Designation: D 5473 – 93

AMERICAN SOCIETY FOR TESTING AND MATERIALS
1916 Race St. Philadelphia, Pa 19103

Standard Test Method for (Analytical Procedure for) Analyzing the Effects of Partial Penetration of Control Well and Determining the Horizontal and Vertical Hydraulic Conductivity in a Nonleaky Confined Aquifer[1]

This standard is issued under the fixed designation D 5473; 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 (ϵ) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers an analytical solution for determining the horizontal and vertical hydraulic conductivity of an aquifer by analysis of the response of water levels in the aquifer to the discharge from a well that partially penetrates the aquifer.

1.2 *Limitations*—The limitations of the technique for determination of the horizontal and vertical hydraulic conductivity of aquifers are primarily related to the correspondence between the field situation and the simplifying assumption of this test method.

1.3 The values stated in either inch-pound or SI units are to be regarded separately as the standard. The values given in parentheses are for information only.

1.4 *This standard does not purport to address all of the safety problems, 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[2]

D 4050 Test Method for (Field Procedure for) Withdrawal and Injection Well Tests for Determining Hydraulic Properties of Aquifer Systems[2]

D 4105 Test Method for (Analytical Procedure for) Determining Transmissivity and Storativity of Nonleaky Confined Aquifers by the Modified Theis Nonequilibrium Method[2]

D 4750 Test Method for Determining Subsurface Liquid Levels in a Borehole or Monitoring Well (Observation Well)[2]

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 *confining bed*—a hydrogeologic unit of less permeable material bounding one or more aquifers.

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

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

3.1.5 *hydraulic conductivity*—(field aquifer tests), 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.

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

3.1.7 *piezometer*—a device so constructed and sealed as to measure hydraulic head at a point in the subsurface.

3.1.8 *specific storage*—the volume of water released from or taken into storage per unit volume of the porous medium per unit change in head.

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 at the existing kinematic viscosity that will move in a unit time under a unit hydraulic gradient through a unit width of the aquifer.

3.1.11 *unconfined aquifer*—an aquifer that has a water table.

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

3.2 *Symbols and Dimensions:*

3.2.1 a [nd]—$(K_z/K_r)^{1/2}$.

3.2.2 b [L]—thickness of aquifer.

3.2.3 d [L]—distance from top of aquifer to top of screened interval of control well.

3.2.4 d' [L]—distance from top of aquifer to top of screened interval of observation well.

3.2.5 f_s [nd]—dimensionless drawdown factor.

3.2.6 K [LT^{-1}]—hydraulic conductivity.

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

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

3.2.9 K_0—modified Bessel function of the second kind and zero order.

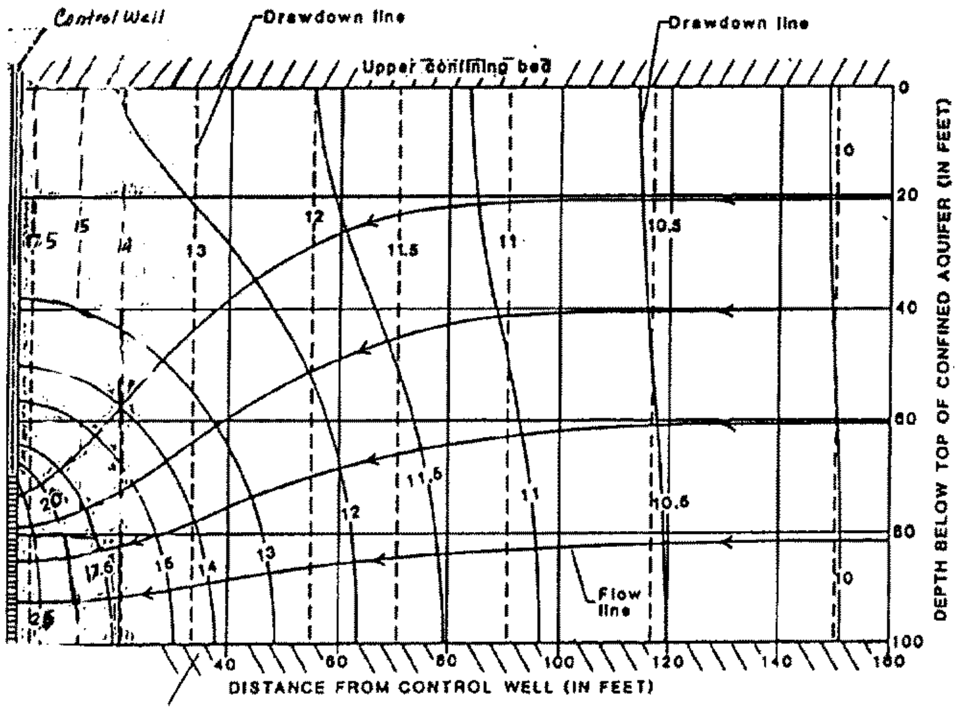
3.2.10 l [L]—distance from top of aquifer to bottom of screened interval of control well.

3.2.11 l' [L]—distance from top of aquifer to bottom of screened interval of observation well.

[1] 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.

Current edition approved Nov. 15, 1993. Published January 1994.

[2] *Annual Book of ASTM Standards*, Vol 04.08.



NOTE—Solid lines are for a well screened in the bottom three tenths of the aquifer; dashed lines are for a well screened the full thickness.

FIG. 1 Vertical Section Showing Drawdown Lines and Approximate Flow Paths Near a Pumped Well in an Ideal Artesian Aquifer

3.2.12 Q [L^3T^{-1}]—discharge.

3.2.13 r [L]—radial distance from control well.

3.2.14 r_c—distance from pumped well at which an observed drawdown deviation, δs, would occur in the equivalent isotropic aquifer.

3.2.15 S [nd]—storage coefficient.

3.2.16 s [L]—drawdown.

3.2.17 S_s [L^{-1}]—specific storage.

3.2.18 T [L^2T^{-1}]—transmissivity.

3.2.19 u [nd]—$(r^2S)/(4Tt)$.

3.2.20 $W(u)$ [nd]—an exponential integral known in hydrology as the well function of u.

3.2.21 $W(u, f_s)$—partial-penetration control well function.

3.2.22 δs [L]—drawdown deviation due to partial penetration from that given by equations for purely radial flow.

3.2.23 z [L]—distance from top of aquifer to bottom of piezometer.

4. Summary of Test Method

4.1 This test method uses the deviations in drawdown near a partially penetrating control well from those that would occur near a control well fully penetrating the aquifer. These deviations occur when a well partially penetrating the aquifer is pumped because water levels are drawn down more near the level of the screen, and less at levels somewhat above or below the screened interval, than they would be if the pumped well fully penetrated the aquifer. These effects are shown in Fig. 1 by comparing drawdown and flow lines for fully penetrating and partially penetrating control wells in an isotropic aquifer. Drawdown deviations due to partial penetration are amplified when the vertical permeability is less than the horizontal permeability, as often occurs in stratified sediments **(1)**.[3] Hantush **(2)** has shown that at a distance, r, from the control well the drawdown deviation due to pumping a partially penetrating well at a constant rate is the same as that at a distance $r(K_z/K_r)^{1/2}$ if the aquifers were transformed into an equivalent isotropic aquifer.

4.2 *Solutions*—Solutions are given by Hantush **(2)** for the drawdown near a partially penetrating control well being pumped at a constant rate and tapping a homogeneous, isotropic artesian aquifer:

$$s = \frac{Q}{4\pi T}[W(u) + f_s] \tag{1}$$

where:

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

and f_s is the dimensionless drawdown correction factor. The function $[W(u) + f_s]$ in Eq 1 can be referred to as the partial penetration well function.

4.2.1 The dimensionless drawdown correction factor for a piezometer is given by:

$$f_s = f\left(u, \frac{ar}{b}, \frac{l}{b}, \frac{d}{b}, \frac{z}{b}\right) = \frac{2b}{\pi(l-d)} \sum_{n=1}^{\infty} \frac{1}{n}\left(\sin\frac{n\pi l}{b} - \sin\frac{n\pi d}{b}\right)\cos\frac{n\pi z}{b}\, W\left(u, \frac{n\pi ar}{b}\right) \tag{3}$$

and the solution for the dimensionless drawdown correction

[3] The boldface numbers in parentheses refer to a list of references at the end of the text.

factor for an observation well is given by:

$$f_s = f\left(u, \frac{ar}{b}, \frac{l}{b}, \frac{d}{b}, \frac{l'}{b}, \frac{d'}{b}\right) = \frac{2b^2}{\pi^2(l-d)(l'-d')} \sum_{n=1}^{\infty} \frac{1}{n^2}\left(\sin\frac{n\pi l}{b} - \sin\frac{n\pi d}{b}\right) \left(\sin\frac{n\pi l'}{b} - \sin\frac{n\pi d'}{b}\right) W\left(u, \frac{n\pi ar}{b}\right) \quad (4)$$

where:

$$W(m, x) = \int_u^{\infty} \frac{\exp\left(-y - \frac{x^2}{4y}\right)}{y} dy \quad (5)$$

The hydrogeologic conditions and symbols used in connection with piezometer and well geometries are shown in Fig. 2.

4.2.2 For large values of time, that is, for $t > b^2S/(2a^2T)$ or $t > bS/(2K_z)$, the effects of partial penetration are constant in time, and $W(u, (n\pi ar)/b))$ can be approximated by $2K_0((n\pi ar)/b)$ **(2)**. K_0 is the modified Bessel function of the second kind of order zero.

4.2.3 Equation 1 can be written

$$s = \frac{Q}{4\pi T} W(u) + \frac{Q}{4\pi T} f_s \quad (6)$$

The first term in Eq 6 is the drawdown in an isotropic homogeneous confined aquifer under radial flow, as given by Theis **(3)**. The second term is deviation from the Theis drawdown caused by partial penetration of the control well. This term is designated as the drawdown deviation by Weeks **(1)** and is given by:

$$\delta s = \frac{Q}{4\pi T} f_s \quad (7)$$

4.2.4 The effects of partial penetration need to be considered for $ar/b < 1.5$. There is a response curve for each value of ar/b, d/b, l/b, and either z/b for piezometers, or l'/b and d'/b for observation wells. A table of dimensionless drawdown factors for piezometers from Weeks **(1)** is given in Table 1 covering 56 different partial-penetration situations. A graph of one of the many families of curves showing the dimensionless drawdown factor f_s versus ar/b for a control well screened, or open, from $z = 0.6b$ to $z = 0.9b$ for various values of piezometer penetration, z/b, is shown in Fig. 3. Because of the even greater number of possible drawdown factors for observation wells, drawdown correction factors for wells are not tabulated.

5. Significance and Use

5.1 *Assumptions:*

5.1.1 Control well discharges at a constant rate, Q.

5.1.2 Control well is of infinitesimal diameter and partially penetrates the aquifer.

5.1.3 The nonleaky artesian aquifer is homogeneous, and aerially extensive. The aquifer may also be anisotropic and, if so, the directions of maximum and minimum hydraulic conductivity are horizontal and vertical, respectively. The methods may be used to analyze tests on unconfined aquifers under conditions described in a following section.

