



# Standard Test Method (Analytical Procedure) for Tests of Anisotropic Unconfined Aquifers by Neuman Method<sup>1</sup>

This standard is issued under the fixed designation D 5920; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon ( $\epsilon$ ) indicates an editorial change since the last revision or reapproval.

## 1. Scope

1.1 This test method covers an analytical procedure for determining the transmissivity, storage coefficient, specific yield, and horizontal-to-vertical hydraulic conductivity ratio of an unconfined aquifer. It is used to analyze the drawdown of water levels in piezometers and partially or fully penetrating observation wells during pumping from a control well at a constant rate.

1.2 The analytical procedure given in this test method is used in conjunction with Guide D 4043 and Test Method D 4050.

1.3 The valid use of the Neuman method is limited to determination of transmissivities for aquifers in hydrogeologic settings with reasonable correspondence to the assumptions of the theory.

1.4 The values stated in SI units are to be regarded as standard.

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

## 2. Referenced Documents

### 2.1 ASTM Standards:

D 653 Terminology Relating to Soil, Rock, and Contained Fluids<sup>2</sup>

D 4043 Guide for Selection of Aquifer-Test Method in Determining Hydraulic Properties by Well Techniques<sup>2</sup>

D 4050 Test Method (Field Procedure) for Withdrawal and Injection Well Tests for Determining Hydraulic Properties of Aquifer Systems<sup>2</sup>

D 4105 Test Method (Analytical Procedure) for Determining Transmissivity and Storage Coefficient of Nonleaky Confined Aquifers by the Modified Theis Nonequilibrium Method<sup>2</sup>

D 4106 Test Method (Analytical Procedure) for Determining Transmissivity and Storage Coefficient of Nonleaky

Confined Aquifers by the Theis Nonequilibrium Method<sup>2</sup>  
D 4750 Test Method for Determining Subsurface Liquid Levels in a Borehole or Monitoring Well<sup>2</sup>

## 3. Terminology

### 3.1 Definitions:

3.1.1 *aquifer, confined*—an aquifer bounded above and below by confining beds and in which the static head is above the top of the aquifer.

3.1.2 *aquifer, unconfined*—an aquifer that has a water table.

3.1.3 *control well*—a well by which the head and flow in the aquifer is changed by pumping, injecting, or imposing a constant change of head.

3.1.4 *drawdown*—the vertical distance the static head is lowered due to removal of water.

3.1.5 *head, static*—the height above a standard datum the surface of a column of water can be supported by the static pressure at a point.

3.1.6 *hydraulic conductivity—field aquifer test*, the volume of water at the existing kinematic viscosity that will move in a unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

3.1.7 *observation well*—a well open to all or part of an aquifer.

3.1.8 *piezometer*—a device used to measure static head at a point in the subsurface.

3.1.9 *storage coefficient*—the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head.

3.1.10 *transmissivity*—the volume of water of the prevailing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit width of the aquifer.

3.1.11 For definitions of other terms used in this test method, see Terminology D 653.

### 3.2 Symbols: Symbols and Dimensions:

3.2.1  $b$  [ $L$ ]—initial saturated thickness of the aquifer.

3.2.2  $d$  [ $L$ ]—vertical distance between top of screen in pumping well and initial position of the water table.

3.2.3  $d_D$  [nd]—dimensionless  $d$ , equal to  $d/b$ .

3.2.4  $J_0(x)$ —zero-order Bessel function of the first kind.

3.2.5  $K_r$  [ $LT^{-1}$ ]—hydraulic conductivity in the plane of the aquifer, radially from the control well.

3.2.6  $K_z$  [ $LT^{-1}$ ]—hydraulic conductivity normal to the plane of the aquifer.

<sup>1</sup> This test method is under the jurisdiction of ASTM Committee D-18 on Soil and Rock and is the direct responsibility of Subcommittee D18.21 on Ground Water and Vadose Zone Investigations.

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<sup>2</sup> *Annual Book of ASTM Standards*, Vol 04.08.

3.2.6.1 Discussion—The use of the symbol  $K$  for the hydraulic conductivity is the predominant usage in ground water literature by hydrogeologists, whereas, the symbol  $k$  is commonly used for this term in soil and rock mechanics and soil science.

3.2.7  $l$  [ $L$ ]—vertical distance between bottom of screen in control well and initial position of water table.

3.2.8  $l_D$  [ $nd$ ]—dimensionless  $l$ , equal to  $l/b$ .

3.2.9  $Q$  [ $L^3T^{-1}$ ]—discharge rate.

3.2.10  $r$  [ $L$ ]—radial distance from control well.

3.2.11  $s$  [ $L$ ]—drawdown.

3.2.12  $s_c$  [ $L$ ]—corrected drawdown.

3.2.13  $s_D$  [ $nd$ ]—dimensionless drawdown, equal to  $4\pi Ts/Q$ .

3.2.14  $s_{wt}$  [ $L$ ]—drawdown of the water table.

3.2.15  $S$  [ $nd$ ]—storage coefficient, equal to  $S_s b$ .

3.2.16  $S_s$  [ $L^{-1}$ ]—specific storage.

3.2.17  $S_y$  [ $nd$ ]—specific yield.

3.2.18  $t$  [ $T$ ]—time since pumping started.

3.2.19  $t_r$  [ $T$ ]—time since recovery started.

3.2.20  $t_s$  [ $nd$ ]—dimensionless time with respect to  $S_s$ , equal to  $Tt/Sr^2$ .

3.2.21  $t_y$  [ $nd$ ]—dimensionless time with respect to  $S_y$ , equal to  $Tt/S_y r^2$ .

3.2.22  $t_\beta$  [ $T$ ]—time,  $t$ , corresponding to intersection of a horizontal line through the intermediate data with an inclined line through late data on semilogarithmic paper.

3.2.23  $t_{y\beta}$  [ $nd$ ]—dimensionless time,  $t_y$ , corresponding to the intersection of a horizontal line through intermediate data with an inclined line through late data in Fig. 1.

3.2.24  $(t/r^2)_e$  [ $T$ ]— $t/r^2$  corresponding to the intersection of a straight line through the early data with  $s = 0$  on semilogarithmic paper [ $TL^{-2}$ ].

3.2.25  $(t/r^2)_l$  [ $T$ ]— $t/r^2$  corresponding to the intersection of a straight line through the late data with  $s = 0$  on semilogarithmic paper.

3.2.26  $T$  [ $L^2T^{-1}$ ]—transmissivity,  $K_b$ .

3.2.27  $z$  [ $L$ ]—vertical distance above the bottom of the aquifer.

3.2.28  $z_1$  [ $L$ ]—vertical distance of the bottom of the observation well screen above the bottom of the aquifer.

3.2.29  $z_2$  [ $L$ ]—vertical distance of the top of the observation well screen above the bottom of the aquifer.

3.2.30  $z_D$  [ $nd$ ]—dimensionless elevation, equal to  $z/b$ .

3.2.31  $z_{1D}$  [ $nd$ ]—dimensionless elevation of base of screen, equal to  $z_1/b$ .

