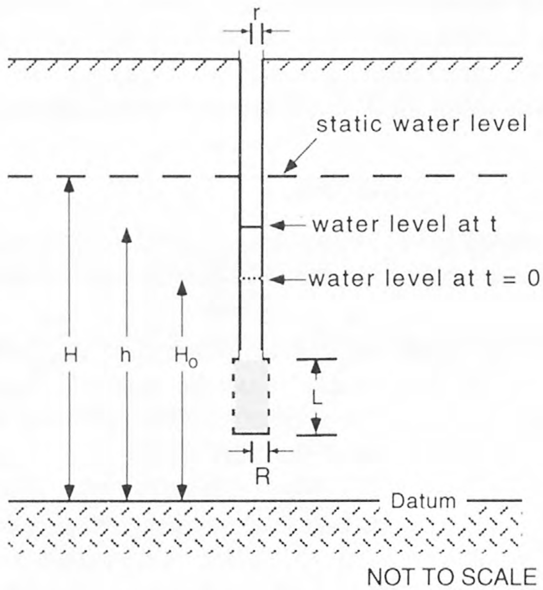


Figure 4. Schematic diagram illustrating bail test. (Modified from Freeze and Cherry, 1979, fig. 8.20a.)

Hvorslev (1951) related changes in water stored in the well to a modified form of Darcy's law:

$$q(t) = \pi r_c^2 \frac{dh}{dt} = FK(H-h), \quad (33)$$

where $q$ = flow rate into or out of the aquifer (length$^3$/time),
$r_c$ = radius of the well casing (length),
$h$ = water level above datum at time = $t$ (length),
$H$ = static water level (length),
$H_0$ = water level at time = 0 (length),
$F$ = shape factor for the piezometer intake configuration, and
$K$ = hydraulic conductivity (length/time).

This equation neglects storage effects in the aquifer. Solving for $K$, and substituting for $F$, Hvorslev (1951) derived the following equation for the hydraulic conductivity of the formation:

$$K = \frac{r^2 \ln(L/R)}{2LT_0} \quad \text{for} \quad L/R > 8, \quad (34)$$

where $L$ = length of intake (length), and
$R$ = radius of intake (length).

**The Cooper, Bredehoeft, and Papadopulos Slug-Test Method:** Instantaneous Change in Water Level in a Fully Penetrating Well in a Nonleaky Confined Aquifer

Cooper, Bredehoeft, and Papadopulos (1967) developed a graphical curve-matching method for determining the transmissivity and storage coefficient from slug tests conducted in fully penetrating wells in confined aquifers. As discussed by Lohman

(1972) and Reed (1980), Cooper and others (1967) derived the following solution for flow to the well in the model described:

$$h = 8(H - H_0)\frac{\alpha}{\pi^2}\int_0^\infty \exp\left(\frac{-\beta u^2}{\alpha}\right)\frac{du}{u\Delta u}, \qquad (35)$$

where $h$ = head in the well at time $t$ after the initial perturbation (length),
$H$ = steady-state head (length),
$H_0$ = the instantaneous water level at $t = 0$ (length),
$u$ = the variable of integration, and

$$\Delta u = \left[uJ_0(u) - 2\alpha J_1(u)\right]^2 + \left[uY_0(u) - 2\alpha Y_1(u)^2\right]. \qquad (36)$$

In equation (36) $J_0$ and $Y_0$ are zero-order Bessel functions of the first and second kind, and $J_1$ and $Y_1$ are first-order Bessel functions of the first and second kind. In equation (35) the parameters $\alpha$ and $\beta$ are

$$\alpha = \frac{r_s{}^2 S}{r_c{}^2} \text{ (dimensionless)} \qquad (37)$$

and

$$\beta = \frac{Tt}{r_c{}^2} \text{ (dimensionless)}, \qquad (38)$$

where $r_s$ = radius of well screen (length), and
$r_c$ = radius of well casing (length).

(Some of the original notation of Cooper and others (1967) was modified for consistency with the discussion of other methods in this report.)

The curve-matching analysis consists of plotting the dimensionless head, $(H-h)/(H-H_0)$, as a function of time using semilogarithmic scaling and overlaying the family of type curves, where each curve corresponds to a different value of $\alpha$. The curves are shifted horizontally to achieve the best possible fit. The values of $T$ and $S$ are calculated using the coordinates of this matchpoint (or matchline) from

$$T = \beta r_c{}^2 / t \qquad (39)$$

and

$$S = \alpha r_c{}^2 / r_s{}^2 . \qquad (40)$$

However, Cooper and others (1967, p. 267) noted that there is a high degree of uncertainty in the value of $S$ as determined by this method. The shapes of the curves are similar, complicating the choice of $\alpha$ that determines $S$ in equation (40). The value of $T$, which is determined by the relative position of the type curve to the data, changes less with curve selection.

# USING *MACPUMP*

## Installing *MACPUMP* and System Requirements

***MACPUMP*** is a stand-alone application written for the Apple Macintosh family of computers and requires 390K of disk space. The package will run on the Macintosh SE, but this is not recommended because of computational limitations associated with the

68020 and earlier CPU's. The software is mouse-driven and features Macintosh-style windows, pull-down menus, and push-buttons. It can be used with either color or black-and-white 13-inch, 15-inch, 19-inch, and Powerbook monitors. (If running the program with a Portrait monitor, use the 15-inch option; with a 9-inch monitor choose the Powerbook option.) The screen size can be interactively changed when the program is first run (see fig. 5). However, the present version of ***MACPUMP*** does require that the Macintosh computer includes a math coprocessor (FPU). Hence, ***MACPUMP*** will not run on a Macintosh that does not include an FPU chip, such as a Power Mac, unless it also has a software FPU emulator.

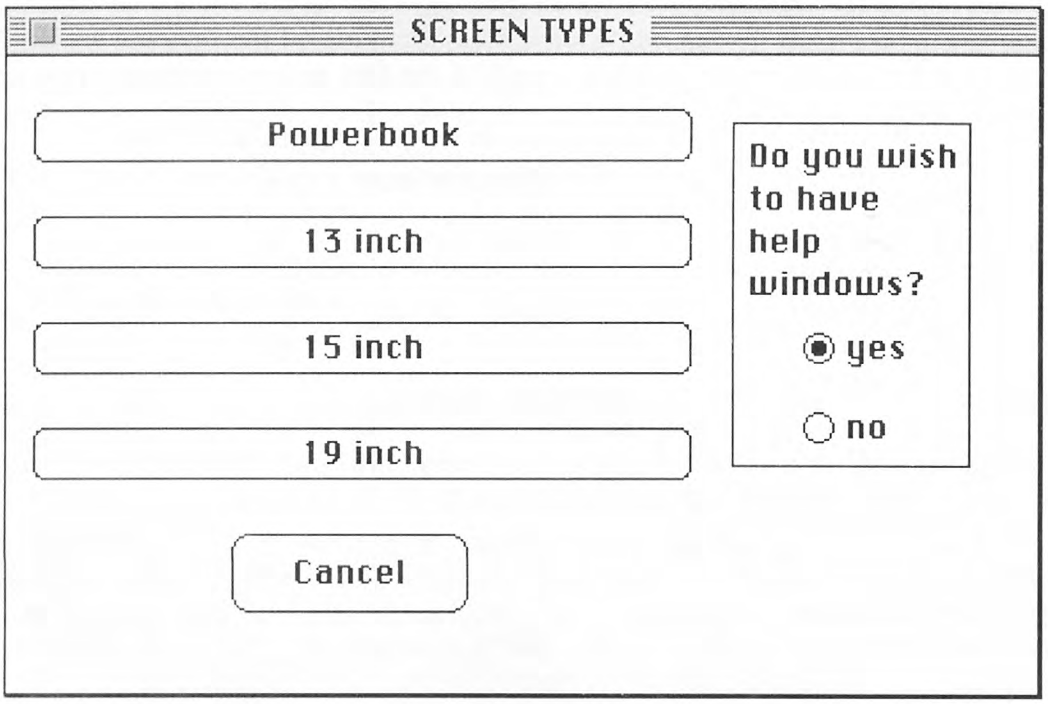


Figure 5. Data window used by *MACPUMP* to set the screen size.

Before using ***MACPUMP***, first copy the application, the sample data files, and the text file "slugvals" from the 3.5-inch floppy disk provided with the documentation onto your hard-drive. Drag the file icons with the mouse to the desired folder on your hard-drive. Data files may be read from any folder on any disk, but the file "slugvals," which contains the type-curve coordinates for the solution of Cooper and others (1967), must reside in the same folder as the application. ***MACPUMP*** requires two megabytes of RAM to run. The program may also be run from a floppy disk, but this will slow the program significantly. We also recommend you deactivate any screen-saver programs when running ***MACPUMP***, as it may erase graphical output on the screen.

## Running the Program

Use of ***MACPUMP*** routines is controlled by a menu bar (see Table 1). The functions performed by each menu-item are outlined below. At any time during execution, active menu-items are displayed in black and inactive items are shown in half-tone gray (and can not be selected). Only those options applicable to the current data set and step in the analysis will be active.