5.1.4 Discharge from the well is derived exclusively from storage in the aquifer.

5.1.5 The geometry of the assumed aquifer and well conditions are shown in Fig. 2.

5.2 *Implications of Assumptions*—The vertical flow components in the aquifer are induced by a control well that partially penetrates the aquifer, that is, a well that is not open to the aquifer through its full thickness. The effects of vertical flow components are measured in piezometers near the control well, that is, within a distance, r, in which vertical flow components are significant, that is:

$$r < 1.5b\sqrt{K_r/K_z} \quad (8)$$

5.3 *Application of Method to Unconfined Aquifers:*

5.3.1 Although the assumptions are applicable to artesian or confined conditions, Weeks **(1)** has pointed out that the solution may be applied to unconfined aquifers if drawdown is small compared with the saturated thickness of the aquifer or if the drawdown is corrected for reduction in thickness of

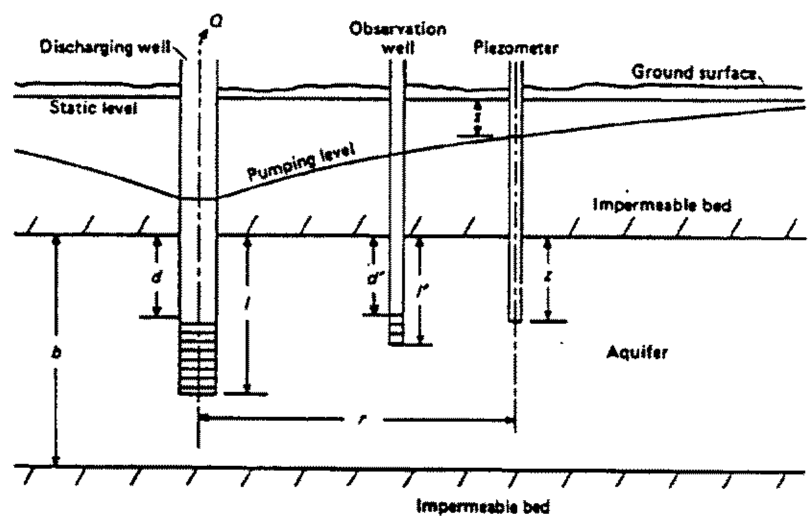


FIG. 2 Cross Section Through a Discharging Well That is Screened in a Part of a Nonleaky Aquifer

TABLE 1 Tabulated Values of the Dimensionless Drawdown Correction Factor

All values, including those for piezometer depth, are listed for percentages of the aquifer thickness, as measured from the top of the aquifer or from the pumped well.

The $f(s)$ values listed are for an isotropic aquifer. For an anisotropic aquifer the value of $f(s)$ would be read as the value of $r/b[Kz/Kr]^{1/2}]$, expressed as a percentage, equivalent to the r value listed.

Each of the tables listed below may also be used for the situation where values for the bottom and the top of the screen are reversed by reading the z value in the table equivalent to (100 z) for the field situation. For example, the first table listed could also be used to determine values of $f(s)$ for a well screened from the top of the aquifer down to a depth equal to 90 % of the aquifer thickness. If the piezometers penetrated 20 % of the aquifer thickness, the correction value for a given r/b value would be found from the z = 80 listing.

Frequently it would be necessary to make a double or triple interpolation to use the data from these tables. Such interpolation probably would be best accomplished from a plot of $f(s)$ versus log r/b for each of the d/b, zw/b, and z/b values bounding the actual values of these parameters.

Bottom of Screen in Pumped Well is 100. Per Cent of Aquifer Thickness Below Top of Aquifer

Top of Screen in Pumped Well is 90. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0	−4.828	−3.457	−2.674	−2.134	−1.732	−1.421	−0.972	−0.673	−0.468	−0.229	−0.113	−0.056	−0.020
10.	−4.785	−3.415	−2.633	−2.095	−1.696	−1.387	−0.944	−0.650	−0.451	−0.219	−0.219	−0.053	−0.019
20.	−4.651	−3.284	−2.506	−1.976	−1.585	−1.284	−0.860	−0.584	−0.400	−0.191	−0.093	−0.046	−0.016
30.	−4.408	−3.048	−2.280	−1.763	−1.388	−1.104	−0.715	−0.471	−0.315	−0.145	−0.069	−0.034	−0.012
40.	−4.020	−2.674	−1.925	−1.434	−1.086	−0.833	−0.503	−0.312	−0.198	−0.085	−0.039	−0.018	−0.006
50.	−3.415	−2.095	−1.387	−0.944	−0.650	−0.451	−0.219	−0.108	−0.053	−0.013	−0.003	−0.001	0.000
60.	−2.444	−1.185	−0.566	−0.225	−0.035	0.067	0.138	0.135	0.111	0.063	0.033	0.017	0.006
70.	−0.736	0.341	0.725	0.829	0.808	0.736	0.556	0.399	0.280	0.137	0.067	0.033	0.012
80.	2.897	3.170	2.791	2.312	1.875	1.511	0.983	0.648	0.432	0.199	0.095	0.046	0.016
90.	13.344	8.218	5.575	3.974	2.926	2.207	1.322	0.831	0.539	0.241	0.113	0.055	0.019
100.	21.264	11.404	7.087	4.778	3.395	2.499	1.454	0.899	0.578	0.256	0.120	0.058	0.020

Top of Screen in Pumped Well is 80. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0	−4.785	−3.415	−2.633	−2.095	−1.696	−1.387	−0.944	−0.650	−0.451	−0.219	−0.108	−0.053	−0.019
10.	−4.739	−3.371	−2.590	−2.055	−1.658	−1.352	−0.916	−0.628	−0.434	−0.210	−0.103	−0.051	−0.018
20.	−4.597	−3.232	−2.457	−1.929	−1.542	−1.246	−0.829	−0.561	−0.383	−0.182	−0.089	−0.044	−0.015
30.	−4.336	−2.979	−2.216	−1.705	−1.335	−1.059	−0.681	−0.448	−0.299	−0.138	−0.066	−0.032	−0.011
40.	−3.912	−2.572	−1.834	−1.354	−1.019	−0.778	−0.467	−0.290	−0.184	−0.079	−0.036	−0.017	−0.006
50.	−3.232	−1.929	−1.246	−0.829	−0.561	−0.383	−0.182	−0.089	−0.044	−0.011	−0.003	−0.001	0.000
60.	−2.076	−0.877	−0.331	−0.057	0.079	0.142	0.168	0.145	0.114	0.062	0.032	0.016	0.006
70.	0.227	0.992	1.113	1.044	0.920	0.789	0.561	0.391	0.272	0.131	0.064	0.032	0.011
80.	6.304	4.280	3.150	2.401	1.867	1.471	0.939	0.615	0.410	0.189	0.090	0.044	0.015
90.	12.080	7.287	4.939	3.545	2.635	2.005	1.219	0.773	0.505	0.228	0.107	0.052	0.018
100.	13.344	8.218	5.575	3.973	2.926	2.207	1.322	0.831	0.539	0.241	0.113	0.055	0.019

Top of Screen in Pumped Well is 70. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0	−4.710	−3.342	−2.562	−2.029	−1.634	−1.330	−0.897	−0.613	−0.423	−0.204	−0.100	−0.049	−0.017
10.	−4.659	−3.293	−2.515	−1.985	−1.593	−1.293	−0.868	−0.591	−0.406	−0.195	−0.095	−0.047	−0.017
20.	−4.500	−3.138	−2.368	−1.848	−1.468	−1.179	−0.778	−0.523	−0.355	−0.168	−0.082	−0.040	−0.014
30.	−4.203	−2.853	−2.100	−1.601	−1.245	−0.981	−0.626	−0.410	−0.273	−0.126	−0.600	−0.029	−0.010
40.	−3.705	−2.381	−1.666	−1.212	−0.902	−0.683	−0.408	−0.254	−0.162	−0.071	−0.033	−0.016	−0.005
50.	−2.853	−1.601	−0.981	−0.626	−0.410	−0.273	−0.126	−0.060	−0.029	−0.007	−0.002	−0.000	0.000
60.	−1.189	−0.230	0.100	0.218	0.251	0.248	0.206	0.157	0.115	0.059	0.030	0.015	0.005
70.	3.064	2.155	1.638	1.286	1.028	0.830	0.553	0.374	0.255	0.122	0.059	0.029	0.010
80.	7.239	4.463	3.104	2.289	1.745	1.359	0.859	0.561	0.374	0.173	0.083	0.040	0.014
90.	8.651	5.592	3.958	2.925	2.220	1.716	1.067	0.687	0.453	0.206	0.098	0.048	0.017
100.	9.019	5.915	4.223	3.134	2.382	1.840	1.140	0.731	0.481	0.218	0.103	0.050	0.017

Top of Screen in Pumped Well is 60. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0	−4.597	−3.232	−2.457	−1.929	−1.542	−1.246	−0.829	−0.561	−0.383	−0.182	−0.089	−0.044	−0.015
10.	−4.538	−3.175	−2.403	−1.880	−1.497	−1.206	−0.799	−0.538	−0.367	−0.174	−0.084	−0.041	−0.015
20.	−4.348	−2.994	−2.233	−1.725	−1.358	−1.082	−0.705	−0.470	−0.318	−0.149	−0.072	−0.035	−0.012
30.	−3.986	−2.650	−1.918	−1.442	−1.110	−0.868	−0.549	−0.358	−0.239	−0.110	−0.053	−0.026	−0.009
40.	−3.336	−2.055	−1.394	−0.993	−0.731	−0.552	−0.331	−0.208	−0.135	−0.060	−0.028	−0.014	−0.005
50.	−2.055	−0.993	−0.552	−0.331	−0.208	−0.135	−0.060	−0.028	−0.014	−0.003	−0.001	−0.000	0.000
60.	1.196	0.854	0.658	0.524	0.424	0.347	0.236	0.163	0.113	0.055	0.027	0.013	0.005
70.	4.424	2.679	1.847	1.358	1.037	0.811	0.518	0.342	0.231	0.108	0.052	0.026	0.009
80.	5.634	3.670	2.622	1.958	1.502	1.174	0.745	0.488	0.326	0.152	0.073	0.035	0.012
90.	6.154	4.140	3.026	2.295	1.777	1.397	0.890	0.582	0.388	0.179	0.086	0.042	0.015
100.	6.304	4.280	3.150	2.401	1.867	1.471	0.939	0.615	0.410	0.189	0.090	0.044	0.015

TABLE 1 *Continued*

Top of Screen in Pumped Well is 50. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0	−4.434	−3.075	−2.307	−1.791	−1.415	−1.131	−0.739	−0.493	−0.333	−0.156	−0.075	−0.037	−0.013
10.	−4.360	−3.005	−2.243	−1.732	−1.364	−1.087	−0.707	−0.470	−0.317	−0.149	−0.072	−0.035	−0.012
20.	−4.119	−2.777	−2.036	−1.549	−1.205	−0.951	−0.611	−0.403	−0.271	−0.127	−0.061	−0.030	−0.010
30.	−3.626	−2.327	−1.642	−1.214	−0.924	−0.719	−0.453	−0.296	−0.198	−0.092	−0.044	−0.022	−0.008
40.	−2.609	−1.486	−0.976	−0.691	−0.513	−0.392	−0.243	−0.157	−0.105	−0.048	−0.023	−0.011	−0.004
50.	−0.000	−0.000	−0.000	−0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
60.	2.609	1.486	0.976	0.691	0.513	0.392	0.243	0.157	0.105	0.048	0.023	0.011	0.004
70.	3.626	2.327	1.642	1.214	0.924	0.719	0.453	0.296	0.198	0.092	0.044	0.022	0.008
80.	4.119	2.777	2.036	1.549	1.205	0.951	0.611	0.403	0.271	0.127	0.061	0.030	0.010
90.	4.360	3.005	2.243	1.732	1.364	1.087	0.707	0.470	0.317	0.149	0.072	0.035	0.012
100.	4.434	3.075	2.307	1.791	1.415	1.131	0.739	0.493	0.333	0.156	0.075	0.037	0.013