3.2.32  $z_{2D}$  [ $nd$ ]—dimensionless elevation of top of screen, equal to  $z_2/b$ .

3.2.33  $\alpha$ —degree of anisotropy, equal to  $K_z/K_r$ .

3.2.34  $\beta$  [ $nd$ ]—dimensionless parameter  $\alpha r^2/b^2$ .

3.2.35  $\Delta s_e$  [ $L$ ]—the difference in drawdown over one log cycle of time along a straight line through early data on semilogarithmic paper.

3.2.36  $\Delta s_l$  [ $L$ ]—the difference in drawdown over one log cycle of time along a straight line through late data on semilogarithmic paper.

3.2.37  $\sigma$  [ $nd$ ]—dimensionless parameter  $S/S_y$ .

#### 4. Summary of Test Method

4.1 Procedure—This test method describes a procedure for analyzing data collected during a withdrawal well test. This test method should have been selected using Guide D 4043 on the basis of the hydrologic characteristics of the site. The field test (Test Method D 4050) requires pumping a control well that is open to all or part of an unconfined aquifer at a constant rate for a specified period and observing the drawdown in piezometers or observation wells that either partly or fully penetrate the aquifer. This test method may also be used to analyze an injection test with the appropriate change in sign. The rate of drawdown of water levels in the aquifer is a function of the location and depths of screened open intervals of the control

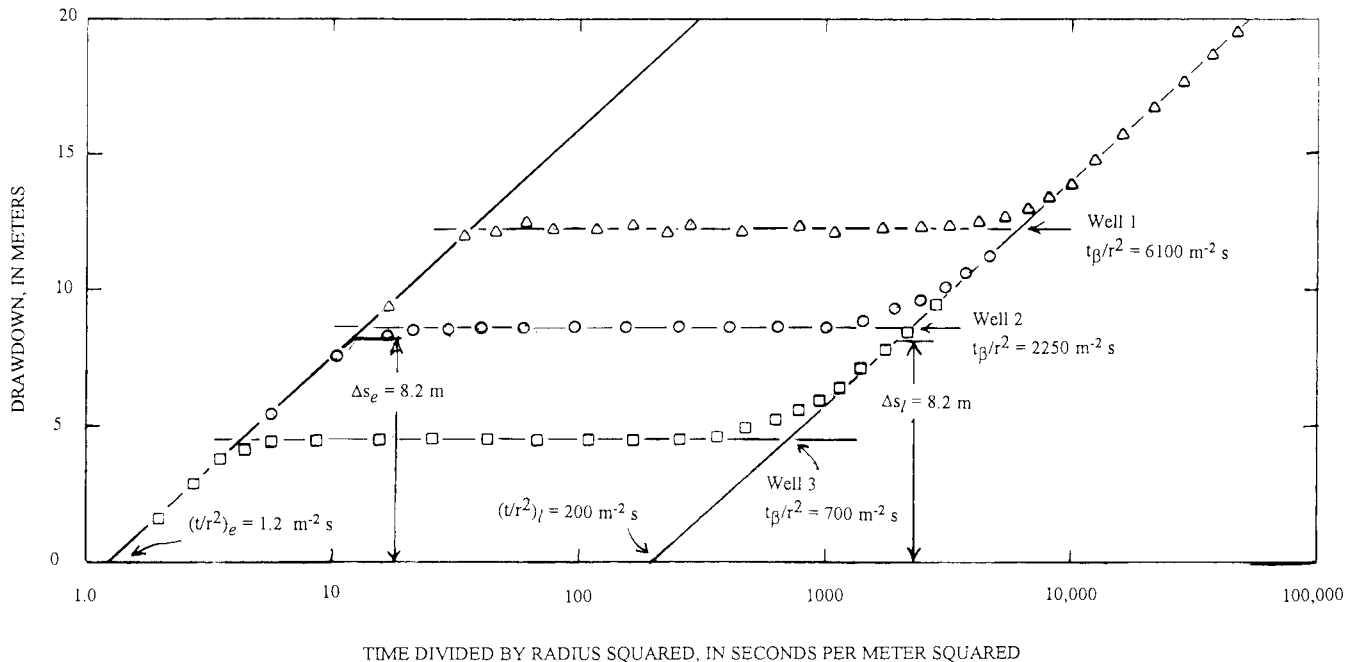


FIG. 1 Aquifer-Test Analysis, Example Two

well, observation wells, and piezometers. The drawdown may be analyzed to determine the transmissivity, storage coefficient, specific yield, and ratio of vertical to horizontal hydraulic conductivity of the aquifer. The accuracy with which any property can be determined depends on the location and length of the well screen in observation wells and piezometers. Two methods of analysis, a type curve method and a semilogarithmic method, are described.

4.2 *Solution*—The solution given by Neuman (1)<sup>3</sup> can be expressed as:

$$s(r, z, t) = \frac{Q}{4\pi T} \int_0^\infty 4yJ_0(y\beta^{1/2})[u_0(y) + \sum_{n=1}^\infty u_n(y)]dy \quad (1)$$

where, for piezometers, Neuman's (1) Eqs 27 and 28 are as follows:

$$u_0(y) = \frac{\{1 - \exp[-t_s\beta(y^2 - \gamma_0^2)]\} \cosh(\gamma_0 z_D)}{\{y^2 + (1 + \sigma)\gamma_0^2 - (y^2 - \gamma_0^2)^2/\sigma\} \cosh(\gamma_0)} \cdot \frac{\sinh[\gamma_0(1 - d_D)] - \sinh[\gamma_0(1 - l_D)]}{(l_D - d_D) \sinh(\gamma_0)} \quad (2)$$

and:

$$u_n(y) = \frac{\{1 - \exp[-t_s\beta(y^2 + \gamma_n^2)]\} \cos(\gamma_n z_D)}{\{y^2 - (1 + \sigma)\gamma_n^2 - (y^2 + \gamma_n^2)^2/\sigma\} \gamma_n} \cdot \frac{\sin[\gamma_n(1 - d_D)] - \sin[\gamma_n(1 - l_D)]}{(l_D - d_D) \sin(\gamma_n)} \quad (3)$$

and the terms  $\gamma_0$  and  $\gamma_n$  are the roots of the following equations:

$$\sigma\gamma_0 \sinh(\gamma_0) - (y^2 - \gamma_0^2) \cosh(\gamma_0) = 0 \quad (4)$$

$$\gamma_0^2 < y^2$$

$$\sigma\gamma_n \sin(\gamma_n) + (y^2 + \gamma_n^2) \cos(\gamma_n) = 0 \quad (5)$$

$$(2n - 1)(\pi/2) < \gamma_n < n\pi \quad n \geq 1$$

4.2.1 The drawdown in an observation well is the average over the screened interval, of which  $u_0(y)$  and  $u_n(y)$  are described by Neuman's (1) Eqs 29 and 30:

$$u_0(y) = \frac{\{1 - \exp[-t_s\beta(y^2 - \gamma_0^2)]\} [\sinh(\gamma_0 z_{2D}) - \sinh(\gamma_0 z_{1D})]}{\{\sinh[\gamma_0(1 - d_D)] - \sinh[\gamma_0(1 - l_D)]\}} \cdot \frac{1}{\{y^2 + (1 + \sigma)\gamma_0^2 - (y^2 - \gamma_0^2)^2/\sigma\} \cosh(\gamma_0)} \cdot (z_{2D} - z_{1D})\gamma_0(l_D - d_D) \sinh(\gamma_0) \quad (6)$$

$$u_n(y) = \frac{\{1 - \exp[-t_s\beta(y^2 + \gamma_n^2)]\} [\sin(\gamma_n z_{2D}) - \sin(\gamma_n z_{1D})]}{\{\sin[\gamma_n(1 - d_D)] - \sin[\gamma_n(1 - l_D)]\}} \cdot \frac{1}{\{y^2 - (1 + \sigma)\gamma_n^2 - (y^2 + \gamma_n^2)^2/\sigma\} \cos(\gamma_n)} \cdot (z_{2D} - z_{1D})\gamma_n(l_D - d_D) \sin(\gamma_n) \quad (7)$$

4.2.2 In the case in which the control well and observation well fully penetrate the aquifer, the equations reduce to Neuman's (1) Eqs 2 and 3 as follows:

$$u_0(y) = \frac{\{1 - \exp[-t_s\beta(y^2 - \gamma_0^2)]\} \tanh(\gamma_0)}{\{y^2 + (1 + \sigma)\gamma_0^2 - [(y^2 - \gamma_0^2)^2/\sigma]\}\gamma_0} \quad (8)$$

and:

<sup>3</sup> The boldface numbers in parentheses refer to a list of references at the end of the text.

$$u_n(y) = \frac{\{1 - \exp[-t_s\beta(y^2 + \gamma_n^2)]\} \tan(\gamma_n)}{\{y^2 - (1 + \sigma)\gamma_n^2 - (y^2 + \gamma_n^2)^2/\sigma\}\gamma_n} \quad (9)$$

## 5. Significance and Use

### 5.1 Assumptions:

5.1.1 The control well discharges at a constant rate,  $Q$ .

5.1.2 The control well, observation wells, and piezometers are of infinitesimal diameter.

5.1.3 The unconfined aquifer is homogeneous and really extensive.

5.1.4 Discharge from the control well is derived initially from elastic storage in the aquifer, and later from gravity drainage from the water table.

5.1.5 The geometry of the aquifer, control well, observation wells, and piezometers is shown in Fig. 2. The geometry of the test wells should be adjusted depending on the parameters of interest.

### 5.2 Implications of Assumptions:

5.2.1 Use of the Neuman (1) method assumes the control well is of infinitesimal diameter. The storage in the control well may adversely affect drawdown measurements obtained in the early part of the test. See 5.2.2 of Test Method D 4106 for assistance in determining the duration of the effects of well-bore storage on drawdown.

5.2.2 If drawdown is large compared with the initial saturated thickness of the aquifer, the late-time drawdown may need to be adjusted for the effect of the reduction in saturated thickness. Section 5.2.3 of Test Method D 4106 provides guidance in correcting for the reduction in saturated thickness. According to Neuman (1) such adjustments should be made only for late-time values.

## 6. Apparatus

6.1 *Analysis*—Analysis of data from the field procedure (see Test Method D 4050) by this test method requires that the control well and observation wells meet the requirements specified in the following subsections.

6.2 *Construction of Control Well*—Install the control well in the aquifer, and equip with a pump capable of discharging water from the well at a constant rate for the duration of the test.

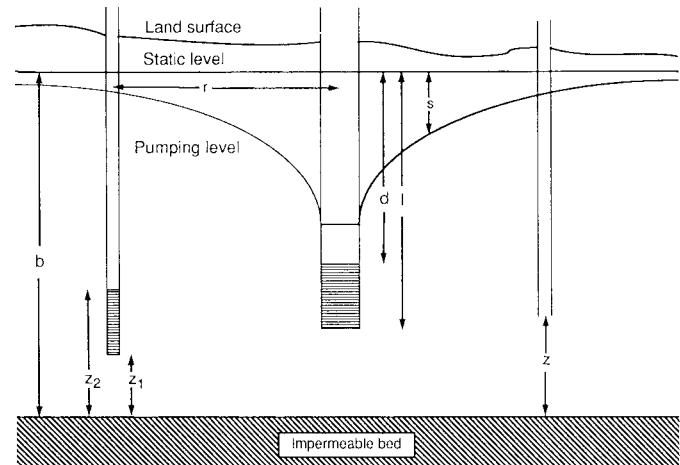


FIG. 2 Cross Section Through a Discharging Well Screened in Part of an Unconfined Aquifer