**Table 1.** Main menu bar

| FILE | PLOT OPTIONS | CALCULATIONS | SOLUTIONS |
|---|---|---|---|
| Open | Plot Data | Select Matchpoint | Theis, 1935 |
| Add Data | Curve Parameters | Compute T, S, K | Hantush and Jacob, 1955 |
| Print | Curve Range | Output Units | Hvorslev, 1951 |
| Clear | Show Data File | t/r**2 transform | Cooper and Jacob r-s, 1946 |
| Help | | s**2/2b transform | Cooper and Jacob t-s, 1946 |
| Quit | | | Cooper and others, 1967 |

**FILE:** The file menu allows the user to read data files, print the contents of the current window, activate and deactivate the on-line help, and exit the program.

**Open:** Prompts user to select a new data file and begin a new analysis.

**Add Data:** Reads in additional data files corresponding to well data for a multiple-well pumping test. This item is active only when the **t/r**2 transform** has been previously chosen and the current data set describes a pumping test. The files read must describe the same pumping test; that is, $Q$ must be constant for all files.

**Print:** Initiates a screen dump of the current window.

**Clear:** Closes the active window. After choosing this menu-item, data may be reanalyzed.

**Help:** Toggles help windows on and off.

**Quit:** Exits the program.

**PLOT OPTIONS:** The **Plot Options** menu allows the user to plot and display the data, change the interval of the type curve plotted, and change the leakance values for the leaky artesian type curve.

**Plot Data:** Plots the data as semi-log or log-log according to the method chosen or indicated in the data file.

**Curve Parameters:** Allows the user to choose new $r/B$ values when evaluating pumping-test data using the Hantush and Jacob (1955) solution or $\alpha$ values when applying the Cooper, Bredehoeft, and Papadopulos (1967) solution to slug-test data. Values of $r/B$ may range from 0.0 to 6.0, with $r/B$ = 0.0 corresponding to the Theis Curve for nonleaky conditions.

**Curve Range:** When employing either the Theis, leaky artesian, or Cooper and others solutions, the user may desire to change the range of the curve plotted against the data. This allows the user to ignore noncritical sections of the type curve and zoom in on the part where data are clustered. For the Theis and leaky artesian solutions, values of $1/u$ must lie between $1/10^1$ and $1/10^{-15}$, and the new range is specified by entering integer values for the powers of 10. For the Cooper and others solution, $\beta$ must lie between $10^{-3}$ and $10^3$, and the new range is specified by entering integer values for the powers of 10.

**Show Data File:** Displays the current data files.

<u>CALCULATIONS</u>: The **Calculations** menu contains items involved in selecting the desired units for output, selecting the matchpoint, calculating aquifer/confining layer parameters, and performing transformations of the data.

**Select Matchpoint:** This menu-item should be chosen after achieving the best possible fit between the Theis, leaky artesian, or Cooper and others curves and the data. The matchpoint is chosen by positioning the mouse-pointer at the desired location and depressing the mouse-button. The program automatically computes the matchpoint coordinates for use in calculating transmissivity and storativity, and displays the coordinates at the bottom of the screen. (Not applicable for the straight-line methods.)

**Compute T/K/S:** Selection of this menu-item invokes subroutines to compute the aquifer/confining layer parameters according to the method and test being applied. The results will be converted to the output units specified with the **Output Units** menu-item and displayed on the screen. In the case of the leaky artesian or Cooper and others analyses, the program will prompt the user to indicate the $r/B$ or $\alpha$ value corresponding to the best-fit curve.

**Output Units:** The subroutines called when this menu-item is chosen allow the user to specify the units desired for the final results.

**t/r**2 transformation:** Once this item is toggled on, time-drawdown pumping-test data will be plotted as $s$ as a function of $t/r^2$, and the **Add Data** item will be activated, allowing for the production of composite plots.

**s**2/2b correction:** When this item is toggled on, Jacob's correction for drawdown in unconfined aquifers will be applied in subsequent distance-drawdown analyses.

<u>SOLUTIONS</u>: Selection of an item in this menu calls subroutines that apply one of the six available analytical solutions.

**Theis, 1935:** When this item is chosen, the program calculates points along the curve using subroutines from Reed (1980), and then plots the data and the Theis type curve at the same scale. At this point the user may interactively fit the curve to the data by dragging it with the mouse.

**Hantush and Jacob, 1955:** When this item is chosen, the program prompts the user to enter three leakance values, then calculates points along the curve using the subroutine for computing $L(u,v)$ from Reed (1980), and plots the curves for these values. The user may drag the type curves as described under **Theis, 1935** above. To generate curves for different $r/B$ values, select the **Curve Parameters** menu item.

**Hvorslev, 1951:** After plotting slug test data, choose this menu item to apply the Hvorslev Method. A line will be drawn that may be fit to the data by dragging its endpoints along the axes. Locate the mouse pointer to the left of the *y*-axis or below the *x*-axis and depress the mouse button. When satisfied with the fit, select the menu item **Compute T/S/K**.

**Cooper and Jacob r-s, 1946:** Choose this menu item to fit a straight line to distance-drawdown data. Follow the same procedure as with **Hvorslev, 1951** above.

**Cooper and Jacob t-s, 1946:** Choose this menu item to perform straight-line analysis of time-drawdown aquifer test data. Drag the endpoints of the best fit line by placing the mouse pointer below the *x*-axis or to the right of the graph and depressing the mouse button.

**Cooper and others, 1967:** Select this menu item to apply the Cooper, Bredehoeft, and Papadopulos (1967) solution to slug-test data. The curves are shifted horizontally by dragging with the mouse, as with **Theis, 1935** above. Initially nine curves are plotted, corresponding to $\alpha$ values of $10^{-1}$ to $10^{-9}$. The curves are labeled with the exponents -1 to -9. Reselection of the $\alpha$ values may be made by choosing the **Curve Parameters** item. The range of the curves may be changed by selecting the **Curve Range** item and indicating the maximum and minimum $\beta$ values. Once a satisfactory fit has been made, choose **Select Matchpoint**.

## Creating a Data File

The ***MACPUMP*** data file is list-directed and may be assembled using any word processing program, spreadsheet, or text editor that can create ASCII formatted files. When using a word processing program, be sure to "save as" ASCII or "text only"; otherwise, the file may be stored in another format that cannot be read by ***MACPUMP***.

***MACPUMP*** accepts three flexible data-file formats corresponding to the different methods of analysis offered by the package: time-drawdown aquifer-test data (Table 2), distance-drawdown aquifer-test data (Table 3), and slug-test data (Table 4). The program

**Table 2.** Explanation of aquifer-test time-drawdown data-file variables

| Variable | Description |
|---|---|
| 'METHOD' | upper-case character string between apostrophes, indicating the data format |
| 'Title' | title of data between apostrophes |
| Q | rate of pumping (length$^3$/time) |
| r | distance from pumping well to observation well |
| 'length units' | character strings in apostrophes indicating units of length: 'inches', 'feet', or 'meters' |
| 'time units' | character strings in apostrophes indicating units of time: 'seconds', 'minutes', or 'days' |
| Time | time at observation |
| Drawdown | drawdown at observation |

**Table 3.** Explanation of aquifer-test distance-drawdown data file variables (allowing multiple observation wells)

| Variable | Description |
|---|---|
| 'METHOD' | upper-case character string between apostrophes, indicating the data format |
| 'Title' | title of data between apostrophes |
| NSets | number of lines of data (integer) |
| 'length units' | character strings in apostrophes indicating units of length: 'inches', 'feet', or 'meters' |
| 'time units' | character strings in apostrophes indicating units of time: 'seconds', 'minutes', or 'days' |
| Time | time at observation |
| Distance | distance to observation well |
| Drawdown | drawdown at observation well |

**Table 4.** Explanation of slug-test data file variables

| Variable | Description |
|---|---|
| 'METHOD' | upper-case character string between apostrophes, indicating the data format |
| 'Title' | title of data between apostrophes |
| H | static head |
| $H_o$ | number of lines of data (integer) |
| LWell | number of lines of data (integer) |
| $r_c$ | number of lines of data (integer) |
| $r_s$ | number of lines of data (integer) |
| NSets | number of lines of data (integer) |
| 'length units' | character strings in apostrophes indicating units of length: 'inches', 'feet', or 'meters' |
| 'time units' | character strings in apostrophes indicating units of time: 'seconds', 'minutes', or 'days' |
| Time | time at observation |
| h | head at observation |

fills the data arrays by reading each line into a character variable of length 80, and extracting the expected information from this variable. The first variable read indicates the test method and must be one of three strings: 'PUMP', 'DIDR', or 'SLUG'. Next the data title is read, which may be up to 78 characters in length and must reside between apostrophes on only one line. Input units are also specified by character strings. Unit specifiers for time are 'seconds', 'minutes', and 'days'; length specifiers include 'inches', 'feet', and 'meters'. Comment lines, indicated by a "C" in the first column, are ignored, as are blank lines. Data may be separated by semi-colons, tabs, spaces, or commas and may reside in any column between the first and the eightieth. Comments following the data on the same line will be ignored. Sample files for the various models, taken from Lohman (1972, Tables 4, 6, 10, and 11), are found in Tables 5 to 8 and are included on the floppy disk.