Top of Screen in Pumped Well is 40. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0	−4.203	−2.853	−2.100	−1.601	−1.245	−0.981	−0.626	−0.410	−0.273	−0.126	−0.060	−0.029	−0.010
10.	−4.102	−2.760	−2.017	−1.530	−1.185	−0.931	−0.593	−0.388	−0.259	−0.120	−0.057	−0.028	−0.010
20.	−3.756	−2.447	−1.748	−1.305	−1.002	−0.783	−0.497	−0.325	−0.218	−0.101	−0.048	−0.024	−0.008
30.	−2.949	−1.786	−1.231	−0.905	−0.691	−0.541	−0.345	−0.228	−0.154	−0.072	−0.035	−0.017	−0.006
40.	−0.798	−0.569	−0.439	−0.349	−0.282	−0.231	−0.157	−0.108	−0.075	−0.037	−0.018	−0.009	−0.003
50.	1.370	0.662	0.368	0.220	0.139	0.090	0.040	0.019	0.009	0.002	0.001	0.000	0.000
60.	2.224	1.370	0.929	0.662	0.488	0.368	0.220	0.139	0.090	0.040	0.019	0.009	0.003
70.	2.657	1.767	1.279	0.961	0.740	0.578	0.366	0.239	0.159	0.074	0.035	0.017	0.006
80.	2.899	1.996	1.489	1.150	0.905	0.722	0.470	0.313	0.212	0.100	0.048	0.024	0.008
90.	3.025	2.117	1.602	1.253	0.998	0.804	0.532	0.359	0.244	0.116	0.056	0.028	0.010
100.	3.064	2.155	1.638	1.286	1.028	0.830	0.553	0.374	0.255	0.122	0.059	0.029	0.010

Top of Screen in Pumped Well is 20. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0	−3.336	−2.055	−1.394	−0.993	−0.731	−0.552	−0.331	−0.208	−0.135	−0.060	−0.028	−0.014	−0.005
10.	−3.020	−1.822	−1.235	−0.886	−0.659	−0.501	−0.305	−0.193	−0.126	−0.057	−0.027	−0.013	−0.005
20.	−1.576	−1.070	−0.788	−0.600	−0.467	−0.368	−0.235	−0.154	−0.102	−0.047	−0.023	−0.011	−0.004
30.	−0.057	−0.248	−0.278	−0.261	−0.230	−0.197	−0.140	−0.098	−0.068	−0.033	−0.016	−0.008	−0.003
40.	0.519	0.219	0.083	0.014	−0.020	−0.036	−0.042	−0.036	−0.028	−0.015	−0.008	−0.004	−0.001
50.	0.808	0.482	0.311	0.207	0.140	0.096	0.046	0.022	0.011	0.003	0.001	0.000	0.000
60.	0.978	0.643	0.458	0.338	0.255	0.194	0.117	0.072	0.046	0.020	0.009	0.004	0.001
70.	1.084	0.745	0.554	0.426	0.334	0.265	0.170	0.112	0.075	0.034	0.016	0.008	0.003
80.	1.149	0.808	0.614	0.482	0.385	0.311	0.207	0.140	0.096	0.046	0.022	0.011	0.004
90.	1.185	0.843	0.647	0.514	0.415	0.338	0.229	0.157	0.109	0.053	0.026	0.013	0.005
100.	1.196	0.854	0.658	0.524	0.424	0.347	0.236	0.163	0.113	0.055	0.027	0.013	0.005

Bottom of Screen in Pumped Well is 90. Per Cent of Aquifer Thickness Below Top of Aquifer

Top of Screen in Pumped Well is 80. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0	−4.743	−3.373	−2.592	−2.057	−1.660	−1.354	−0.916	−0.628	−0.434	−0.210	−0.103	−0.051	−0.018
10.	−4.694	−3.326	−2.547	−2.015	−1.621	−1.318	−0.887	−0.606	−0.417	−0.201	−0.098	−0.048	−0.017
20.	−4.547	−3.179	−2.407	−1.883	−1.499	−1.207	−0.799	−0.538	−0.366	−0.174	−0.084	−0.041	−0.015
30.	−4.263	−2.910	−2.151	−1.666	−1.283	−1.013	−0.648	−0.425	−0.283	−0.131	−0.062	−0.030	−0.011
40.	−3.803	−2.470	−1.747	−1.274	−0.952	−0.722	−0.431	−0.267	−0.170	−0.074	−0.034	−0.016	−0.006
50.	−3.048	−1.763	−1.104	−0.715	−0.471	−0.315	−0.145	−0.069	−0.034	−0.008	−0.002	−0.001	0.000
60.	−1.708	−0.569	−0.096	0.111	0.193	0.218	0.198	0.156	0.116	0.061	0.031	0.015	0.006
70.	1.189	1.644	1.500	1.258	1.032	0.843	0.566	0.384	0.263	0.125	0.061	0.030	0.011
80.	9.712	5.389	3.509	2.491	1.859	1.431	0.895	0.582	0.387	0.179	0.086	0.042	0.015
90.	10.816	6.356	4.303	3.117	2.344	1.803	1.115	0.716	0.471	0.214	0.101	0.049	0.017
100.	5.425	5.032	4.064	3.168	2.457	1.915	1.190	0.763	0.500	0.226	0.107	0.052	0.018

Top of Screen in Pumped Well is 70. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0	−4.651	−3.284	−2.506	−1.976	−1.585	−1.284	−1.860	0.584	−0.400	−0.191	−0.093	−0.046	−0.016
10.	−4.597	−3.232	−2.457	−1.929	−1.542	−1.246	−0.829	−0.561	−0.383	−0.182	−0.089	−0.044	−0.015
20.	−4.424	−3.085	−2.299	−1.784	−1.409	−1.127	−0.737	−0.492	−0.333	−0.157	−0.076	−0.037	−0.013
30.	−4.100	−2.755	−2.010	−1.520	1.173	−0.919	−0.582	−0.379	−0.252	−0.116	−0.056	−0.027	−0.009
40.	−3.547	−2.235	−1.536	−1.101	−0.810	−0.069	−0.361	−0.224	−0.144	−0.064	−0.030	−0.014	−0.005
50.	−2.572	−1.354	−0.778	−0.467	−0.290	−0.184	−0.079	−0.036	−0.017	−0.004	−0.001	−0.000	0.000
60.	−0.562	0.248	0.433	0.439	0.395	0.339	0.240	0.168	0.117	0.057	0.028	0.014	0.005
70.	4.965	3.061	2.094	1.515	1.138	0.878	0.551	0.362	0.243	0.114	0.055	0.027	0.009
80.	9.410	5.109	3.260	2.277	1.680	1.283	0.796	0.517	0.344	0.160	0.076	0.037	0.013
90.	6.304	4.280	3.150	2.401	1.867	1.471	0.939	0.615	0.410	0.189	0.090	0.044	0.015
100.	2.897	3.170	2.791	2.312	1.875	1.511	0.983	0.648	0.432	0.199	0.095	0.046	0.016

TABLE 1 *Continued*

Top of Screen in Pumped Well is 60. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0	−4.520	−3.157	−2.384	−1.861	−1.478	−1.187	−0.782	−0.524	−0.355	−0.167	−0.081	−0.039	−0.014
10.	−4.455	−3.095	−2.326	−1.808	−1.431	−1.145	−0.750	−0.501	−0.334	−0.159	−0.077	−0.037	−0.013
20.	−4.247	−2.897	−2.142	−1.641	−1.282	−1.015	−0.654	−0.432	−0.290	−0.136	−0.065	−0.032	−0.011
30.	−3.845	−2.517	−1.797	−1.335	−1.017	−0.789	−0.494	−0.321	−0.213	−0.009	−0.047	−0.023	−0.008
40.	−3.108	−1.848	−1.217	−0.847	−0.613	−0.458	−0.273	−0.173	−0.114	−0.052	−0.025	−0.012	−0.004
50.	−1.601	−0.626	−0.273	−0.126	−0.060	−0.029	−0.007	−0.002	−0.000	0.000	0.000	0.000	0.000
60.	2.410	1.533	1.066	0.774	0.577	0.440	0.269	0.172	0.113	0.052	0.025	0.012	0.004
70.	6.144	3.458	2.220	1.534	1.113	0.836	0.506	0.374	0.214	0.099	0.047	0.023	0.008
80	6.547	3.837	2.566	1.840	1.378	1.062	0.666	0.435	0.291	0.136	0.065	0.032	0.011
90	3.757	2.780	2.176	1.735	1.395	1.127	0.746	0.500	0.338	0.159	0.077	0.037	0.013
100.	1.316	1.905	1.838	1.609	1.358	1.129	0.767	0.520	0.354	0.167	0.081	0.039	0.014

Top of Screen in Pumped Well is 50. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0	−4.336	−2.979	−2.216	−1.705	−1.335	−1.059	−0.681	−0.448	−0.299	−0.138	−0.066	−0.032	−0.011
10.	−4.254	−2.902	−2.145	−1.642	−1.280	−1.012	−0.648	−0.425	−0.284	−0.131	−0.063	−0.030	−0.011
20.	−3.986	−2.650	−1.918	−1.442	−1.110	−0.868	−0.549	−0.358	−0.239	−0.110	−0.053	−0.026	−0.009
30.	−3.430	−2.146	−1.482	−1.076	−0.809	−0.672	−0.388	−0.253	−0.169	−0.079	−0.038	−0.019	−0.007
40.	−2.256	−1.189	−0.739	−0.506	−0.369	−0.282	−0.177	−0.118	−0.081	−0.039	−0.019	−0.010	−0.003
50.	0.854	0.524	0.347	0.236	0.163	0.113	0.055	0.027	0.013	0.003	0.001	0.000	0.000
60.	3.872	2.154	1.362	0.920	0.650	0.473	0.269	0.163	0.103	0.045	0.021	0.010	0.003
70.	4.716	2.823	1.871	1.310	0.953	0.714	0.428	0.271	0.177	0.081	0.038	0.019	0.007
80.	4.424	2.679	1.847	1.358	1.037	0.811	0.518	0.342	0.231	0.108	0.052	0.026	0.009
90.	2.114	1.701	1.410	1.172	0.973	0.807	0.554	0.380	0.262	0.125	0.061	0.030	0.011
100.	0.227	0.992	1.113	1.044	0.920	0.789	0.561	0.391	0.272	0.131	0.064	0.032	0.011