**TABLE 2 Values of  $S_D$  for the Construction of Type B Curves for Fully Penetrating Wells (1)<sup>A</sup>**

$t_y$	$\beta = 0.001$	$\beta = 0.004$	$\beta = 0.01$	$\beta = 0.03$	$\beta = 0.06$	$\beta = 0.1$	$\beta = 0.2$	$\beta = 0.4$	$\beta = 0.6$
$1 \times 10^{-4}$	$5.62 \times 10^0$	$4.30 \times 10^0$	$3.46 \times 10^0$	$2.50 \times 10^0$	$1.94 \times 10^0$	$1.56 \times 10^0$	$1.09 \times 10^0$	$6.97 \times 10^{-1}$	$5.08 \times 10^{-1}$
$2 \times 10^{-4}$	...	...	...	...	...	...	...	...	...
$3.5 \times 10^{-4}$	...	...	...	...	...	...	...	...	...
$6 \times 10^{-4}$	...	...	...	...	...	...	...	...	...
$1 \times 10^{-3}$	...	...	...	...	...	...	...	$6.97 \times 10^{-1}$	$5.08 \times 10^{-1}$
$2 \times 10^{-3}$	...	...	...	...	...	...	...	$6.97 \times 10^{-1}$	$5.09 \times 10^{-1}$
$3.5 \times 10^{-3}$	...	...	...	...	...	...	...	$6.98 \times 10^{-1}$	$5.10 \times 10^{-1}$
$6 \times 10^{-3}$	...	...	...	...	...	...	...	$7.00 \times 10^{-1}$	$5.12 \times 10^{-1}$
$1 \times 10^{-2}$	...	...	...	...	...	...	...	$7.03 \times 10^{-1}$	$5.16 \times 10^{-1}$
$2 \times 10^{-2}$	...	...	...	...	...	$1.56 \times 10^0$	$1.09 \times 10^0$	$7.10 \times 10^{-1}$	$5.24 \times 10^{-1}$
$3.5 \times 10^{-2}$	...	...	...	...	$1.94 \times 10^0$	$1.56 \times 10^0$	$1.10 \times 10^0$	$7.20 \times 10^{-1}$	$5.37 \times 10^{-1}$
$6 \times 10^{-2}$	...	...	...	$2.50 \times 10^0$	$1.95 \times 10^0$	$1.57 \times 10^0$	$1.11 \times 10^0$	$7.37 \times 10^{-1}$	$5.57 \times 10^{-1}$
$1 \times 10^{-1}$	...	...	...	$2.51 \times 10^0$	$1.96 \times 10^0$	$1.58 \times 10^0$	$1.13 \times 10^0$	$7.63 \times 10^{-1}$	$5.89 \times 10^{-1}$
$2 \times 10^{-1}$	$5.62 \times 10^0$	$4.30 \times 10^0$	$3.46 \times 10^0$	$2.52 \times 10^0$	$1.98 \times 10^0$	$1.61 \times 10^0$	$1.18 \times 10^0$	$8.29 \times 10^{-1}$	$6.67 \times 10^{-1}$
$3.5 \times 10^{-1}$	$5.63 \times 10^0$	$4.31 \times 10^0$	$3.47 \times 10^0$	$2.54 \times 10^0$	$2.01 \times 10^0$	$1.66 \times 10^0$	$1.24 \times 10^0$	$9.22 \times 10^{-1}$	$7.80 \times 10^{-1}$
$6 \times 10^{-1}$	$5.63 \times 10^0$	$4.31 \times 10^0$	$3.49 \times 10^0$	$2.57 \times 10^0$	$2.06 \times 10^0$	$1.73 \times 10^0$	$1.35 \times 10^0$	$1.07 \times 10^0$	$9.54 \times 10^{-1}$
$1 \times 10^0$	$5.63 \times 10^0$	$4.32 \times 10^0$	$3.51 \times 10^0$	$2.62 \times 10^0$	$2.13 \times 10^0$	$1.83 \times 10^0$	$1.50 \times 10^0$	$1.29 \times 10^0$	$1.20 \times 10^0$
$2 \times 10^0$	$5.64 \times 10^0$	$4.35 \times 10^0$	$3.56 \times 10^0$	$2.73 \times 10^0$	$2.31 \times 10^0$	$2.07 \times 10^0$	$1.85 \times 10^0$	$1.72 \times 10^0$	$1.68 \times 10^0$
$3.5 \times 10^0$	$5.65 \times 10^0$	$4.38 \times 10^0$	$3.63 \times 10^0$	$2.88 \times 10^0$	$2.55 \times 10^0$	$2.37 \times 10^0$	$2.23 \times 10^0$	$2.17 \times 10^0$	$2.15 \times 10^0$
$6 \times 10^0$	$5.67 \times 10^0$	$4.44 \times 10^0$	$3.74 \times 10^0$	$3.11 \times 10^0$	$2.86 \times 10^0$	$2.75 \times 10^0$	$2.68 \times 10^0$	$2.66 \times 10^0$	$2.65 \times 10^0$
$1 \times 10^1$	$5.70 \times 10^0$	$4.52 \times 10^0$	$3.90 \times 10^0$	$3.40 \times 10^0$	$3.24 \times 10^0$	$3.18 \times 10^0$	$3.15 \times 10^0$	$3.14 \times 10^0$	$3.14 \times 10^0$
$2 \times 10^1$	$5.76 \times 10^0$	$4.71 \times 10^0$	$4.22 \times 10^0$	$3.92 \times 10^0$	$3.85 \times 10^0$	$3.83 \times 10^0$	$3.82 \times 10^0$	$3.82 \times 10^0$	$3.82 \times 10^0$
$3.5 \times 10^1$	$5.85 \times 10^0$	$4.94 \times 10^0$	$4.58 \times 10^0$	$4.40 \times 10^0$	$4.38 \times 10^0$	$4.38 \times 10^0$	$4.37 \times 10^0$	$4.37 \times 10^0$	$4.37 \times 10^0$
$6 \times 10^1$	$5.99 \times 10^0$	$5.23 \times 10^0$	$5.00 \times 10^0$	$4.92 \times 10^0$	$4.91 \times 10^0$	$4.91 \times 10^0$	$4.91 \times 10^0$	$4.91 \times 10^0$	$4.91 \times 10^0$
$1 \times 10^2$	$6.16 \times 10^0$	$5.59 \times 10^0$	$5.46 \times 10^0$	$5.42 \times 10^0$	$5.42 \times 10^0$	$5.42 \times 10^0$	$5.42 \times 10^0$	$5.42 \times 10^0$	$5.42 \times 10^0$
$\beta = 0.8$	$\beta = 1.0$	$\beta = 1.5$	$\beta = 2.0$	$\beta = 2.5$	$\beta = 3.0$	$\beta = 4.0$	$\beta = 5.0$	$\beta = 6.0$	$\beta = 7.0$
$3.95 \times 10^{-1}$	$3.18 \times 10^{-1}$	$2.04 \times 10^{-1}$	$1.42 \times 10^{-1}$	$1.03 \times 10^{-1}$	$7.80 \times 10^{-2}$	$4.79 \times 10^{-2}$	$3.14 \times 10^{-2}$	$2.15 \times 10^{-2}$	$1.53 \times 10^{-2}$
...	...	...	...	...	$7.81 \times 10^{-2}$	$4.80 \times 10^{-2}$	$3.15 \times 10^{-2}$	$2.16 \times 10^{-2}$	$1.53 \times 10^{-2}$
...	...	...	...	$1.03 \times 10^{-1}$	$7.83 \times 10^{-2}$	$4.81 \times 10^{-2}$	$3.16 \times 10^{-2}$	$2.17 \times 10^{-2}$	$1.54 \times 10^{-2}$