**Table 5.** Sample time–drawdown data file (for Theis solution); this data file is named "Lohman_p19.pump" on the floppy disk

| Data Description: | Data File: |
|---|---|
| Line 1: 'METHOD' | 'PUMP' |
| Line 2: 'Title' | 'Data from p19 of Lohman (1972); well N-1; T=13,700ft^2/d; S=.0002' |
| Line 3: comment line | C-- Units: |
| Line 4: 'time units' 'length units' | 'minutes' 'feet' |
| Line 5: comment line | C-- Q r |
| Line 6: Q, r | 66.667 200 |
| Line 7: comment line | C-- Time s |
| Lines 8-32: Time, Drawdown | 1.0 0.66 |
| | 1.5 0.87 |
| | 2.0 0.99 |
| | 2.5 1.11 |
| | 3.0 1.21 |
| | 4.0 1.36 |
| | 5.0 1.49 |
| | 6.0 1.59 |
| | 8.0 1.75 |
| | 10. 1.86 |
| | 12. 1.97 |
| | 14. 2.08 |
| | 18. 2.20 |
| | 24. 2.36 |
| | 30. 2.49 |
| | 40. 2.65 |
| | 50. 2.78 |
| | 60. 2.88 |
| | 80. 3.04 |
| | 100. 3.16 |
| | 120. 3.28 |
| | 150. 3.42 |
| | 180. 3.51 |
| | 210. 3.61 |
| | 240. 3.67 |

**Table 6.** Sample time–drawdown data file (for leaky aquifer); this data file is named "Lohman_p31.leaky" on the floppy disk

| Data Description: | Data File: | |
|---|---|---|
| Line 1: 'METHOD' | 'PUMP' | |
| Line 2: 'Title' | 'Data from p31 of Lohman (1972); well #1; T=13,300ft^2/d; S=.0001' | |
| Line 3: comment line | C--Units: | |
| Line 4: 'time units' 'length units' | 'minutes' | 'feet' |
| Line 5: comment line | C-- Q | r |
| Line 6: Q, r | 133.69 | 100 |
| Line 7: comment line | C-- Time | s |
| Lines 8-18: Time, Drawdown | .2 | 1.76 |
| | .5 | 2.75 |
| | 1. | 3.59 |
| | 2. | 4.26 |
| | 5. | 5.28 |
| | 10. | 5.90 |
| | 20. | 6.47 |
| | 50. | 6.92 |
| | 100. | 7.11 |
| | 200. | 7.20 |
| | 500. | 7.21 |
| | 1000. | 7.21 |

**Table 7.** Sample distance–drawdown data file (for multiple observation wells); this data file is named "Lohman_p12.didr" on the floppy disk

| Data Description: | Data File: | | |
|---|---|---|---|
| Line 1: 'METHOD' | 'DIDR' | | |
| Line 2: 'Title' | 'Data from p12, Lohman (1972); T=20,700ft^2/d; S=.35' | | |
| Line 3: comment line | C- The saturated thickness, b, is 26.8ft | | |
| Line 4: comment line | C- Time in: | Length in: | |
| Line 5: 'time units' 'length units' | 'days' | 'feet' | |
| Line 6: comment line | C- Q | Time | |
| Line 7: Q, t | 192513.369 | 18. | |
| Line 8: comment line | C- Distance: | Drawdown: | |
| Lines 9-14: Time, Drawdown | 49.2; | 5.91 ; | North |
| | 100.7; | 4.58 ; | North |
| | 189.4; | 3.42 ; | North |
| | 49.0; | 5.48 ; | South |
| | 100.4; | 4.31 ; | South |
| | 190.0; | 3.19 ; | South |

**Table 8.** Sample slug-test data file; this data file is named "Lohman_p29.slug" on the floppy disk

| Data Description: | Data File: |
|---|---|
| Line 1: 'METHOD' | 'SLUG' |
| Line 2: 'Title' | 'Recovery-Test Data from p29, Lohman (1972); T=490ft^2/d' |
| Line 3: comment line | C--time length |
| Line 4: 'time units' 'length units' | 'seconds' 'meters' |
| Line 5: comment line | C-- H Ho LWell rWell rgrvpck |
| Line 6: H, $H_o$, $L_{well}$, $r_c$, $r_s$ | .896 .336 122. .076 .076 |
| Line 7: comment line | C--Time head |
| Lines 8-29: Time, Head | 0. .336 |
| | 3. .439 |
| | 6. .504 |
| | 9. .551 |
| | 12. .588 |
| | 15. .616 |
| | 18. .644 |
| | 21. .672 |
| | 24. .691 |
| | 27. .709 |
| | 30. .728 |
| | 33. .747 |
| | 36. .756 |
| | 39. .765 |
| | 42. .784 |
| | 45. .788 |
| | 48. .803 |
| | 51. .807 |
| | 54. .814 |
| | 57. .821 |
| | 60. .825 |
| | 63. .831 |

In the following section tutorials lead the user step by step through analyses of sample data files corresponding to the various test conditions. The procedure allows for comparison of aquifer parameters calculated with ***MACPUMP*** to those presented in Lohman (1972).

## Tutorial

Included on the floppy disk and described in the previous section are four sample data files: "Lohman_p19.pump" for the Theis (1935) and Cooper and Jacob *t-s* (1946) methods; "Lohman_p31.leaky" for the Hantush and Jacob (1955) solution; "Lohman_p12.didr" for Cooper and Jacob *r-s* (1946); and "Lohman_p29.slug" for Cooper and others (1967) and Hvorslev (1951) (Tables 5-8 respectively). This section details the steps in analyses of these data sets, beginning with the time-drawdown data in "Lohman_p19.pump".

## Theis Curve Analysis

1. Enter the application by double clicking its icon. At this point, choose whether to run the program with or without help windows by selecting the appropriate radio-button, then click on the push-button corresponding to your monitor screen size (fig. 5). On-line help may be activated and deactivated using the **Help** menu-item. Once read, help windows may be removed by clicking on the "okay" button or pressing <return>.
2. Next the ***MACPUMP*** logo window appears, providing information about the program. This window will disappear after about five seconds.
3. Read in the data file "Lohman_p19.pump" (Table 5) by selecting the **Open** item under the **File** menu. The standard system window for opening files will appear. Click on the file; then click on "open". The data will be displayed on the screen. Click on the 'ok' button (or press <return>) to move on to the next step.
4. Now plot the data to the screen by choosing the **Plot Data** menu item under the "**PLOT OPTIONS**" menu, which produces the plot shown in figure 6.

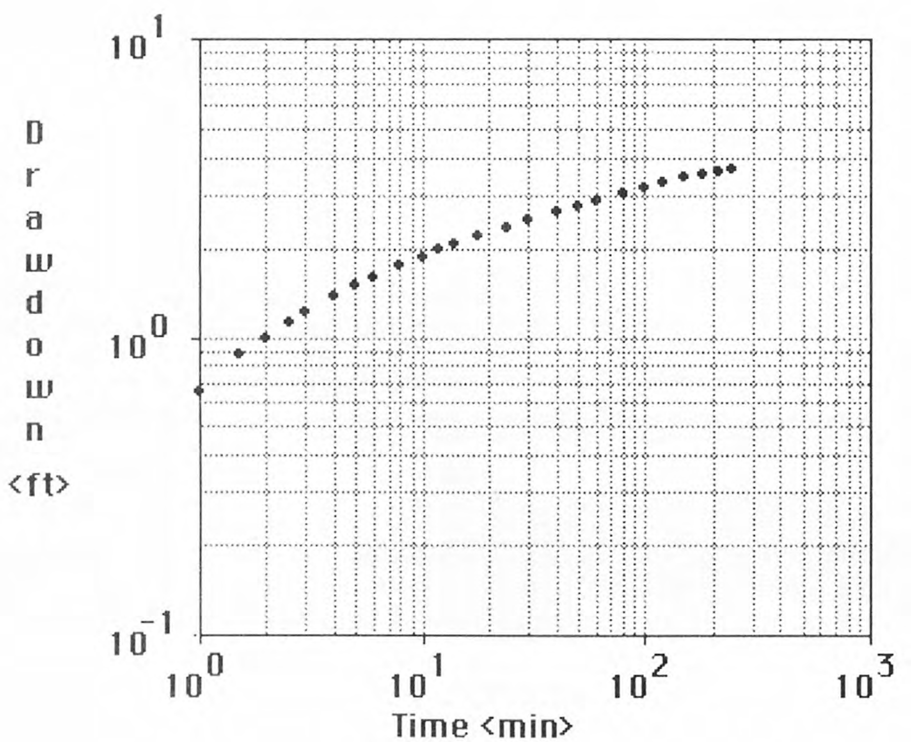


Figure 6. *MACPUMP* plot of aquifer-test data. The time-drawdown data are from Lohman (1972, table 6, p. 19).

5. Choose a solution: select **Theis, 1935** under the **SOLUTIONS** menu. ***MACPUMP*** calculates points along the curve. It then overlays the type curve on the data with scaling factors common to both.

6. Observe that more of the Theis Curve than necessary is plotted and, consequently, the data are clustered in only a small area of the plot. To change the $1/u$ interval over which the curve is plotted, select **Curve Range** under **PLOT OPTIONS**. The program will display the present minimum and maximum $1/u$ values and prompt the user to enter the new range by specifying the integer exponents of $u$. To decrease the maximum $1/u$ by several log cycles, enter "-1" in the first box (thus keeping $1/10^{-1}$ as the minimum) and enter "-3" in the second box (fig. 7).