Top of Screen in Pumped Well is 40. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0	−4.078	−2.732	−1.985	−1.494	−1.147	−0.893	−0.557	−0.357	−0.234	−0.105	−0.050	−0.024	−0.008
10.	−3.966	−2.629	−1.894	−1.417	−1.083	−0.840	−0.523	−0.336	−0.220	−0.100	−0.047	−0.023	0.008
20.	−3.577	−2.279	−1.596	−1.171	−0.885	−0.683	−0.424	−0.274	−0.181	−0.083	−0.040	−0.019	−0.007
30.	−2.658	−1.533	−1.021	−0.734	−0.552	−0.428	−0.272	−0.180	−0.122	−0.058	−0.028	−0.014	−0.005
40.	−0.153	−0.148	−0.141	−0.132	−0.122	−0.111	−0.088	−0.068	−0.051	−0.027	−0.014	−0.007	−0.003
50.	2.327	1.214	0.719	0.453	0.296	0.198	0.092	0.044	0.022	0.005	0.001	0.000	0.000
60.	3.158	1.881	1.228	0.840	0.592	0.428	0.237	0.139	0.086	0.036	0.016	0.008	0.003
70.	3.336	2.052	1.389	0.988	0.726	0.547	0.328	0.207	0.135	0.061	0.029	0.014	0.005
80.	2.899	1.761	1.228	0.917	0.711	0.564	0.368	0.247	0.168	0.080	0.039	0.019	0.007
90.	0.961	0.896	0.807	0.709	0.612	0.523	0.374	0.264	0.185	0.091	0.045	0.022	0.008
100.	−0.575	0.305	0.548	0.588	0.555	0.497	0.373	0.269	0.191	0.095	0.047	0.023	0.008

Top of Screen in Pumped Well is 30. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0	−3.705	−2.381	−1.666	−1.212	−0.902	−0.683	−0.408	−0.254	−0.162	−0.071	−0.033	−0.016	−0.005
10.	−3.528	−2.227	−1.540	−1.113	−0.827	−0.627	−0.376	−0.235	−0.151	−0.067	−0.031	−0.015	−0.005
20.	−2.844	−1.684	−1.134	−0.815	−0.608	−0.465	−0.286	−0.183	−0.120	−0.055	−0.026	−0.013	−0.004
30.	−0.798	−0.569	−0.439	−0.349	−0.283	−0.231	−0.157	−0.108	−0.075	−0.037	−0.018	−0.009	−0.003
40.	1.264	0.560	0.271	0.130	0.055	0.015	−0.019	−0.026	−0.024	−0.015	−0.008	−0.004	−0.002
50.	1.996	1.150	0.722	0.470	0.313	0.212	0.100	0.048	0.024	0.006	0.001	0.000	0.000
60.	2.260	1.388	0.927	0.643	0.457	0.331	0.181	0.104	0.063	0.025	0.011	0.005	0.002
70.	2.224	1.370	0.929	0.662	0.488	0.368	0.220	0.139	0.090	0.040	0.019	0.009	0.003
80.	1.767	1.041	0.719	0.539	0.421	0.338	0.225	0.154	0.106	0.051	0.025	0.012	0.004
90.	0.106	0.277	0.328	0.330	0.309	0.279	0.213	0.157	0.113	0.057	0.029	0.014	0.005
100.	−1.189	−0.230	0.100	0.218	0.251	0.248	0.206	0.157	0.115	0.059	0.030	0.015	0.005

Top of Screen in Pumped Well is 20. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0	−3.123	−1.854	−1.211	−0.830	−0.588	−0.428	−0.239	−0.141	−0.087	−0.036	−0.016	−0.008	−0.003
10.	−2.768	−1.594	−1.035	−0.714	−0.511	−0.375	−0.213	−0.128	−0.080	−0.034	−0.015	−0.007	−0.002
20.	−1.137	−0.754	−0.542	−0.404	−0.307	−0.237	−0.145	−0.092	−0.060	−0.027	−0.013	−0.006	−0.002
30.	0.565	0.152	0.008	−0.046	−0.065	−0.068	−0.058	−0.044	−0.033	−0.017	−0.008	−0.004	−0.002
40.	1.167	0.603	0.370	0.221	0.133	0.078	0.024	0.003	−0.004	−0.006	−0.004	−0.002	−0.001
50.	1.411	0.851	0.554	0.372	0.253	0.174	0.083	0.041	0.020	0.005	0.001	0.000	0.000
60.	1.467	0.904	0.605	0.419	0.296	0.114	0.114	0.063	0.037	0.014	0.006	0.003	0.000
70.	1.344	0.802	0.530	0.369	0.266	0.197	0.115	0.071	0.045	0.020	0.009	0.004	0.002
80.	0.899	0.471	0.303	0.221	0.173	0.140	0.096	0.068	0.048	0.024	0.012	0.006	0.002
90.	−0.552	−0.211	−0.056	0.020	0.056	0.071	0.073	0.061	0.047	0.026	0.013	0.007	0.002
100.	−1.670	−0.653	−0.260	−0.084	−0.000	0.039	0.062	0.057	0.046	0.026	0.014	0.007	0.003

TABLE 1 *Continued*

Top of Screen in Pumped Well is 10. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0	−2.055	−0.993	−0.552	−0.331	−0.208	−0.135	−0.060	−0.028	−0.014	−0.003	−0.001	−0.000	−0.000
10.	−1.070	−0.600	−0.368	−0.235	−0.154	−0.102	−0.047	−0.023	−0.011	−0.003	−0.001	−0.000	−0.000
20.	0.219	−0.014	−0.036	−0.042	−0.036	−0.028	−0.015	−0.008	−0.004	−0.001	−0.000	−0.000	−0.000
30.	0.643	0.338	0.194	0.117	0.072	0.046	0.020	0.009	0.004	0.001	0.000	0.000	−0.000
40.	0.808	0.482	0.311	0.207	0.140	0.096	0.046	0.022	0.011	0.003	0.001	0.000	−0.000
50.	0.854	0.524	0.347	0.236	0.163	0.113	0.055	0.027	0.013	0.003	0.001	0.000	0.000
60.	0.808	0.482	0.311	0.207	0.140	0.096	0.046	0.022	0.011	0.003	0.001	0.000	0.000
70.	0.643	0.338	0.194	0.117	0.072	0.046	0.020	0.009	0.004	0.001	0.000	0.000	0.000
80.	0.219	0.014	−0.036	−0.042	−0.036	−0.028	−0.015	−0.008	−0.004	−0.001	−0.000	−0.000	0.000
90.	−1.070	−0.600	−0.368	−0.235	−0.154	−0.102	−0.047	−0.023	−0.011	−0.003	−0.001	−0.000	0.000
100.	−2.054	−0.993	−0.552	−0.331	−0.208	−0.135	−0.060	−0.028	−0.014	−0.003	−0.001	−0.000	0.000

Bottom of Screen in Pumped Well is 80. Per Cent of Aquifer Thickness Below Top of Aquifer

Top of Screen in Pumped Well is 70. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0	−4.560	−3.196	−2.421	−1.895	−1.509	−1.215	−0.803	−0.539	−0.366	−0.172	−0.083	−0.041	−0.014
10.	−4.500	−3.137	−2.366	−1.844	−1.463	−1.174	−0.771	−0.516	−0.349	−0.164	−0.079	−0.039	−0.014
20.	−4.306	−2.952	−2.192	−1.685	−1.320	−1.047	−0.676	−0.447	−0.300	−0.140	−0.067	−0.033	−0.012
30.	−3.937	−2.601	−1.868	−1.393	−1.063	−0.825	−0.515	−0.334	−0.221	−0.102	−0.049	−0.024	−0.008
40.	−3.292	−1.999	−1.330	−0.927	−0.668	−0.495	−0.240	−0.182	−0.119	−0.054	−0.026	−0.013	−0.004
50.	−2.095	−0.944	−0.451	−0.219	−0.108	−0.053	−0.003	−0.003	−0.000	0.000	0.000	0.000	0.000
60.	0.584	1.065	0.962	0.768	0.596	0.460	0.282	0.180	0.118	0.054	0.026	0.013	0.004
70.	8.740	4.479	2.688	1.772	1.244	0.913	0.537	0.339	0.223	0.102	0.049	0.024	0.008
80.	9.109	4.830	3.012	2.063	1.500	1.135	0.698	0.452	0.302	0.140	0.067	0.033	0.012
90.	1.792	2.203	1.997	1.686	1.390	1.139	0.763	0.514	0.349	0.164	0.079	0.039	0.014
100.	0.369	1.308	1.519	1.456	1.294	1.108	0.776	0.532	0.364	0.172	0.083	0.041	0.014

Top of Screen in Pumped Well is 60. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0	−4.408	−3.048	−2.280	−1.763	−1.388	−1.104	−0.715	−0.471	−0.315	−0.145	−0.069	−0.034	−0.012
10.	−4.336	−2.979	−2.216	−1.705	−1.335	−1.059	−0.681	−0.448	−0.299	−0.138	−0.066	−0.032	−0.011
20.	−4.100	−2.755	−2.010	−1.520	−1.173	−0.919	−0.582	−0.379	−0.252	−0.116	−0.056	−0.027	−0.009
30.	−3.636	−2.321	−1.620	−1.180	−0.884	−0.677	−0.417	−0.269	−0.178	−0.083	−0.040	−0.020	−0.007
40.	−2.761	−1.537	−0.954	−0.633	−0.444	−0.326	−0.194	−0.126	−0.085	−0.041	−0.020	−0.010	−0.004
50.	−0.877	−0.057	0.147	0.168	0.145	0.114	0.062	0.032	0.016	0.004	0.001	0.000	0.000
60.	4.468	2.585	1.647	1.105	0.769	0.551	0.304	0.180	0.112	0.048	0.022	0.011	0.004
70.	8.622	4.365	2.581	1.672	1.154	0.833	0.475	0.293	0.140	0.086	0.040	0.020	0.007
80.	4.965	3.061	2.094	1.515	1.138	0.878	0.551	0.362	0.243	0.114	0.055	0.027	0.009
90.	0.227	0.992	1.113	1.044	0.920	0.789	0.561	0.391	0.272	0.131	0.064	0.037	0.011
100.	−0.736	0.341	0.725	0.829	0.808	0.736	0.556	0.399	0.280	0.137	0.067	0.033	0.012

Top of Screen in Pumped Well is 50. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0	−4.200	−2.848	−2.090	−1.587	−1.227	−0.961	−0.603	−0.388	−0.254	−0.114	−0.054	−0.026	−0.009
10.	−4.108	−2.760	−2.011	−1.517	−1.167	−0.910	−0.568	−0.365	−0.239	−0.108	−0.051	−0.024	−0.008
20.	−3.800	−2.474	−1.755	−1.295	−0.980	−0.755	−0.466	−0.298	−0.196	−0.089	−0.042	−0.021	−0.007
30.	−3.153	−1.892	−1.259	−0.886	−0.650	−0.492	−0.301	−0.195	−0.131	−0.062	−0.030	−0.015	−0.005
40.	−1.741	−0.762	−0.404	−0.250	−0.175	−0.135	−0.093	−0.069	−0.051	−0.028	−0.014	−0.007	−0.003
50.	2.155	1.286	0.830	0.553	0.374	0.255	0.122	0.059	0.029	0.007	0.002	0.000	0.000
60.	5.732	3.062	1.847	1.190	0.802	0.558	0.292	0.165	0.099	0.040	0.017	0.008	0.003
70.	5.892	3.216	1.994	1.327	0.927	0.672	0.382	0.233	0.149	0.066	0.031	0.015	0.005
80.	2.662	1.775	1.292	0.981	0.763	0.604	0.393	0.263	0.179	0.085	0.041	0.020	0.007
90.	−0.786	0.150	0.445	0.524	0.516	0.475	0.366	0.268	0.192	0.096	0.048	0.024	0.008
100.	−1.506	−0.354	0.129	0.335	0.408	0.414	0.351	0.268	0.195	0.100	0.050	0.025	0.009