...	...	...	...	$1.04 \times 10^{-1}$	$7.85 \times 10^{-2}$	$4.84 \times 10^{-2}$	$3.18 \times 10^{-2}$	$2.19 \times 10^{-2}$	$1.56 \times 10^{-2}$
$3.95 \times 10^{-1}$	$3.18 \times 10^{-1}$	$2.04 \times 10^{-1}$	$1.42 \times 10^{-1}$	$1.04 \times 10^{-1}$	$7.89 \times 10^{-2}$	$4.78 \times 10^{-2}$	$3.21 \times 10^{-2}$	$2.21 \times 10^{-2}$	$1.58 \times 10^{-2}$
$3.96 \times 10^{-1}$	$3.19 \times 10^{-1}$	$2.05 \times 10^{-1}$	$1.43 \times 10^{-1}$	$1.05 \times 10^{-1}$	$7.99 \times 10^{-2}$	$4.96 \times 10^{-2}$	$3.29 \times 10^{-2}$	$2.28 \times 10^{-2}$	$1.64 \times 10^{-2}$
$3.97 \times 10^{-1}$	$3.21 \times 10^{-1}$	$2.07 \times 10^{-1}$	$1.45 \times 10^{-1}$	$1.07 \times 10^{-1}$	$8.14 \times 10^{-2}$	$5.09 \times 10^{-2}$	$3.41 \times 10^{-2}$	$2.39 \times 10^{-2}$	$1.73 \times 10^{-2}$
$3.99 \times 10^{-1}$	$3.23 \times 10^{-1}$	$2.09 \times 10^{-1}$	$1.47 \times 10^{-1}$	$1.09 \times 10^{-1}$	$8.38 \times 10^{-2}$	$5.32 \times 10^{-2}$	$3.61 \times 10^{-2}$	$2.57 \times 10^{-2}$	$1.89 \times 10^{-2}$
$4.03 \times 10^{-1}$	$3.27 \times 10^{-1}$	$2.13 \times 10^{-1}$	$1.52 \times 10^{-1}$	$1.13 \times 10^{-1}$	$8.79 \times 10^{-2}$	$5.68 \times 10^{-2}$	$3.93 \times 10^{-2}$	$2.86 \times 10^{-2}$	$2.15 \times 10^{-2}$
$4.12 \times 10^{-1}$	$3.37 \times 10^{-1}$	$2.24 \times 10^{-1}$	$1.62 \times 10^{-1}$	$1.24 \times 10^{-1}$	$9.80 \times 10^{-2}$	$6.61 \times 10^{-2}$	$4.78 \times 10^{-2}$	$3.62 \times 10^{-2}$	$2.84 \times 10^{-2}$
$4.25 \times 10^{-1}$	$3.50 \times 10^{-1}$	$2.39 \times 10^{-1}$	$1.78 \times 10^{-1}$	$1.39 \times 10^{-1}$	$1.13 \times 10^{-1}$	$8.06 \times 10^{-2}$	$6.12 \times 10^{-2}$	$4.86 \times 10^{-2}$	$3.98 \times 10^{-2}$
$4.47 \times 10^{-1}$	$3.74 \times 10^{-1}$	$2.65 \times 10^{-1}$	$2.05 \times 10^{-1}$	$1.66 \times 10^{-1}$	$1.40 \times 10^{-1}$	$1.06 \times 10^{-1}$	$8.53 \times 10^{-2}$	$7.14 \times 10^{-2}$	$6.14 \times 10^{-2}$
$4.83 \times 10^{-1}$	$4.12 \times 10^{-1}$	$3.07 \times 10^{-1}$	$2.48 \times 10^{-1}$	$2.10 \times 10^{-1}$	$1.84 \times 10^{-1}$	$1.49 \times 10^{-1}$	$1.28 \times 10^{-1}$	$1.13 \times 10^{-1}$	$1.02 \times 10^{-1}$
$5.71 \times 10^{-1}$	$5.06 \times 10^{-1}$	$4.10 \times 10^{-1}$	$3.57 \times 10^{-1}$	$3.23 \times 10^{-1}$	$2.98 \times 10^{-1}$	$2.66 \times 10^{-1}$	$2.45 \times 10^{-1}$	$2.31 \times 10^{-1}$	$2.20 \times 10^{-1}$
$6.97 \times 10^{-1}$	$6.42 \times 10^{-1}$	$5.62 \times 10^{-1}$	$5.17 \times 10^{-1}$	$4.89 \times 10^{-1}$	$4.70 \times 10^{-1}$	$4.45 \times 10^{-1}$	$4.30 \times 10^{-1}$	$4.19 \times 10^{-1}$	$4.11 \times 10^{-1}$
$8.89 \times 10^{-1}$	$8.50 \times 10^{-1}$	$7.92 \times 10^{-1}$	$7.63 \times 10^{-1}$	$7.45 \times 10^{-1}$	$7.33 \times 10^{-1}$	$7.18 \times 10^{-1}$	$7.09 \times 10^{-1}$	$7.03 \times 10^{-1}$	$6.99 \times 10^{-1}$
$1.16 \times 10^0$	$1.13 \times 10^0$	$1.10 \times 10^0$	$1.08 \times 10^0$	$1.07 \times 10^0$	$1.07 \times 10^0$	$1.06 \times 10^0$	$1.06 \times 10^0$	$1.05 \times 10^0$	$1.05 \times 10^0$
$1.66 \times 10^0$	$1.65 \times 10^0$	$1.64 \times 10^0$	$1.63 \times 10^0$	$1.63 \times 10^0$	$1.63 \times 10^0$	$1.63 \times 10^0$	$1.63 \times 10^0$	$1.63 \times 10^0$	$1.63 \times 10^0$
$2.15 \times 10^0$	$2.14 \times 10^0$	$2.14 \times 10^0$	$2.14 \times 10^0$	$2.14 \times 10^0$	$2.14 \times 10^0$	$2.14 \times 10^0$	$2.14 \times 10^0$	$2.14 \times 10^0$	$2.14 \times 10^0$
$2.65 \times 10^0$	$2.65 \times 10^0$	$2.65 \times 10^0$	$2.64 \times 10^0$	$2.64 \times 10^0$	$2.64 \times 10^0$	$2.64 \times 10^0$	$2.64 \times 10^0$	$2.64 \times 10^0$	$2.64 \times 10^0$
$3.14 \times 10^0$	$3.14 \times 10^0$	$3.14 \times 10^0$	$3.14 \times 10^0$	$3.14 \times 10^0$	$3.14 \times 10^0$	$3.14 \times 10^0$	$3.14 \times 10^0$	$3.14 \times 10^0$	$3.14 \times 10^0$
$3.82 \times 10^0$	$3.82 \times 10^0$	$3.82 \times 10^0$	$3.82 \times 10^0$	$3.82 \times 10^0$	$3.82 \times 10^0$	$3.82 \times 10^0$	$3.82 \times 10^0$	$3.82 \times 10^0$	$3.82 \times 10^0$
$4.37 \times 10^0$	$4.37 \times 10^0$	$4.37 \times 10^0$	$4.37 \times 10^0$	$4.37 \times 10^0$	$4.37 \times 10^0$	$4.37 \times 10^0$	$4.37 \times 10^0$	$4.37 \times 10^0$	$4.37 \times 10^0$
$4.91 \times 10^0$	$4.91 \times 10^0$	$4.91 \times 10^0$	$4.91 \times 10^0$	$4.91 \times 10^0$	$4.91 \times 10^0$	$4.91 \times 10^0$	$4.91 \times 10^0$	$4.91 \times 10^0$	$4.91 \times 10^0$
$5.42 \times 10^0$	$5.42 \times 10^0$	$5.42 \times 10^0$	$5.42 \times 10^0$	$5.42 \times 10^0$	$5.42 \times 10^0$	$5.42 \times 10^0$	$5.42 \times 10^0$	$5.42 \times 10^0$	$5.42 \times 10^0$