7. To fit the curve to the data, depress the mouse button and move the mouse pointer. The type curve will follow the mouse's movements while the button is down, centering itself around the pointer. The procedure is easiest if the button is pressed continuously until the best fit is obtained.

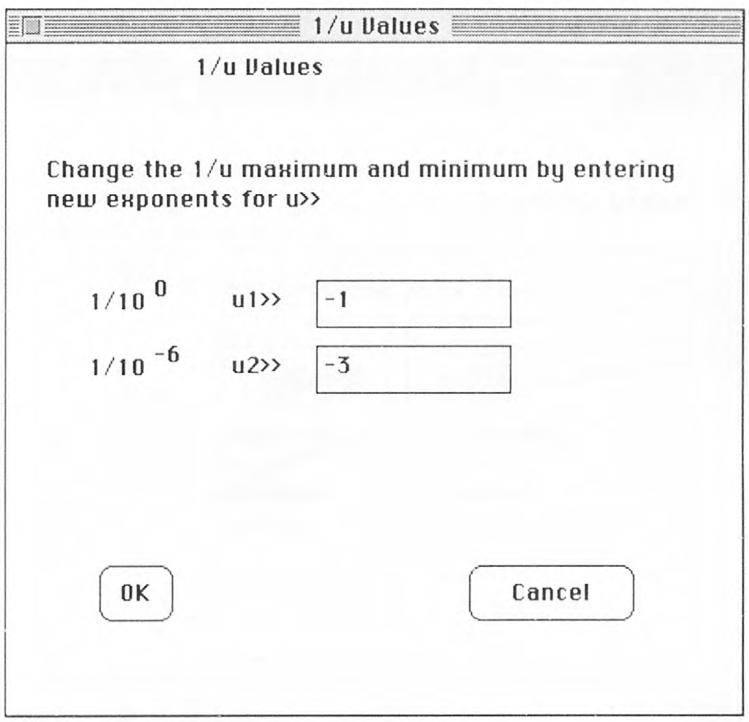


Figure 7. Window for changing the range of values for $1/u$ over which the Theis curve is plotted.

8. After achieving the best possible fit to the data, choose the **Select Matchpoint** menu-item. Select an arbitrary matchpoint by moving the mouse pointer to the desired location and pressing the mouse button. ***MACPUMP*** will compute the matchpoint coordinates and display them on the screen. The matchpoint may be changed by choosing **Select Matchpoint** again and repeating the procedure. Reselection will not affect the final results obviously, but may be desirable for graphical reasons if the previous point obscured data.

9. Pull down the **CALCULATIONS** menu and select **Output units**; choose feet and days (as shown in fig. 8). To calculate $T$ and $S$, choose **Compute T/S/K**. The program will display the values at the top of the window (see fig. 9). To make a printout, choose **Print** under the **File** menu. Applying the Theis Method to these data for an observation well 200 feet from a pumping well that was discharging at a rate of 96,000 $ft^3$/day, Lohman (1972) found $T$ = 13,700 $ft^2$/day and $S$ = 0.0002.

10. A straight-line analysis can be performed on the same data set. Choose the **Cooper and Jacob t-s, 1946** menu item under **SOLUTIONS**. ***MACPUMP*** will produce a semi-log plot of drawdown as a function of time and a straight line that can be moved to fit the data. Drag the endpoints of the line by locating the pointer below the $x$-axis or to the right of the graph box and holding down the mouse button.

11. After achieving the best fit, select **Compute T/S/K**. The program will find $t_o$ and calculate $T$, $S$, and $t_{critical}$ for $u$<0.05 (fig. 10). Data before $t_{critical}$ should not have been considered in fitting the line. The method should be reapplied, if necessary, by selecting the **Cooper and Jacob t-s, 1946** item again.

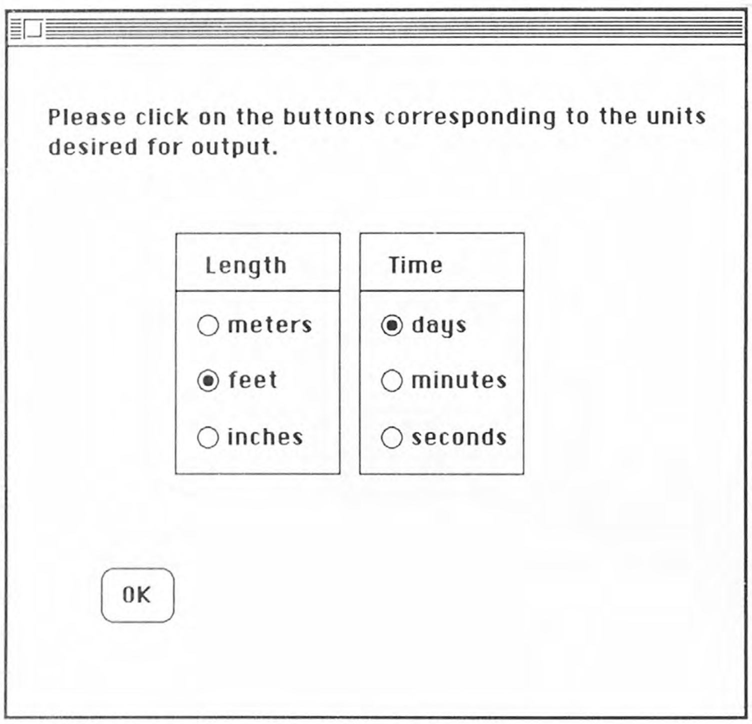


Figure 8. Window for specifying the units for calculated values of aquifer properties.

### Leaky-Artesian Aquifer Analysis

1. Read in the data for the leaky response by selecting the **Open** item, and choosing the file "Lohman_p31.leaky". The data will appear on the screen. Click on 'ok' to move on to the next step. Select **Plot Data** and then the appropriate solution, **Hantush and Jacob, 1955** under **SOLUTIONS**. The program will prompt you to enter three $r/B$ values. Values must lie between 0.0 and 6.0, with $r/B$ = 0.0 corresponding to the

Theis solution (for nonleaky conditions). Accept the default values by pressing the 'okay' button. ***MACPUMP*** will generate and plot the three curves (fig. 11). Try fitting each to the data just as with the Theis solution above.

2. To try new *r/B* values and thus find a better curve, go to **Curve Parameters** under **Plot Options**. Select new values between the two closest previously--in this case, between 0.0 and 0.10. If the screen appears cluttered with three curves, generate fewer by repeating values.
3. For these data Lohman (1972) suggests a best fit is produced for $v$ = 0.025 (corresponding to *r/B* = 0.05). Fit this curve to the data, then **Select Matchpoint** and **Compute T/S/K**. When prompted for the best fit *r/B*, specify .05 by clicking on the appropriate radio button. When prompted for the radius to be used in calculating *K'/b'*, specify 100 feet (the distance from the pumping well to the observation well). Lohman (1972) found $T$ = 13,300 $ft^2$/day, $S$ = 0.0001 and $K'/b'$ = 0.0033 $day^{-1}$. Results using ***MACPUMP*** are comparable (see fig. 12).