Top of Screen in Pumped Well is 40. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0	−3.912	−2.572	−1.834	−1.354	−1.019	−0.778	−0.467	−0.290	−0.184	−0.079	−0.036	−0.017	−0.006
10.	−3.784	−2.454	−1.731	−1.267	−0.948	−0.721	−0.432	−0.268	−0.171	−0.074	−0.034	−0.016	−0.006
20.	−3.336	−2.055	−1.394	−0.993	−0.731	−0.552	−0.331	−0.208	−0.135	−0.060	−0.028	−0.014	−0.005
30.	−2.256	−1.189	−0.739	−0.506	−0.369	−0.282	−0.177	−0.118	−0.081	−0.039	−0.019	−0.010	−0.003
40.	0.759	0.432	0.259	0.153	0.085	0.042	−0.002	−0.018	−0.021	−0.015	−0.009	−0.005	−0.002
50.	3.670	1.958	1.174	0.745	0.488	0.326	0.152	0.073	0.035	0.009	0.002	0.001	0.000
60.	4.374	2.493	1.559	1.022	0.692	0.480	0.246	0.135	0.078	0.029	0.012	0.006	0.002
70.	3.872	2.154	1.362	0.920	0.650	0.473	0.269	0.163	0.103	0.045	0.021	0.010	0.003
80.	1.196	0.854	0.658	0.524	0.424	0.347	0.236	0.163	0.113	0.055	0.027	0.013	0.005
90.	−1.503	−0.469	−0.067	0.107	0.180	0.203	0.189	0.151	0.114	0.060	0.031	0.015	0.006
100.	−2.076	−0.877	−0.331	−0.057	0.079	0.142	0.168	0.145	0.114	0.062	0.032	0.016	0.006

TABLE 1 *Continued*

Top of Screen in Pumped Well is 30. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0	−3.497	−2.183	−1.481	−1.042	−0.751	−0.549	−0.307	−0.179	−0.108	−0.043	−0.019	−0.009	−0.003
10.	−3.295	−2.007	−1.339	−0.933	−0.669	−0.489	−0.274	−0.161	−0.098	−0.040	−0.018	−0.008	−0.003
20.	−2.506	−1.385	−0.880	−0.601	−0.430	−0.317	−0.183	−0.112	−0.071	−0.031	−0.014	−0.007	−0.002
30.	−0.104	−0.101	−0.096	−0.090	−0.083	−0.075	−0.059	−0.045	−0.034	−0.018	−0.009	−0.005	−0.002
40.	2.278	1.167	0.674	0.411	0.257	0.162	0.063	0.022	0.005	−0.004	−0.003	−0.002	−0.001
50.	3.005	1.732	1.087	0.707	0.470	0.317	0.149	0.072	0.035	0.009	0.002	0.001	0.000
60.	3.053	1.780	1.132	0.750	0.510	0.353	0.178	0.094	0.052	0.018	0.007	0.003	0.001
70.	2.431	1.315	0.815	0.543	0.379	0.273	0.151	0.089	0.055	0.023	0.010	0.005	0.002
80.	0.178	0.171	0.161	0.148	0.134	0.119	0.091	0.068	0.049	0.025	0.013	0.006	0.002
90.	−2.036	−0.939	−0.466	−0.227	−0.098	−0.026	0.033	0.045	0.041	0.026	0.014	0.007	0.003
100.	−2.512	−1.282	−0.693	−0.372	−0.190	−0.085	0.009	0.036	0.038	0.026	0.014	0.008	0.003

Top of Screen in Pumped Well is 20. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0	−2.853	−1.601	−0.981	−0.626	−0.410	−0.273	−0.126	−0.060	−0.029	−0.007	−0.002	−0.000	−0.000
10.	−2.447	−1.305	−0.783	−0.497	−0.325	−0.218	−0.101	−0.048	−0.024	−0.006	−0.001	−0.000	−0.000
20.	−0.569	−0.349	−0.231	−0.157	−0.108	−0.075	−0.037	−0.018	−0.009	−0.002	−0.001	−0.000	−0.000
30.	1.370	0.662	0.368	0.220	0.139	0.090	0.040	0.019	0.009	0.002	0.001	0.000	−0.000
40.	1.996	1.150	0.722	0.470	0.313	0.212	0.100	0.048	0.024	0.006	0.001	0.000	−0.000
50.	2.155	1.286	0.830	0.553	0.374	0.255	0.122	0.059	0.029	0.007	0.002	0.000	0.000
60.	1.996	1.150	0.722	0.470	0.313	0.212	0.100	0.048	0.024	0.006	0.001	0.000	0.000
70.	1.370	0.662	0.368	0.220	0.139	0.090	0.040	0.019	0.009	0.002	0.001	0.000	0.000
80.	−0.569	−0.349	−0.231	−0.157	−0.108	−0.075	−0.037	−0.018	−0.009	−0.002	−0.001	−0.000	0.000
90.	−2.447	−1.305	−0.783	−0.497	−0.325	−0.218	−0.101	−0.048	−0.024	−0.006	−0.001	−0.000	0.000
100.	−2.853	−1.601	−0.981	−0.626	−0.410	0.273	−0.126	−0.060	−0.029	−0.007	−0.002	−0.000	0.000

Bottom of Screen in Pumped Well is 70. Per Cent of Aquifer Thickness Below Top of Aquifer

Top of Screen in Pumped Well is 60. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0	−4.256	−2.901	−2.140	−1.632	−1.266	−0.994	−0.626	−0.404	−0.264	−0.118	−0.056	−0.027	−0.009
10.	−4.172	−2.821	−2.066	−1.565	−1.208	−0.944	−0.592	−0.380	−0.249	−0.112	−0.053	−0.025	−0.009
20.	−3.895	−2.559	−1.828	−1.355	−1.027	−0.791	−0.488	−0.311	−0.204	−0.093	−0.044	−0.021	−0.007
30.	−3.334	−2.041	−1.371	−0.966	−0.705	−0.529	−0.318	−0.204	−0.136	−0.064	−0.031	−0.015	−0.005
40.	−2.229	−1.075	−0.577	−0.339	−0.219	−0.156	−0.098	−0.070	−0.052	−0.028	−0.015	−0.008	−0.003
50.	0.341	0.829	0.736	0.556	0.399	0.280	0.137	0.067	0.033	0.008	0.002	0.001	0.000
60.	8.352	4.104	2.333	1.442	0.943	0.642	0.326	0.180	0.106	0.042	0.018	0.009	0.003
70.	8.504	4.251	2.473	1.573	1.064	0.752	0.414	0.248	0.157	0.069	0.032	0.016	0.005
80.	0.820	1.293	1.176	0.967	0.775	0.621	0.405	0.271	0.184	0.088	0.043	0.021	0.007
90.	−1.339	−0.219	0.228	0.402	0.450	0.440	0.359	0.269	0.195	0.098	0.049	0.024	0.009
100.	−1.841	−0.626	−0.069	0.203	0.323	0.363	0.335	0.265	0.197	0.102	0.051	0.026	0.009

Top of Screen in Pumped Well is 50. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0	−4.020	−2.674	−1.925	−1.434	−1.086	−0.833	−0.503	−0.312	−0.198	−0.085	−0.039	−0.018	−0.006
10.	−3.912	−2.572	−1.834	−1.354	−1.019	−0.778	−0.467	−0.290	−0.184	−0.079	−0.036	−0.017	−0.006
20.	−3.547	−2.235	−1.536	−1.101	−0.810	−0.609	−0.361	−0.224	−0.144	−0.064	−0.030	−0.014	−0.005
30.	−2.761	−1.537	−0.954	−0.633	−0.444	−0.326	−0.194	−0.126	−0.085	−0.041	−0.020	−0.010	−0.004
40.	−0.965	−0.144	0.059	0.089	0.072	0.045	0.006	−0.013	−0.018	−0.015	−0.009	−0.005	−0.002
50.	4.280	2.401	1.471	0.939	0.615	0.410	0.189	0.090	0.044	0.011	0.003	0.001	0.000
60.	8.306	4.060	2.290	1.401	0.905	0.607	0.297	0.158	0.089	0.032	0.013	0.006	0.002
70.	4.468	2.565	1.647	1.105	0.769	0.551	0.304	0.180	0.112	0.048	0.022	0.011	0.004
80.	−0.562	0.248	0.433	0.439	0.395	0.339	0.240	0.168	0.177	0.057	0.028	0.014	0.005
90.	−2.076	−0.877	−0.331	−0.057	0.079	0.142	0.168	0.145	0.114	0.062	0.032	0.016	0.006
100.	−2.444	−1.185	−0.566	−0.225	−0.035	0.067	0.138	0.135	0.111	0.063	0.033	0.017	0.006

Top of Screen in Pumped Well is 40. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0	−3.695	−2.364	−1.638	−1.173	−0.856	−0.632	−0.355	−0.206	−0.124	−0.048	−0.021	−0.010	−0.003
10.	−3.545	−2.227	−1.519	−1.075	−0.777	−0.570	−0.319	−0.186	−0.112	−0.045	−0.019	−0.009	−0.003
20.	−3.013	−1.756	−1.128	−0.763	−0.535	−0.387	−0.215	−0.128	−0.080	−0.034	−0.015	−0.007	−0.002
30.	−1.696	−0.719	−0.362	−0.210	−0.138	−0.100	−0.065	−0.047	−0.034	−0.018	−0.010	−0.005	−0.002
40.	2.110	1.243	0.788	0.513	0.337	0.221	0.093	0.037	0.012	−0.002	−0.003	−0.002	−0.001
50.	5.592	2.925	1.716	1.067	0.687	0.453	0.206	0.098	0.048	0.012	0.003	0.001	0.000
60.	5.637	2.969	1.758	1.107	0.724	0.487	0.235	0.120	0.065	0.021	0.008	0.003	0.001
70.	2.250	1.379	0.919	0.537	0.458	0.327	0.179	0.104	0.063	0.026	0.011	0.005	0.002
80.	−1.441	−0.471	0.126	0.011	0.065	0.084	0.082	0.065	0.050	0.026	0.013	0.007	0.002
90.	−2.601	−1.359	−0.755	−0.419	−0.224	−0.109	−0.002	0.031	0.036	0.026	0.015	0.008	0.003
100.	−2.890	−1.605	−0.948	−0.562	−0.326	−0.180	−0.034	0.016	0.030	0.025	0.015	0.008	0.003

TABLE 1 *Continued*

Bottom of Screen in Pumped Well is 30. Per Cent of Aquifer Thickness Below Top of Aquifer