<sup>A</sup> Values were obtained from Ref (2) by setting  $\sigma = 10^{-2}$ .

data as possible to the left-most part of the type curve (Type A curves). Select an early-time match point, and record the values of  $s$ ,  $t/r^2$ ,  $s_D$  and  $t_s$ . Moving the data plot horizontally, match as many as possible of the late-time data to the right-most part of the type curves (Type B curves) and select a late-time match point. Record the values of  $s$ ,  $s_D$ ,  $t/r^2$ , and  $t_y$  for this match point. The values of  $s$  and  $s_D$  should be the same for each match point, that is, the data curves should be shifted only horizontally, not vertically, on the type curve, and the values of  $\beta$  for each observation well should be the same for early and late times.

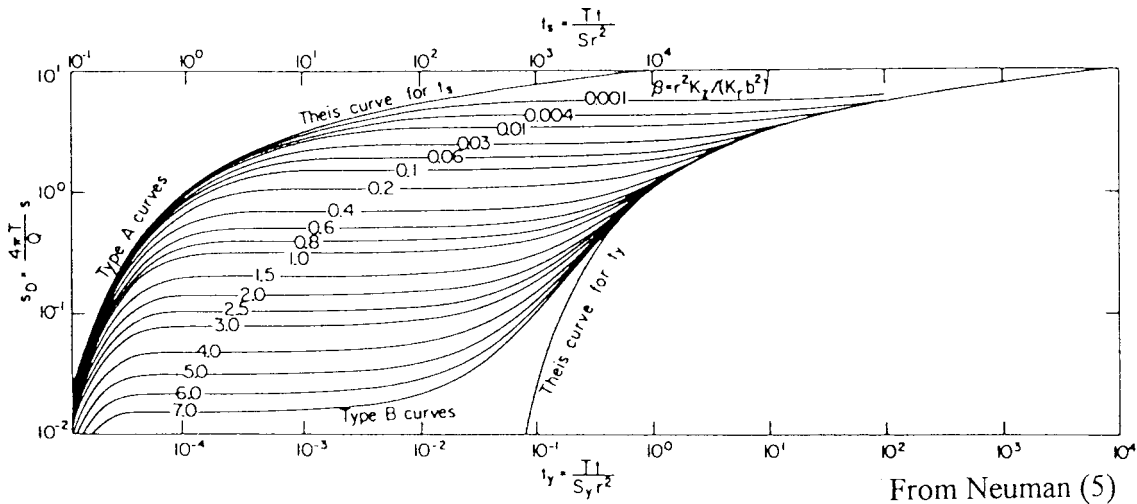
8.1.1.3 Repeat the procedure in 8.1.1.2 for all additional data plots and type curves. The values of  $s$  and  $s_D$  should be the same for all plots in a single test. If necessary, repeat the

analysis for each plot until a consistent set of values is obtained between all plots. Calculate the value of the term  $\beta/r^2$  for every observation well or piezometer. Because the remaining terms in the definition of  $\beta$ ,  $\alpha/b^2$ , should be nearly constant over the area of the test, the term  $\beta/r^2$  should be independent of radius. If not, a new set of match points should be obtained, and  $\beta/r^2$  computed for each well until the values are independent of radius.

8.1.1.4 Calculate the transmissivity, specific yield, storage coefficient, and horizontal hydraulic conductivity from the values of  $s$ ,  $s_D$ ,  $t/r^2$ ,  $t_s$  and  $t_y$ :

$$T = Qs_D/4\pi s \quad (10)$$

$$S_y = (T/t_y)(t/r^2) \quad (11)$$



NOTE 1—From Ref (5).

FIG. 3 Type Curves for Fully Penetrating Wells

$$S = (T/t_s)(t/r^2) \quad (12)$$

$$K_r = T/b \quad (13)$$

The anisotropy can be calculated from:

$$\alpha = (\beta/r^2)b^2 \quad (14)$$

and the vertical permeability from:

$$K_z = \alpha K_r \quad (15)$$

8.1.1.5 The results of a hypothetical aquifer test are shown in Fig. 4. A control well is discharged at a rate of  $0.21 \text{ m}^3 \text{ s}^{-1}$ , and water levels are measured in OW1 at a radius of 9 m from the control well, in OW2 ( $r = 50 \text{ m}$ ), and OW3 ( $r = 185 \text{ m}$ ). A log-log plot of drawdown versus time divided by the radius to the control well, squared, is shown for the three observation wells, superimposed on type curves derived from the data in Table 1 and Table 2. Measurements from each observation well fall on a different  $\beta$  curve.

8.1.1.6 For the example, the transmissivity from Eq 10 is:  
 $T = Q_s d / 4\pi s = (0.21 \text{ m}^3 \text{ s}^{-1} \times 1.0) / (4 \times 3.14 \times 6.5 \text{ m})$   
 $= 2.57 \times 10^{-3} \text{ m}^2 \text{ s}^{-1}$ ,

and the specific yield from Eq 11 is:

$$S_y = (T/t_y)(t/r^2) = (2.57 \times 10^{-3} \text{ m}^2 \text{ s}^{-1} / 1.0)(88 \text{ m}^{-2} \text{ s}) = 0.23$$

The storage coefficient, from Eq 11 is:

$$S = (T/t_s)(t/r^2) = (2.57 \times 10^{-3} \text{ m}^2 \text{ s}^{-1} / 1.0)(0.145 \text{ m}^{-2} \text{ s}) = 3.7 \times 10^{-4}$$

The ratio of vertical to horizontal hydraulic conductivity can be calculated from Eq 14 using an assumed aquifer thickness,  $b$  of 25 m, and data from OW1 as follows:

$$\alpha = (\beta/r^2)b^2 = (0.004/81 \text{ m}^2)(625 \text{ m}^2) = 0.03$$

8.1.2 *Semilogarithmic Method*—This procedure is applicable to tests in which the control and observation wells effectively fully penetrate the aquifer. Plot drawdown on the vertical (arithmetic) axis and time divided by the square of the radius to the control well on the horizontal (logarithmic) axis for all observation wells. The early and late data will tend to fall on parallel straight lines. The intermediate values will fall on horizontal lines between these two extremes.

8.1.2.1 Fit a straight line to the late data. The intersection of this line with the horizontal axis ( $s = 0$ ) is denoted by  $(t/r^2)_l$ . The slope of the line over one log cycle of  $t/r^2$  is denoted  $\Delta s_l$ . The transmissivity and specific yield of the aquifer are then calculated from Jacob's (3) method, using the procedures described in Test Method D 4105.