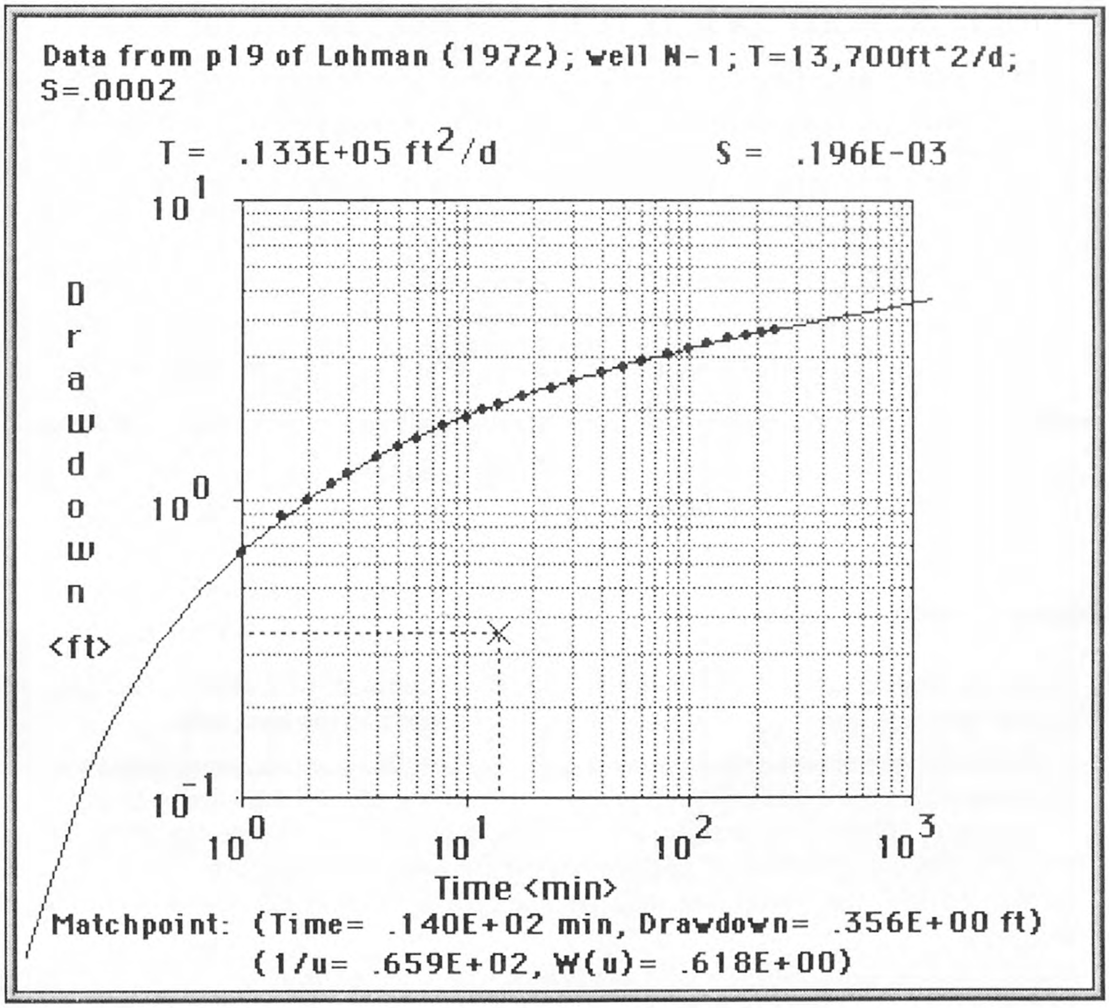


Figure 9. Window from *MACPUMP* showing results of Theis Curve analysis of aquifer-test data. (Data from Lohman, 1972, table 6, p. 19.)

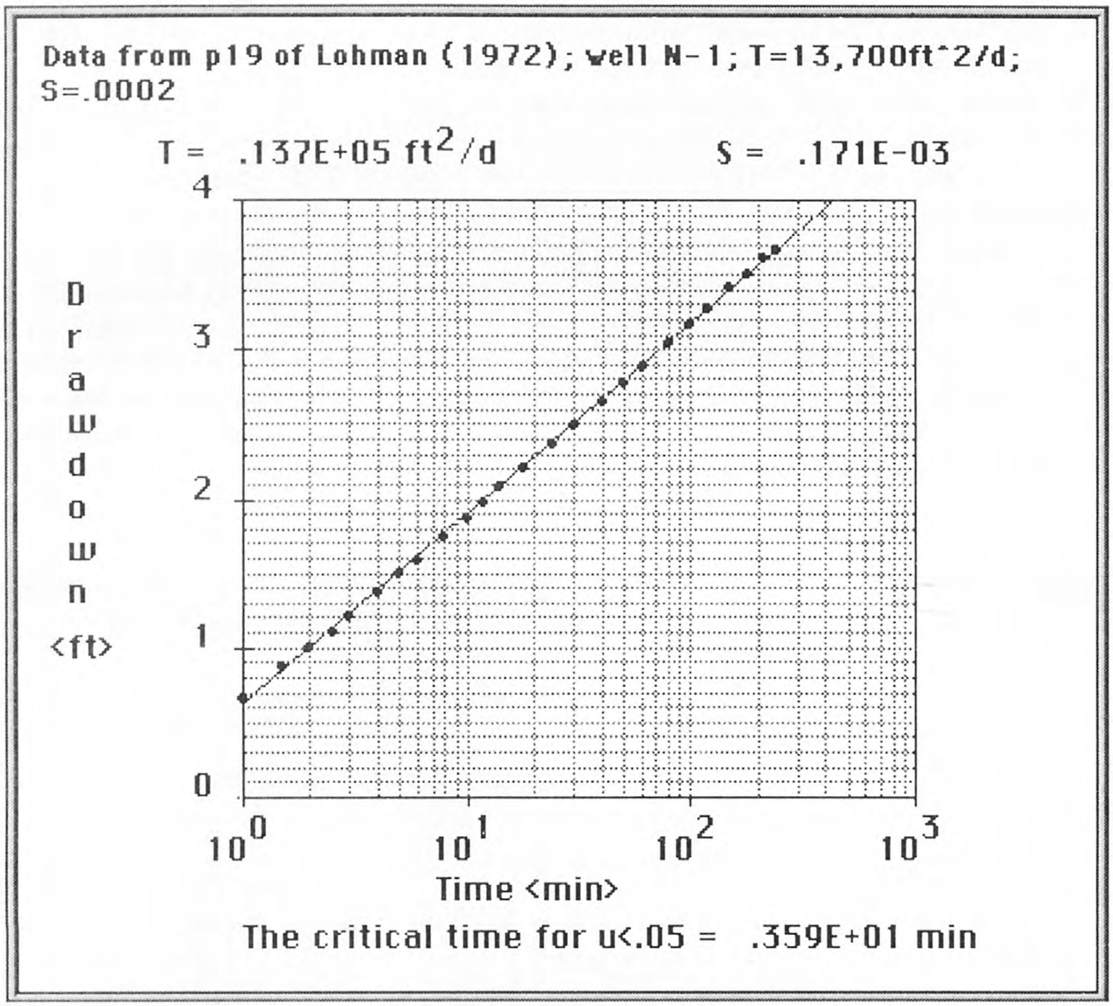


Figure 10. Window from *MACPUMP* showing results of straight-line analysis of aquifer-test data. (Data from Lohman, 1972, table 6, p. 19.)

## Distance-Drawdown Analysis

1. Select the **Open** item and read in the data file "Lohman_p12.didr". The data will appear on the screen. Click on the 'ok' button to move to the next step.
2. Plot the data to the screen by choosing the **Plot Data** menu item under the **Plot Options** menu. ***MACPUMP*** will produce a semi-log plot of drawdown as a function of distance. These data are for an unconfined system, so choose the **s**2/2b** item under **CALCULATIONS** to perform Jacob's drawdown correction. Until this item is toggled off, the correction will be applied in subsequent distance-drawdown analyses.
3. Choose **Jacob r-s** under the **SOLUTIONS** menu. ***MACPUMP*** will plot a straight line that may be moved to fit the data. Drag the endpoints of the line by locating the pointer to the left of the *y*-axis or below the *x*-axis and holding down the mouse button.

4. After obtaining a satisfactory fit, select **Compute T/K/S**. The program will find $r_0$, and calculate $T$, $S$, and $r_{critical}$ for $u$<0.05. If data for distances greater than $r_{critical}$ were considered in fitting the line, repeat steps 3 and 4, fitting the line to data for distances less than the critical radius. Lohman (1972) found $T$ = 20,700 ft$^2$/day and $S$ = 0.35 by applying a straight-line analysis and Jacob's correction to these data. As shown in figure 13, results using ***MACPUMP*** are consistent with these values.

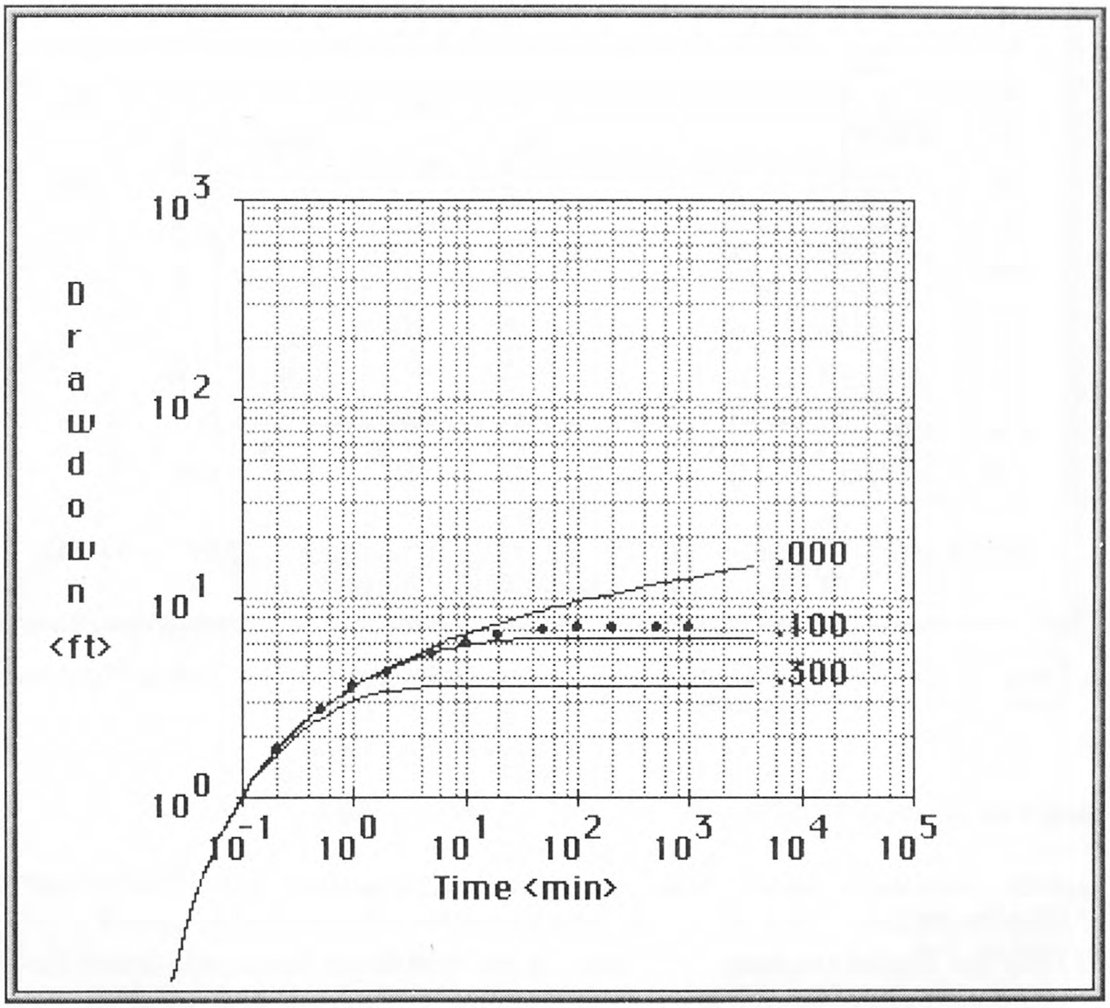


Figure 11. Window showing initial matching of type curves for a leaky confined aquifer to data from Lohman (1972, table 11, p. 31).