Top of Screen in Pumped Well is 90. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0	−3.232	−1.929	−1.246	−0.829	−0.561	−0.383	−0.182	−0.089	−0.044	−0.011	−0.003	−0.001	−0.000
10.	−2.994	−1.725	−1.082	−0.706	−0.470	−0.318	−0.149	−0.072	−0.035	−0.009	−0.002	−0.001	−0.000
20.	−2.055	−0.993	−0.552	−0.331	−0.208	−0.135	−0.060	−0.028	−0.014	−0.003	−0.001	−0.000	−0.000
30.	0.854	0.524	0.347	0.236	0.163	0.113	0.055	0.027	0.013	0.003	0.001	0.000	−0.000
40.	3.670	1.958	1.174	0.745	0.488	0.326	0.152	0.073	0.035	0.009	0.002	0.001	−0.000
50.	4.280	2.401	1.471	0.939	0.615	0.410	0.189	0.090	0.044	0.011	0.003	0.001	0.000
60.	3.670	1.958	1.174	0.745	0.488	0.326	0.152	0.073	0.035	0.009	0.002	0.001	0.000
70.	0.864	0.524	0.347	0.236	0.163	0.113	0.055	0.027	0.013	0.003	0.001	0.000	0.000
80.	−2.055	−0.993	−0.552	−0.331	−0.208	−0.135	−0.060	−0.028	−0.014	−0.003	−0.001	−0.000	0.000
90.	−2.994	−1.725	−1.082	−0.705	−0.470	−0.318	−0.149	−0.072	−0.035	−0.009	−0.002	−0.001	0.000
100.	−3.232	−1.979	−1.246	−0.829	−0.561	−0.383	−0.182	−0.089	−0.044	−0.011	−0.003	−0.001	0.000

Bottom of Screen in Pumped Well is 60. Per Cent of Aquifer Thickness Below Top of Aquifer

Top of Screen in Pumped Well is 50. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0	−3.784	−2.446	−1.711	−1.235	−0.907	−0.673	−0.380	−0.221	−0.132	−0.051	−0.022	−0.010	−0.003
10.	−3.651	−2.323	−1.607	−1.142	−0.830	−0.611	−0.343	−0.199	−0.120	−0.047	−0.020	−0.009	−0.003
20.	−3.200	−1.911	−1.245	−0.846	−0.593	−0.426	−0.234	−0.137	−0.085	−0.035	−0.016	−0.008	−0.003
30.	−2.187	−1.033	−0.537	−0.300	−0.183	−0.123	−0.070	−0.048	−0.035	−0.019	−0.010	−0.005	−0.002
40.	0.298	0.788	0.695	0.517	0.362	0.247	0.109	0.045	0.016	−0.001	−0.003	−0.002	−0.001
50.	8.218	3.973	2.207	1.322	0.831	0.539	0.241	0.113	0.055	0.013	0.003	0.001	0.000
60.	8.261	4.015	2.247	1.361	0.867	0.573	0.269	0.136	0.072	0.023	0.008	0.004	0.001
70.	0.432	0.918	0.821	0.637	0.474	0.350	0.194	0.112	0.067	0.027	0.012	0.006	0.002
80.	−1.944	−0.797	−0.311	−0.088	0.014	0.057	0.075	0.064	0.050	0.027	0.014	0.007	0.003
90.	−2.812	−1.536	−0.890	−0.516	−0.292	−0.155	−0.022	0.022	0.032	0.025	0.015	0.008	0.003
100.	−3.047	−1.745	−1.063	−0.653	−0.394	−0.229	−0.059	0.005	0.025	0.024	0.015	0.008	0.003

Top of Screen in Pumped Well is 40. Per Cent of Aquifer Thickness Below Top of Aquifer

Piez. Depth	Distance of Piezometer from Pumped Well, as Per Cent of Aquifer Thickness												
	5.00	10.00	15.00	20.00	25.00	30.00	40.00	50.00	60.00	80.00	100.00	120.00	150.00
0.0	−3.415	−2.095	−1.387	−0.944	−0.650	−0.451	−0.219	−0.108	−0.053	−0.013	−0.003	−0.001	−0.000
10.	−3.232	−1.929	−1.246	−0.829	−0.561	−0.383	−0.182	−0.089	−0.044	−0.011	−0.003	−0.001	−0.000
20.	−2.572	−1.354	−0.778	−0.467	−0.290	−0.184	−0.079	−0.036	−0.017	−0.004	−0.001	−0.000	−0.000
30.	−0.877	−0.057	0.142	0.168	0.145	0.114	0.062	0.032	0.016	0.004	0.001	0.000	−0.000
40.	4.280	2.401	1.471	0.939	0.615	0.410	0.189	0.090	0.044	0.011	0.003	0.001	−0.000
50.	8.218	3.973	2.207	1.322	0.831	0.539	0.241	0.113	0.055	0.013	0.003	0.001	0.000
60.	4.280	2.401	1.471	0.939	0.615	0.410	0.189	0.090	0.044	0.011	0.003	0.001	0.000
70.	−0.877	−0.057	0.142	0.168	0.145	0.114	0.062	0.032	0.016	0.004	0.001	0.000	0.000
80.	−2.572	−1.354	−0.778	−0.467	−0.290	−0.184	−0.079	−0.036	−0.017	−0.004	−0.001	−0.000	0.000
90.	−3.232	−1.929	−1.246	−0.829	−0.561	−0.383	−0.182	−0.089	−0.044	−0.011	−0.003	−0.001	0.000
100.	−3.415	−2.095	−1.387	−0.944	−0.650	−0.451	−0.219	−0.108	−0.053	−0.013	−0.003	−0.001	0.000

the aquifer, and the effects of delayed gravity response are small. The effects of gravity response become negligible after a time as given, for piezometers near the water table, by the equation:

$$t = \frac{bS_y}{K_z} \tag{9}$$

for values of $ar/b < 0.4$ and by the equation:

$$t = \frac{bS_y}{K_z}\left(0.5 + 1.25\,\frac{r}{b}\sqrt{\frac{K_z}{K_r}}\right) \tag{10}$$

for greater values of ar/b.

5.3.2 Drawdown in an unconfined aquifer is also affected by curvature of the water table or free surface near the control well, and by the decrease in saturated thickness, that causes the transmissivity to decline toward the control well. This test method should be applicable to analysis of tests on water-table aquifers for which the control well is cased to a depth below the pumping level and the drawdown in the control well is less than 0.2b. Moreover, little error would be introduced by effects of water-table curvature, even for a greater drawdown in the control well, if the term ($s^2/2b$) for a given piezometer is small compared to the δs term.

5.3.3 The transmissivity decreases as a result of decreasing thickness of the unconfined aquifer near the control well. Jacob **(4)** has shown that the effect of decreasing transmissivity on the drawdown may be corrected by the equation:

$$s' = s - (s^2/2b) \tag{11}$$

where s is the observed drawdown and s' is the drawdown in an equivalent confined aquifer.

6. Apparatus

6.1 Apparatus for withdrawal tests is given in Test Method D 4050. The apparatus described as follows are those components of the apparatus that require special attributes for this specific test method.

6.2 *Construction of Control Well*—Screen the control well through only part of the vertical extent of the aquifer to be tested. The screened interval of the control well must be known as a function of aquifer thickness.

6.3 *Construction and Placement of Piezometers and Ob-*

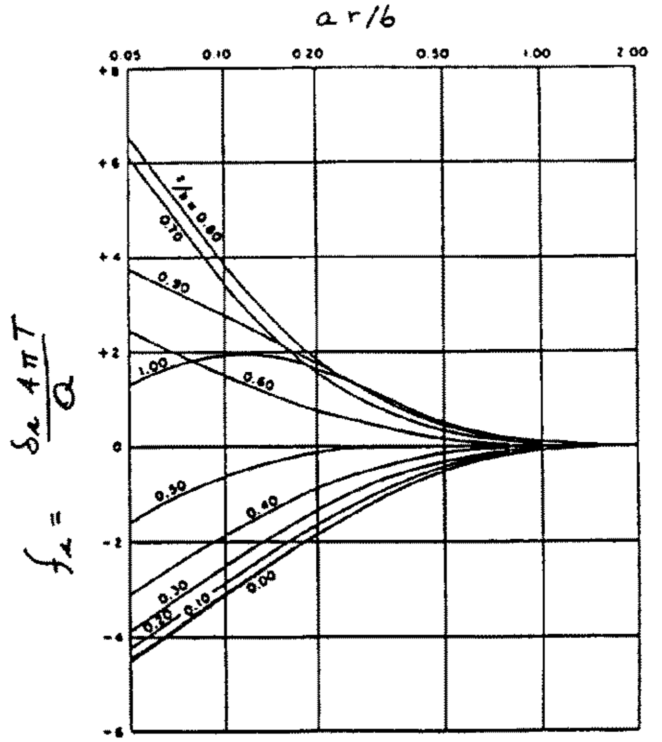


FIG. 3 Graph of Dimension Less Drawdown Factor, f_z, versus ar/b for a Pumped Well Screened from z = 0.86 to z = 0.96 for Values of Piezometer Penetration, z/b

servation Wells—The requirements for observation wells and piezometers are related to the method of analysis to be used. Two methods of analysis are prescribed in Section 8; the observation well and piezometer requirements for each method are given as follows. The piezometers and observation wells may be on the same or various radial lines from the control well.

6.3.1 The type curve fitting methods require one or more piezometers near the control well within the radial distance affected by vertical flow components. This distance is given by $r < 1.5b/(K_z/K_r)^{1/2}$. The depth of the piezometer opening must be known as a function of the aquifer thickness. Construction of piezometers or wells for a specific test shall be identical with respect to distance from the top of the aquifer to the bottom of the piezometers or the screened interval of the wells.

6.3.2 Method 1 of the drawdown deviation methods requires one or more piezometers or wells near the control well within the radial distance affected by vertical flow components. The depth of these piezometers and the screened interval of wells must be known as a function of aquifer thickness. Construction of piezometers or wells for a specific test within the distance affected by vertical flow components shall be identical with respect to distance from the top of the aquifer to the bottom of the piezometers or the screened interval of the wells. In addition, the method requires two or more observation wells or piezometers at a distance from the control well beyond the effect of vertical flow components.

6.3.3 Method 2 of the drawdown deviation methods requires two or more piezometers within the radial distance affected by vertical flow components. Construction of piezometers or wells for a specific test within the distance affected by vertical flow components shall be identical with respect to distance from the top of the aquifer to the bottom of the piezometers or the screened interval of the wells.

NOTE 1—The drawdown deviation methods were originated by Weeks (1) who published tables of the drawdown correction factors for piezometers. Partially penetrating observation wells may be used in place of or in addition to the piezometers. Weeks (1) has found that data from observation wells screened for less than 20 % of the aquifer thickness, using the center of the screen as the piezometer depth, can be used in place of piezometers if the position of the screen in the observation well is above or below that of the screen in the pumped well. However, if the observation well is screened at the same level or overlaps that in the pumped well, Eq 1, or the values in Table 1 derived from Eq 1, should be used only when the screen length of the observation well is less than about 5 % of the aquifer thickness. Data obtained from observation wells open or screened in a larger part of the aquifer thickness could be analyzed by values of the drawdown correction factor derived from Eq 4. Drawdown correction factors can be derived from values of $[W(u) + f_s]$, computed from the Fortran code of Reed (5) or the basic code of Dawson and Istok (6).

7. Procedure

7.1 *Pretest Preparations*—Pretest preparations are given in more detail in Test Method D 4050.