$$T = 2.30 Q / 4\pi \Delta s_l \quad (16)$$

$$S_y = 2.25 T (t/r^2)_l \quad (17)$$

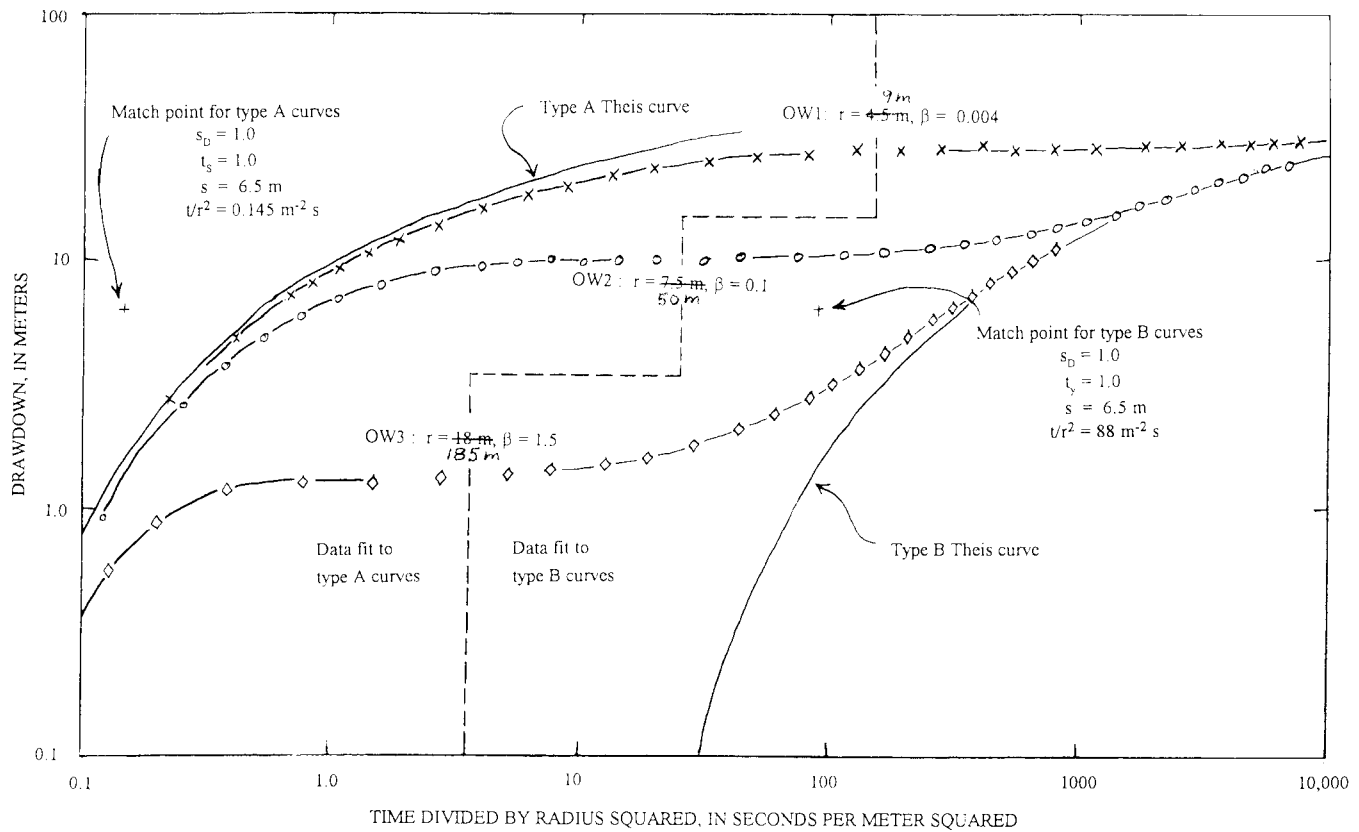


FIG. 4 Aquifer-Test Analysis, Example 1

8.1.2.2 Fit a horizontal straight line to the intermediate data for each observation well. The intersection of the horizontal straight line with the late-time straight line is denoted  $t_\beta$ . The dimensionless time  $t_y\beta$  is then calculated from the following:

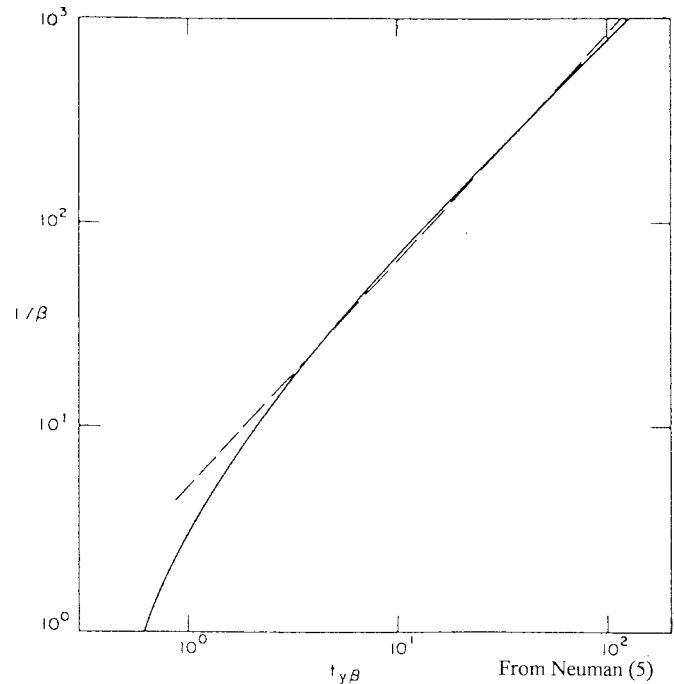
$$t_{y\beta} = (T/S_y)(t_\beta/r^2) \quad (18)$$

Using the values of  $t_y\beta$ , values of  $\beta$  for each observation well may be obtained by interpolation from Table 3 or be picked from Fig. 5. The values of  $\beta$  should be independent of radius, as in 8.1.1.3.

TABLE 3 Values of  $1/\beta$  and  $t_{y\beta}$  used in plotting Fig. 5, (1)

$1/\beta$	$t_{y\beta}$
$2.50 \times 10^{-1}$	$4.52 \times 10^{-1}$
$1.67 \times 10^{-1}$	$4.55 \times 10^{-1}$
$2.00 \times 10^{-1}$	$4.59 \times 10^{-1}$
$2.50 \times 10^{-1}$	$4.67 \times 10^{-1}$
$3.33 \times 10^{-1}$	$4.81 \times 10^{-1}$
$4.00 \times 10^{-1}$	$4.94 \times 10^{-1}$
$5.00 \times 10^{-1}$	$5.13 \times 10^{-1}$
$6.67 \times 10^{-1}$	$5.45 \times 10^{-1}$
$1.00 \times 10^0$	$6.11 \times 10^{-1}$
$1.25 \times 10^0$	$6.60 \times 10^{-1}$
$1.67 \times 10^0$	$7.39 \times 10^{-1}$
$2.50 \times 10^0$	$8.93 \times 10^{-1}$
$5.00 \times 10^0$	$1.31 \times 10^0$
$1.00 \times 10^1$	$2.10 \times 10^0$
$1.67 \times 10^1$	$3.10 \times 10^0$
$3.33 \times 10^1$	$5.42 \times 10^0$
$1.00 \times 10^2$	$1.42 \times 10^1$
$2.50 \times 10^2$	$3.22 \times 10^1$
$1.00 \times 10^3$	$1.23 \times 10^2$

<sup>A</sup> Values were obtained from Ref (2) by setting  $\sigma = 10^{-9}$ .



NOTE 1—From Ref (1).

FIG. 5 Values of  $1/\beta$  Versus  $t_{y\beta}$  for Fully Penetrating Wells

8.1.2.3 Fit a straight line to the early part of the time-drawdown data. The intersection of this line with the horizontal axis is denoted by  $(t/r^2)_e$ , and the slope of this line over one log

cycle is  $\Delta s_e$ . The transmissivity and storage coefficient are calculated from:

$$T = 2.30 Q/4\pi\Delta s_e \quad (19)$$

$$S = 2.25 T (t/r^2)_e \quad (20)$$

8.1.2.4 The slope of the line should be the same as the one computed in 8.1.2.1; that is, the transmissivity should be the same. If not, the type-curve method in 8.1.1 must be used to compute the storage coefficient.