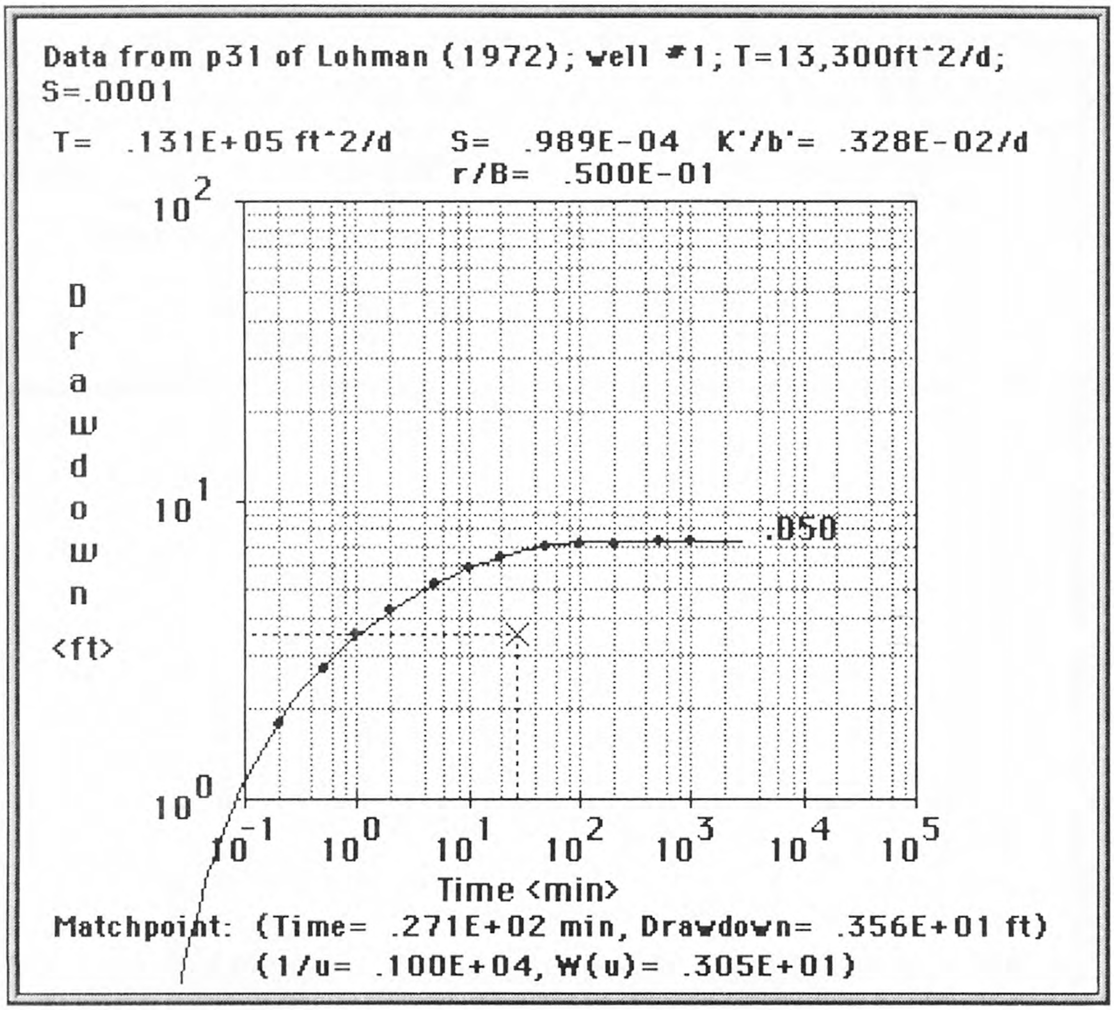


Figure 12. Window showing results of type-curve analysis of leaky confined aquifer data. (Data from Lohman, 1972, table 11, p. 31.)

### Slug-Test Analysis

1. Select the **Open** item and read in the data file "Lohman_p29.slug". ***MACPUMP*** will display the data. Click on the 'ok' button to move to the next step.
2. Plot the data to the screen by choosing the **Plot Data** menu-item under the **Plot Options** menu. ***MACPUMP*** will produce a semi-log plot of dimensionless drawdown as a function of time.
3. Choose the **Cooper and others, 1967** item under the **SOLUTIONS** menu. The program will plot nine curves corresponding to $\alpha$ values from $10^{-1}$ to $10^{-9}$. Drag these curves horizontally by depressing the mouse button and moving the mouse pointer (fig. 14).
4. It may be desirable to plot fewer than nine curves. Choose the **Curve Parameters** item to specify which curves are to be plotted. The program will plot the curves corresponding to check boxes containing an 'X'. Click on the boxes to toggle on and

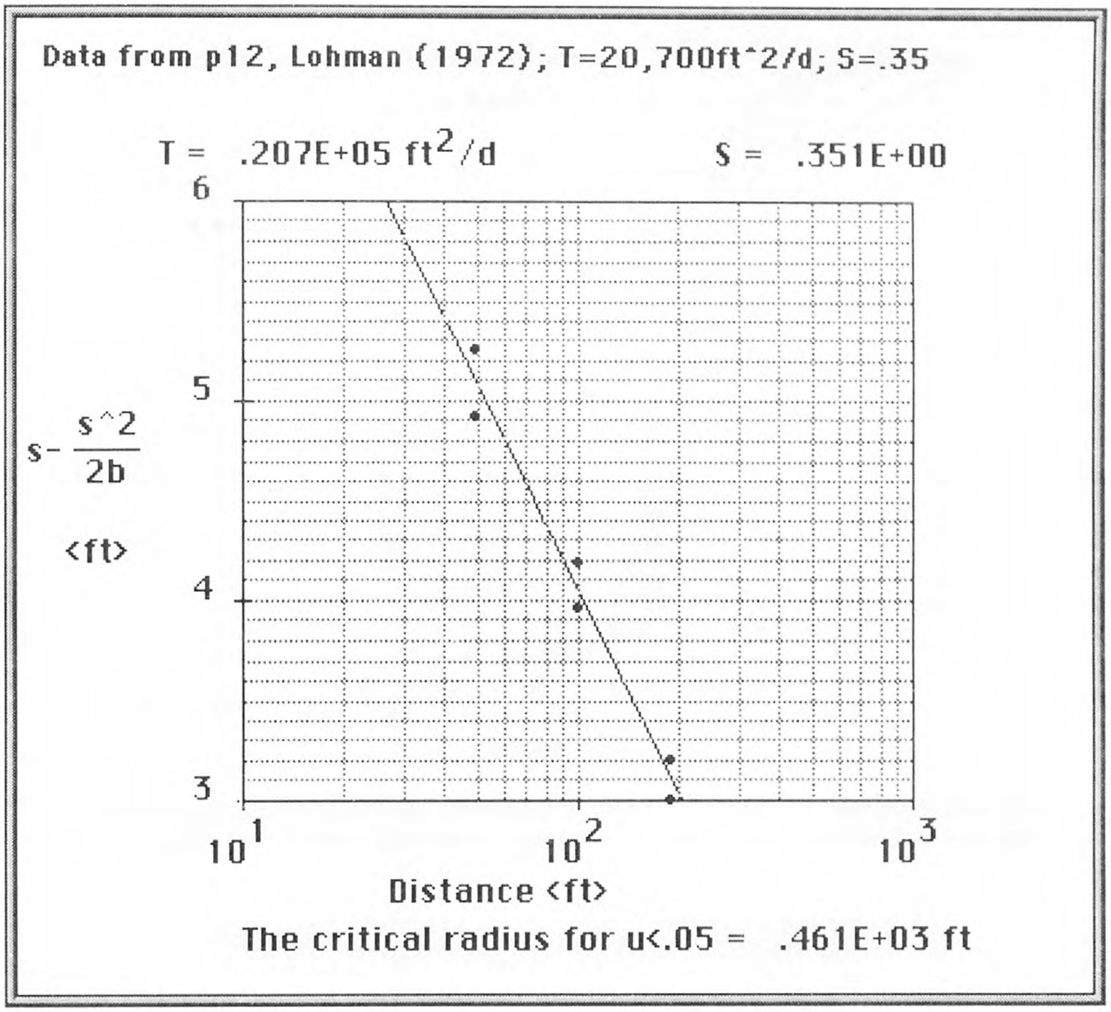


Figure 13. Window showing straight-line analysis of aquifer-test distance-drawdown data. (Data from Lohman, 1972, table 4, p. 12.)

off (fig. 15). For these data, Lohman (1972) found the curve for $\alpha = 10^{-3}$ produced the best fit.