7.1.1 *Testing Response of Piezometers and Observation Wells*—The piezometers and observation wells are tested by pumping or injecting water to assure hydraulic connection between the well and the aquifer.

7.1.2 Measure water levels to determine the trend of water levels before the commencement of the test.

7.1.3 *Step Test*—Pump the control well at steady, progressively greater rates to estimate the transmissivity and select a steady rate of pumping for the aquifer test.

7.2 *Aquifer Testing*—The field procedure summarized below for pumping the control well and measurement of water levels is given in detail in Test Method D 4050.

7.2.1 *Pump Control Well*—Pump the control well at a constant rate. Measure well discharge periodically.

7.2.2 *Measure Water Level in Piezometers and Observation Wells*—Measure water levels frequently during the early phase of pumping; increase the interval between measurements logarithmically as pumping continues.

7.3 *Analysis of the Test Data*—The field test data are analyzed by methods described in Section 8.

8. Calculation and Interpretation of Results

8.1 *Type Curve Methods*—Two type curve methods are presented. The first method is employed by plotting drawdown versus time for each observation well and matching the data plot with prepared-type curves of $[W(u) + f_s]$ versus $1/u$. The second method is employed by plotting drawdown versus r^2/t for one or more wells on the same graph and matching with prepared families of type curves of $[W(u) + f_s]$ versus $1/u$.

8.1.1 *Type Curve Method 1*—This test method is applicable where one or more piezometers or wells are within the distance from the control well affected by vertical flow components.

8.1.2 Select a range of values of $a = (K_z/K_r)^{1/2}$ and prepare a set of type curves for each observation well. For each type curve having values of a and ar/b, plot $[W(u) + f_s]$ versus $1/u$ on logarithmic paper (see Fig. 4).

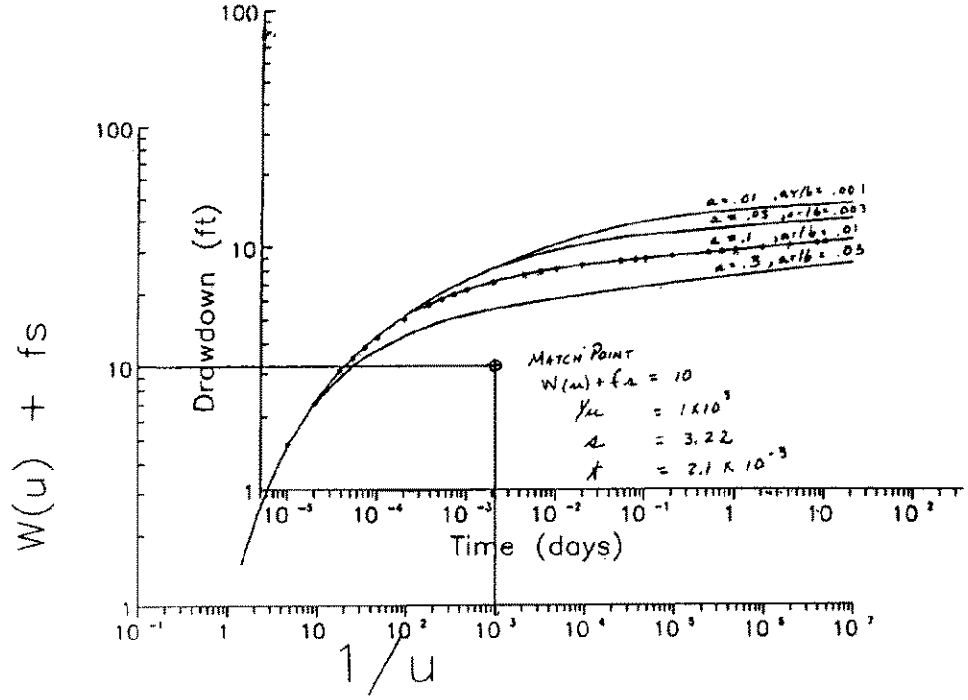


FIG. 4 Data and Type Curves

NOTE 2—The type curves can be plotted from values of $[W(u) + f_s]$ calculated from the Fortran program in Table 2.1 of Reed **(5)** or the Basic program, TYPE6, of Dawson and Istok **(6)**.

8.1.3 For each observation well, prepare plots of data by plotting s versus t using the same logarithmic scales used to plot the type curves (Fig. 4).

8.1.4 Overlay the data plot on the family of type curves developed for that observation well. Shift the plots relative to each other, keeping the axes parallel, until a position of best fit is found between the data plot and one of the type curves.

8.1.5 Select a common match point on the data plot and the type curve. Record the value of a for the type curve and values of $[W(u) + f_s]$, s, u, and t for the data and type curve match point.

8.1.6 Calculate transmissivity, T, from Eq 1.

8.1.7 Calculate $K_r = T/b$.

8.1.8 From the value of $a = (K_z/K_r)^{1/2}$ for the type curve, calculate $K_z = K_r * a^2$.

8.1.9 Substitute values of T, u, t, and r in the equation $u = (r^2S/4Tt)$ and solve for storage coefficient, S.

NOTE 3—From the match point in Fig. 4, transmissivity is calculated:

$$T = Q/4\pi s\,(W(u) + f_s)$$
$$T = (19\,250 * 10)/(4 * \pi * 3.22) = 4800 \text{ ft}^2 \text{ day}^{-1} \text{ (rounded)}$$

The hydraulic conductivity radially from the well is calculated:

$$K_r = T/b = 4800/100 = 480 \text{ ft day}^{-1}$$

The hydraulic conductivity normal to the plane of the aquifer is calculated:

$$K_z = 480 * 0.01 = 4.8 \text{ ft day}^{-1}$$

The storage coefficient is calculated:

$$S = 4Tu(t/r^2)$$
$$S = (4 * 4800 * 2.1 * 10^{-3})/(100 * 1000) = 4 * 10^{-5}$$

Note that the curves are similar for both early and late times. In calculating the values for a single well, both early and late water-level measurements are needed to select the proper curve. Without early and late data to select the proper curve, values of transmissivity, and radial and vertical hydraulic conductivity are affected less than the value of storage coefficient.

8.2.1 *Type Curve Method 2*—This test method is applicable where two or more observation wells are within the distance from the control well affected by vertical flow components.

8.2.2 Prepare a set of family-type curves, each family of several curves for selected values of a. For each family of type curves, with equal a, plot $[W(u) + f_s]$ versus $1/u$ on logarithmic paper (see Fig. 5). The type curves can be plotted from values of $[W(u) + f_s]$ calculated from the Fortran program in Table 2.1 of Reed **(5)** or the basic program, TYPE6, of Dawson and Istok **(6)**.

8.2.3 Prepare a data plot of all observation wells on the same graph. Plot data for each well as s versus r^2/t using the same sized logarithmic scales used to plot the type curves (see Fig. 5).

8.2.4 Overlay the data plots on each family of type curves. Shift the plots relative to each other, keeping the axes parallel, until a position of best fit is found between the data plots and one family of type curves.

8.2.5 Select a common match point on the data plot and the type curve plot. Record values of $[W(u) + f_s]$, s, u, and t for the match point and the value of a for the family of type curves.

8.2.6 Calculate transmissivity, T, from Eq 1.

8.2.7 Calculate the value of $K_r = T/b$.

8.2.8 From the value of $a = (K_z/K_r)^{1/2}$ for the match point, the transmissivity, and the thickness of the aquifer, b, calculate K_z from Eq 12.

8.2.9 Substitute values of T, u, t, and r in the equation $u = (r^2S/4Tt)$ and solve for storage coefficient, S.

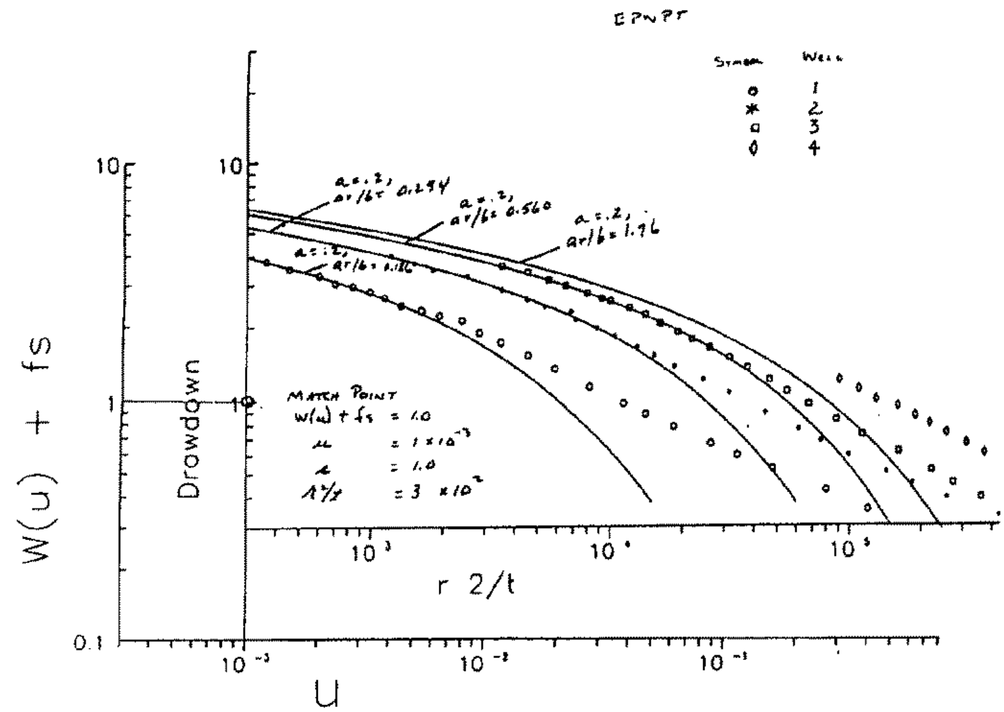


FIG. 5 Data and Type Curves for Multiple Observation Points and Match Point Located

NOTE 4—From the match point in Fig. 5, the transmissivity is calculated:

$$T = Q/4\pi s\,(W(u) + f_s)$$
$$T = (204\,050 \cdot 1.0)/(4 \cdot \pi \cdot 1.0) = 16\,000 \text{ (rounded)}$$

The hydraulic conductivity radially from the control well is calculated:

$$K_r = T/b = 16\,000/80 = 200 \text{ ft day}^{-1}$$

The hydraulic conductivity normal to the plane of the aquifer is calculated:

$$K_z = 200 \cdot 0.04 = 8 \text{ ft day}^{-1}$$

The storage coefficient is calculated:

$$S = 4Tu(t/r^2)$$
$$S = (4 \cdot 16\,000 \cdot 0.001)\,(1/300) = 0.21$$

It is noted in Fig. 5 that the early time data for each well lies above the type curve. This is typical of the water level-data from unconfined aquifers to plot above the type curves for confined aquifers. This response has been attributed to delayed gravity release of water from the aquifer under water table conditions. Applying Eq 9, $t = bS_y/K_z$, the effect of delayed gravity response is negligible after the time, $t = (80 \cdot 0.21)/8 = 2.1$ days or for values of $r^2/t < (50)^2/2.1 = 1190$ for well 1*E* and $r^2/t < (116)^2/2.1 = 6408$ for well 2*E*. Applying Eq 10, $t = (bS_y/K_z)(0.5 + 1.25)(r/b)(K_z/K_r)^{1/2}$ the effect of delayed gravity response is negligible at well 3*E* for $t > ((80 \cdot 0.21)/8)(0.5 + 1.25)(221/80) \cdot 0.2 = 24.0 \cdot (0.5 + 0.69) = 18$, or for values of $r^2/t < 2713$.