8.1.2.5 A hypothetical example of the use of the semilogarithmic method is shown in Fig. 1. In this example a control well is discharged at  $0.01 \text{ m}^3 \text{ s}^{-1}$ , and water levels are measured in a fully penetrating observation Well One ( $r = 4.5 \text{ m}$ ), Well Two ( $r = 7.5 \text{ m}$ ), and Well Three ( $r = 18 \text{ m}$ ). The change in drawdown over one log cycle of time for the late data,  $\Delta s_l$ , is  $8.2 \text{ m}$ . The intersection of a line through the late data with the  $s = 0$  axis,  $(t/r^2)_l$ , is  $200 \text{ m}^{-2}\text{s}$ . The transmissivity and specific yield calculated from Eq 16 and Eq 17 are as follows:

$$T = 2.30 Q/4\pi\Delta s_l = (2.30 \times 0.01 \text{ m}^3 \text{ s}^{-1})/(4 \times 3.14 \times 8.2 \text{ m}) \\ = 2.23 \times 10^{-4} \text{ m}^2 \text{ s}^{-1} \\ S_y = 2.25 T (t/r^2)_l = 2.25 (2.23 \times 10^{-4} \text{ m}^2 \text{ s}^{-1})(200 \text{ m}^{-2} \text{ s}) \\ = 0.10$$

8.1.2.6 From the intersection of the horizontal parts of the data plot with the late-time part, a value of  $t_{\beta}/r^2$  of  $6100 \text{ m}^{-2}\text{s}$  was determined for Well One,  $2250 \text{ m}^{-2}\text{s}$  for Well Two, and  $700 \text{ m}^{-2}\text{s}$  for Well Three. From Eq 18, a value of  $t_{y\beta}$  is calculated for Well One as follows:

$$t_{y\beta} = (T/S_y)(t_{\beta}/r^2) = [(2.23 \times 10^{-4} \text{ m}^2 \text{ s}^{-1})/(6100 \text{ m}^{-2}\text{s})] = 14$$

Similar calculations yield values of  $t_{y\beta}$  of 5 for Well Two and 1.6 for Well Three. From Fig. 5 an approximate value of 100 is estimated for  $1/\beta$  for Well One, 31 for Well Two, and 6 for Well Three.

8.1.2.7 The change in drawdown for one log cycle of time divided by radius squared for early time data,  $\Delta s_e$ , is  $8.2 \text{ m}$ . The transmissivity calculated from the early data using Eq 19 is therefore the same as that calculated from the late data:

$$T = 2.30 Q/4\pi\Delta s_e = (2.30 \times 0.01 \text{ m}^3 \text{ s}^{-1})/ \\ (4 \times 3.14 \times 8.2 \text{ m}) = 2.23 \times 10^{-4} \text{ m}^2 \text{ s}^{-1}$$

8.1.2.8 The intersection of the early data with the horizontal axis at  $s = 0$ ,  $(t/r^2)_e$ , is  $1.2 \text{ m}^{-2}\text{s}$ , so from Eq 20 the storage coefficient is as follows:

$$S = 2.25 T (t/r^2)_e = 2.25 (2.23 \times 10^{-4} \text{ m}^2 \text{ s}^{-1})(1.2 \text{ m}^{-2}\text{s}) \\ = 6 \times 10^{-4}$$

## 9. Report

9.1 *Preparation*—Prepare a report including the following information. The report of the analysis will include information from the field testing procedure.

9.1.1 *Introduction*—The introductory section is intended to present the scope and purpose of the Neuman method for an unconfined, anisotropic aquifer. Summarize the field geohydrologic conditions and the field equipment and instrumentation including the construction of the control well and observation

wells and piezometers, the method of measurement of discharge and water levels, and the duration of the test and pumping rates. Discuss the rationale for selecting the Neuman method.

9.1.2 *Hydrogeologic Setting*—Review the information available on the hydrogeology of the site. Interpret and describe the hydrogeology of the site as it pertains to the selection of this test method for conducting and analyzing an aquifer test. Compare the hydrogeologic characteristics of the site as it conforms and differs from the assumptions in the solution to the aquifer test method.

9.1.3 *Scope of Aquifer Test:*

9.1.3.1 *Equipment*—Report the field installation and equipment for the aquifer test, including the construction, diameter, depth of screened interval, and location of control well and pumping equipment, and the construction, diameter, depth, and screened interval of observation wells or piezometers.

9.1.3.2 *Instrumentation*—Report the field instrumentation for observing water levels, pumping rate, barometric pressure changes, and other environmental conditions pertinent to the test. Include a list of measuring devices used during the test; the manufacturer's name, model number, and basic specifications for each major item; and the name and date of the last calibration, if applicable.

9.1.3.3 *Testing Procedures*—State the steps taken in conducting pretest, drawdown, and recovery phases of the test. Include the frequency of measurements of discharge rate, water level in observation wells, and other environmental data recorded during the testing procedure.

9.1.4 *Presentation and Interpretation of Test Results:*

9.1.4.1 *Data*—Present tables of data collected during the test. Show methods of adjusting water levels for pretest trends, and calculation of drawdown and residual drawdown.

9.1.4.2 *Data Plots*—Present data plots used in analysis of the data. Show data plots with all values of  $\beta$ , all match points, and all match-point values.

9.1.4.3 Evaluate qualitatively the overall accuracy of the test on the basis of the adequacy of instrumentation and observations of stress and response, and the conformance of the hydrogeologic conditions and the conformance of the test to the assumptions of this test method.

## 10. Precision and Bias

10.1 *Precision*—It is not practicable to specify the precision of this test method because the response of aquifer systems during aquifer tests is dependent upon ambient system stresses.

10.2 *Bias*—No statement can be made about bias because no true reference values exist.

## 11. Keywords

11.1 anisotropic aquifers; aquifers; aquifer tests; control wells; ground water; hydraulic properties; observation wells; transmissivity; unconfined aquifers



**REFERENCES**

- (1) Neuman, Shlomo P., "Analysis of Pumping Test Data from Anisotropic Aquifers Considering Delayed Gravity Response," *Water Resources Research*, Vol 11, No. 2, 1975, pp. 329–342.
- (2) Dawson, K. J., and Istok, J. D., *Aquifer Testing, Design and Analysis of Pumping and Slug Tests*, Lewis Publishers, 1991.
- (3) Moench, Alan F., "Computation of Type Curves for Flow to Partially Penetrating Wells in Water-Table Aquifers," *Ground Water*, Vol 31, No. 6, 1993, pp. 966–971.
- (4) Neuman, Shlomo P., "Theory of Unconfined Aquifers Considering Delayed Response of the Water Table," *Water Resources Research*, Vol 8, No. 4, 1972, pp. 1031–1045.
- (5) Neuman, Shlomo P., "Effect of Partial Penetration on Flow in Unconfined Aquifers Considering Delayed Gravity Response," *Water Resources Research*, Vol 10, No. 2, 1974, pp. 303–312.

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