5. It may also be desirable to plot the curves over a smaller range of $\beta$ values. Choose **Curve Range** and specify a new range by entering integer values for the power of 10. In this case, plot one less log cycle of $\beta$. Specify the range from $10^{-3}$ to $10^{2}$ (as illustrated in fig. 16). Note that the menu item **Curve Range** is also used for selecting the range of $1/u$ values when using the Theis or Hantush and Jacob methods.
6. Fit the $\alpha = 10^{-3}$ curve to the data (labeled "-3"). Once a satisfactory fit has been made, choose **Select Matchpoint** and drop the matchpoint at the desired location by pressing the mouse button. Select the **Compute T/S/K** item. The program will prompt you to enter the value of $\alpha$ corresponding to best-fit curve (or an interpolated value if the data lie between curves). Indicate $\alpha = 10^{-3}$ by entering the decimal value of $\alpha$, in this case ".001" (fig. 17). Fitting this curve to these data, Lohman (1972) calculated $T$ = 490 ft$^2$/day. Analysis using ***MACPUMP*** yields comparable results (see fig. 18).

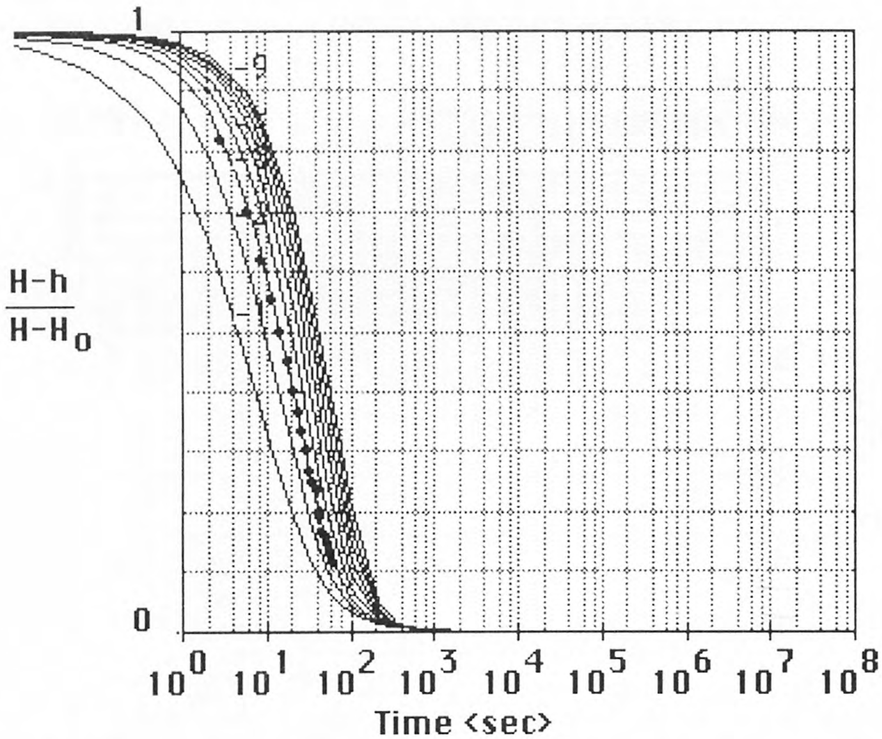


Figure 14. Initial matching of Cooper, Bredehoeft, and Papadopulos type curves for slug-test analysis to recovery data from Lohman (1972, table 10, p. 29).

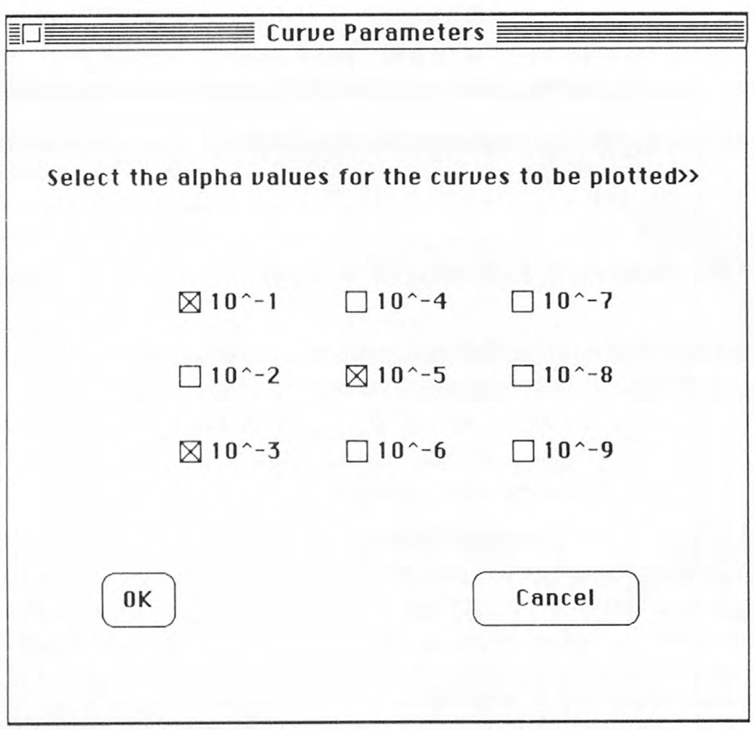


Figure 15. Selection of *a* values for Cooper, Bredehoeft, and Papadopulos (1967) type curves to be plotted.

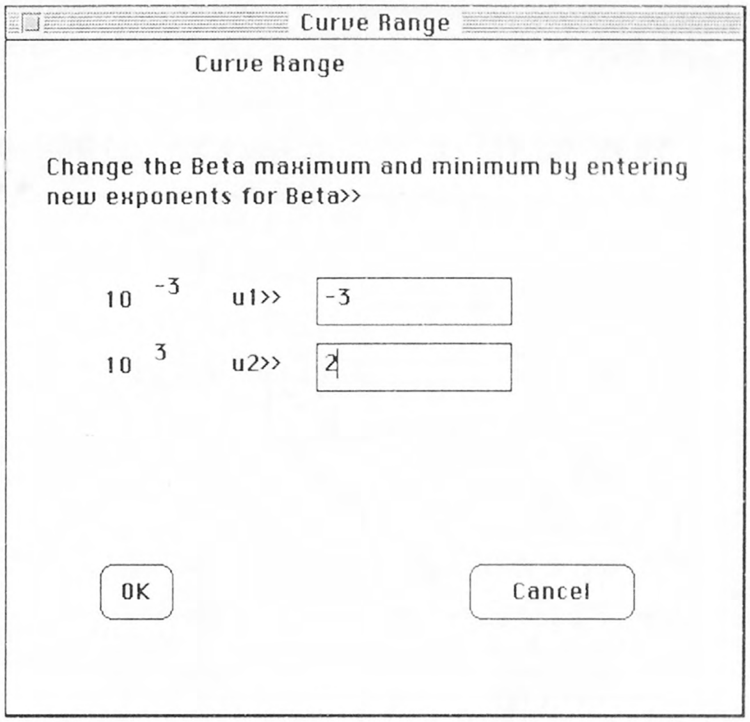


Figure 16. Selection of the range of $\beta$ values over which the Cooper, Bredehoeft, and Papadopulos (1967) type curves are to be plotted.

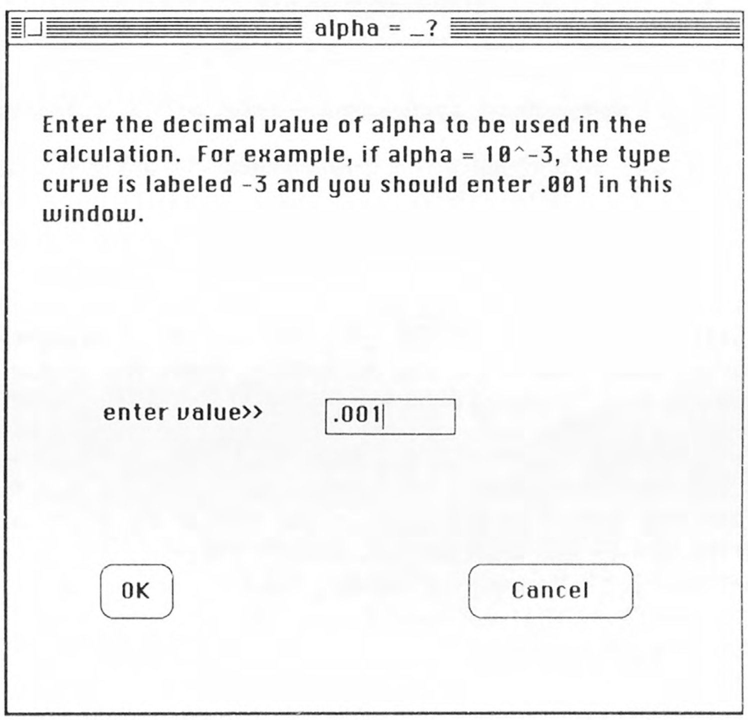


Figure 17. Specification of the $\alpha$ value to be used in the calculation of $T$ for the slug-test analysis.

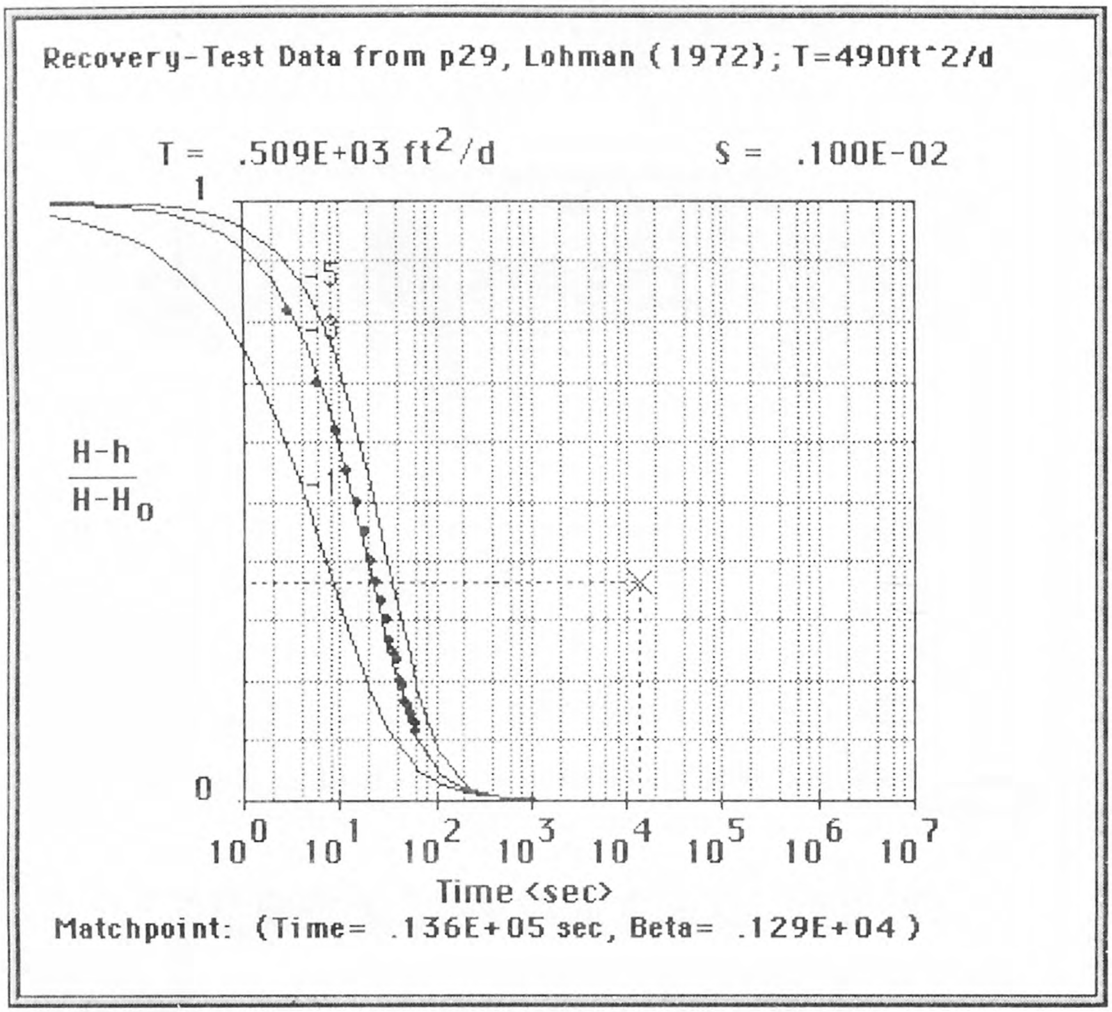


Figure 18. Window from *MACPUMP* showing final results of analysis of slug-test data using the method of Cooper and others (1967).

7. Another solution can be applied to the same data set. Choose the **Hvorslev, 1951** item under the **SOLUTIONS** menu. The program will plot a straight line that can be moved to fit the data. Move the line by holding down the mouse button with the pointer to the left of the *y*-axis or below the *x*-axis.
8. After achieving the best fit, choose the "**Compute T/S/K**" menu item. Note that when time equals 0.0, the dimensionless head should equal 1.0; that is, the head in the well at time equals 0.0 should be the head in the well at the moment of injection or removal. If the best-fit line does not pass through 1.0 on the *y*-axis at time equals 0.0, ***MACPUMP*** will plot a second line having the same slope as one that does. The program will then find $t_0$ and calculate $K$ (fig. 19). Lohman (1972) did not provide an analysis of these data using Hvorslev's method.

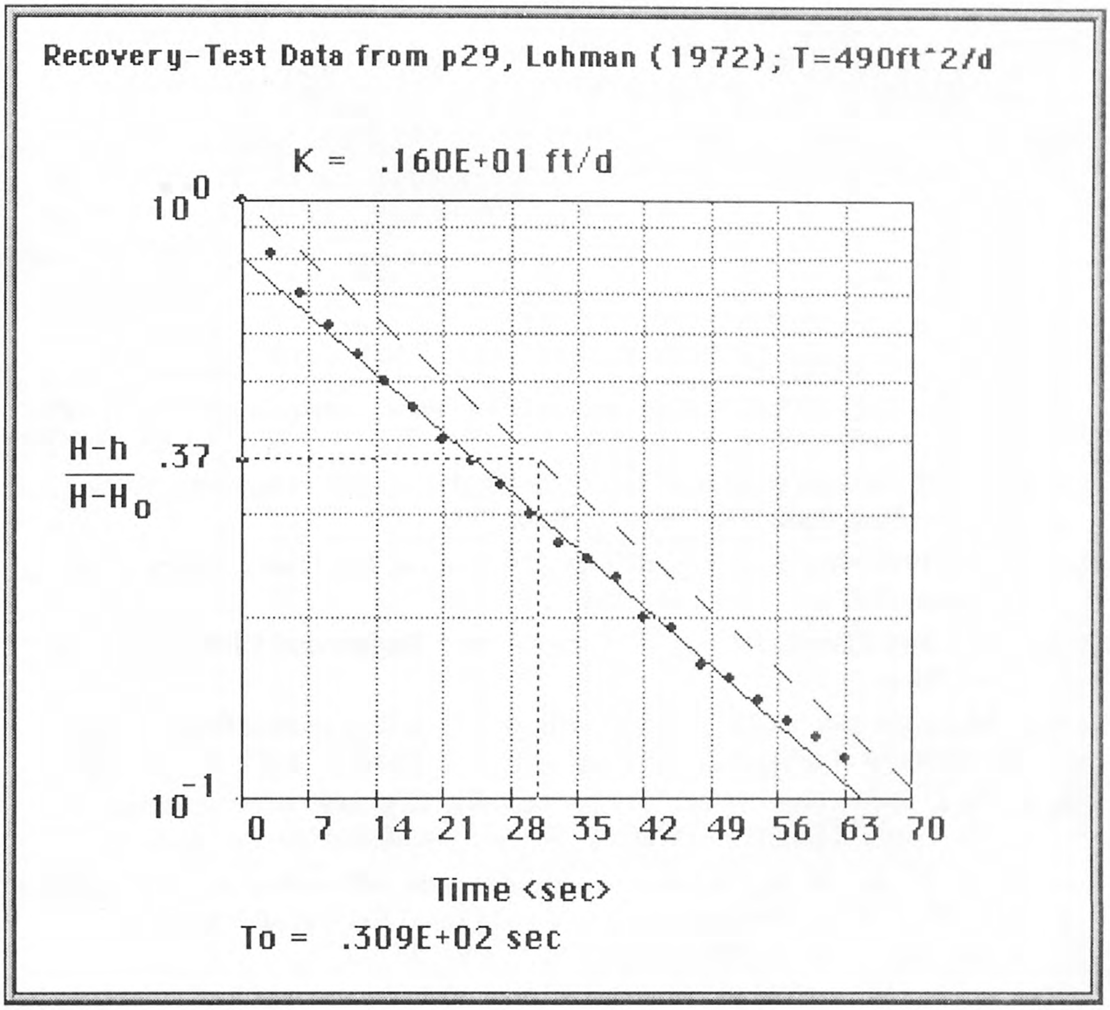


Figure 19. Using *MACPUMP* to apply Hvorslev's method to data from Lohman (1972, table 10, p. 29).

## CONCLUSIONS

The interactive computer graphical approach presented here offers an efficient and effective means to analyze data from aquifer tests. The accuracy achieved is equivalent to that attainable using manual curve-matching techniques, and the approach facilitates the evaluation of alternative conceptual models.

Although the program documented in this report contains only a limited number of models, it should still be useful for analyzing tests that meet their conditions. It is anticipated that the number of modules, representing alternative conceptual models or boundary conditions, will be expanded significantly in future updates. A version of the program for use with UNIX workstations is currently in the development stage.

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