8.3 *Drawdown Deviation Methods*—Drawdown near a partially penetrating control well deviates from drawdown that would occur near a control well fully penetrating the aquifer. These deviations occur when a well partially penetrating the aquifer is pumped because water levels are drawn down more in piezometers open near the level of the screen, and less in piezometers open at an interval somewhat above or below the screened interval, than they would be if the pumped well fully penetrated the aquifer. Drawdown deviations due to partial penetration are amplified when the vertical hydraulic conductivity is less than the horizontal hydraulic conductivity. The drawdown deviation methods (1) employ the relationship between the drawdown deviation in an anisotropic aquifer and the drawdown deviation in an equivalent isotropic aquifer. The drawdown deviation at a given distance, r, due to pumping a partially penetrating well in an anisotropic aquifer is the same as that at the distance $r(K_r/K_z)^{1/2}$ in an equivalent isotropic aquifer. The drawdown deviation due to partial penetration of the control well is determined from the field data by graphical analysis. The theoretical drawdown that would occur for the same pumped well in an equivalent isotropic aquifer is determined using Eq 1. From the computed curve, the distances from the pumped well at which the observed drawdown deviations would occur in the equivalent isotropic aquifer are found, and the ratio of horizontal to vertical hydraulic conductivity is computed by equating the ratio to the square of the ratio of the actual distance to the distance in an equivalent isotropic aquifer.

8.3.1 *Drawdown Deviation Method I*—This method is applicable for aquifer tests for which piezometers are available to define the potentiometric profile of the cone of depression to distances both within and beyond the effects of partial penetration.

8.3.1.1 Prepare a plot of drawdown, s, versus log r for a time, t, at or near the end of the test (see Fig. 6).

8.3.1.2 Compute the transmissivity and storage coefficient from the straight line part of the curve defined by the most distant wells or piezometers using the modified Theis nonequilibrium method. This procedure is given in Test Method D 4105.

8.3.1.3 Evaluate the values of T and S by calculating the value of $u = r^2S/4Tt$ for the data used to calculate T and S. The value of u shall be equal or less than 0.01 for the most distant piezometer or well used in the determination of transmissivity and storage coefficient.

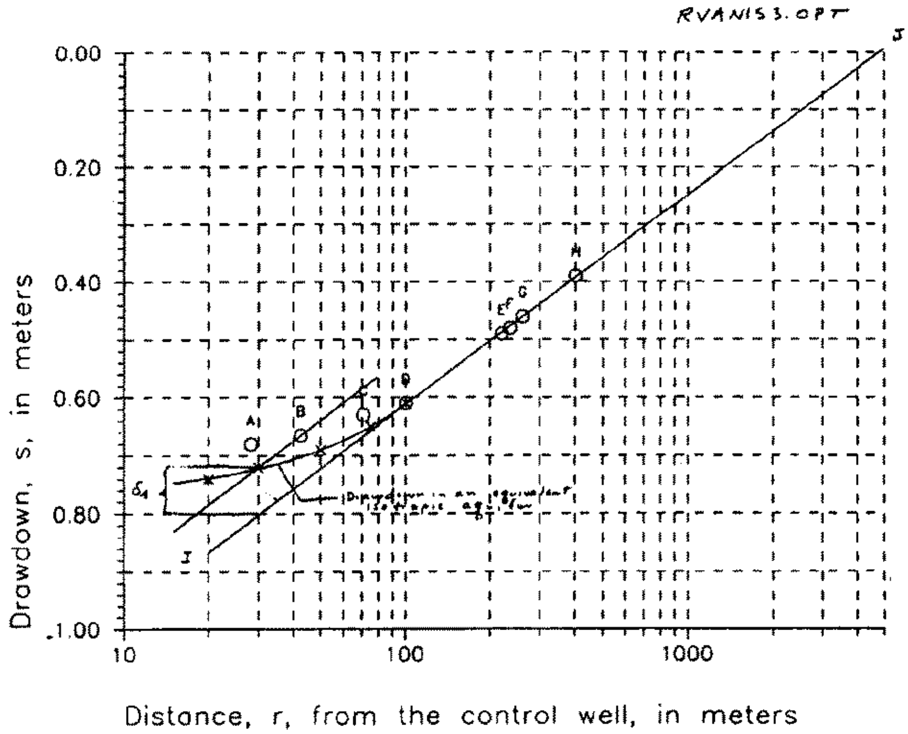


FIG. 6 Drawdown Plot in an Anisotropic Aquifer With Computed Drawdown in an Equivalent Isotropic Aquifer

NOTE 5—The limiting value for u of less than 0.01 may be excessively restrictive in some applications. The errors for small values of u, from Kruseman and De Ridder (7) are:

Error less than:	1 %	2 %	5 %	10 %
For u smaller than:	0.03	0.05	0.1	0.15

NOTE 6—If the values of u are not less than the limiting value for the piezometers used to calculate T and S, calculate T and S from time-drawdown plots at later times as prescribed in Test Method D 4105. Draw line of slope $\Delta s = -2.3Q/2\pi T$ beneath the data points. Continue with 8.3.1.4 through 8.3.1.11. Recalculate the position of the straight line in Fig. 6 and repeat 8.3.1.4 through 8.3.1.11 until the recomputed value of S changes by less than 10 %.

NOTE 7—Wells used to calculate T and S (see 8.1) shall be at a distance beyond the effects of partial penetration, that is, beyond a distance such that $(K_z/K_r)^{1/2}\ r/b > 1.5$. Because K_r and K_z will not be known, this evaluation cannot be made prior to the completion of the final step of the procedure. Proceed through the following steps and recompute the radial distance from the control well affected by vertical flow components. If the piezometers are not beyond the affected distance, it may be possible to evaluate the data by the second drawdown deviation method.

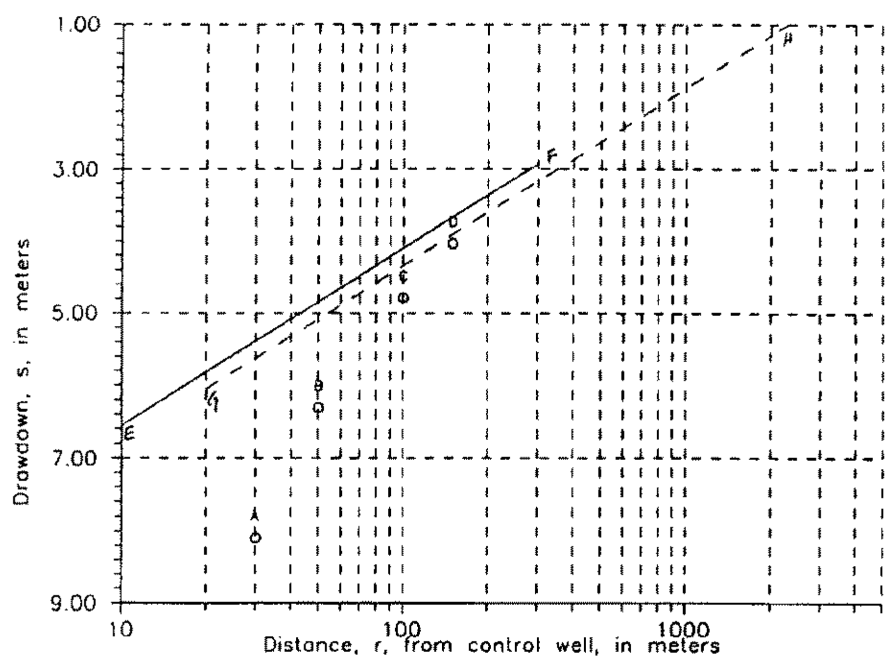


FIG. 7 Data Plots of Drawdown in Piezometer Near a Control Well and Straight-line Plots

8.3.1.4 Extend the straight line down to an r value somewhat smaller than that for the closest piezometer, I-J in Fig. 6.

8.3.1.5 Compute values of drawdown deviation, $\delta s = (Q/4\pi T)f_s$ for assumed values of r within the distance from the control well where the measured drawdown departs from the straight line. This line is shown by deviation from the straight line drawdown in piezometers A, B, and C, in Fig. 6. Values of f_s are calculated from Eq 3 or interpolated from Table 1.

8.3.1.6 Construct the curve representing the drawdown profile that would occur in an equivalent isotropic aquifer by adding, algebraically, the δs term for each of the r values, to the drawdown of the straight line plot, I-J. Connect the resulting points by a smooth curve (see Fig. 6).

8.3.1.7 Draw a line parallel to the line I-J through a point of measured drawdown (such as Piezometer B in Fig. 6) and the computed drawdown profile for the equivalent isotropic aquifer.

8.3.1.8 Determine the r_c value for the intercept of this parallel line with the computed drawdown profile for equivalent isotropic conditions. The distance r_c = 20 m for the intercept of the parallel line through B with the drawdown in an equivalent isotropic aquifer.

8.3.1.9 Compute the ratio of horizontal to vertical hydraulic conductivity from the formula:

$$\frac{K_r}{K_z} = \left(\frac{r}{r_c}\right)^2 \tag{13}$$

where r is the distance from pumped well to piezometer through which the line drawn in 8.1.2 was constructed. In Fig. 6, for Piezometer B:

$$r = 42.4, \quad r_c = 30, \quad K_r/K_z = 2$$

8.3.1.10 Repeat 8.3.1.7 through 8.3.1.9 for each piezometer in which the drawdown deviates from the drawdown in an equivalent isotropic aquifer.

8.3.1.11 Find the storage coefficient from data obtained in piezometers located beyond the effects of partial penetration using the following equation from Test Method D 4105:

$$S = \frac{2.25Tt}{r^2} \tag{14}$$

where r is the value at the zero drawdown intercept.

8.3.2 *Method 2*—This method is applicable where two or more piezometers are within the radial distant affected by partial penetration but where piezometers are not available or the period of pumping is too short to determine the position of the distance-drawdown curve for the region unaffected by partial penetration.

8.3.2.1 Determine values of transmissivity from each piezometer by the modified Theis nonequilibrium method, as described in Test Method D 4105, using the data obtained during the later part of the test.

8.3.2.2 Prepare a semilogarithmic plot, plotting drawdown, s, values for the piezometers for a selected time on the arithmetic scale and distance, r, on the logarithmic scale. Draw any line of slope $\Delta s = -2.3Q/2\pi T$ beneath the plotted drawdown values if δs is indicated to be negative (drawdown less than for an equivalent isotropic aquifer) or above the drawdown value if δs appears to be positive. An example of such a plot is shown in Fig. 7, showing drawdown in piezometers and the straight line plot E-F.

8.3.2.3 Determine values of the drawdown deviation, δs, for each piezometer by subtracting the drawdown value for the straight-line plot, E-F, from the observed drawdown.

8.3.2.4 Use the δs values to compute values of f_s from the formula: $f_s = 4\pi T\delta s/Q$, and prepare a semilogarithmic graph plotting f_s on the arithmetic axis and (r/b) on the logarithmic

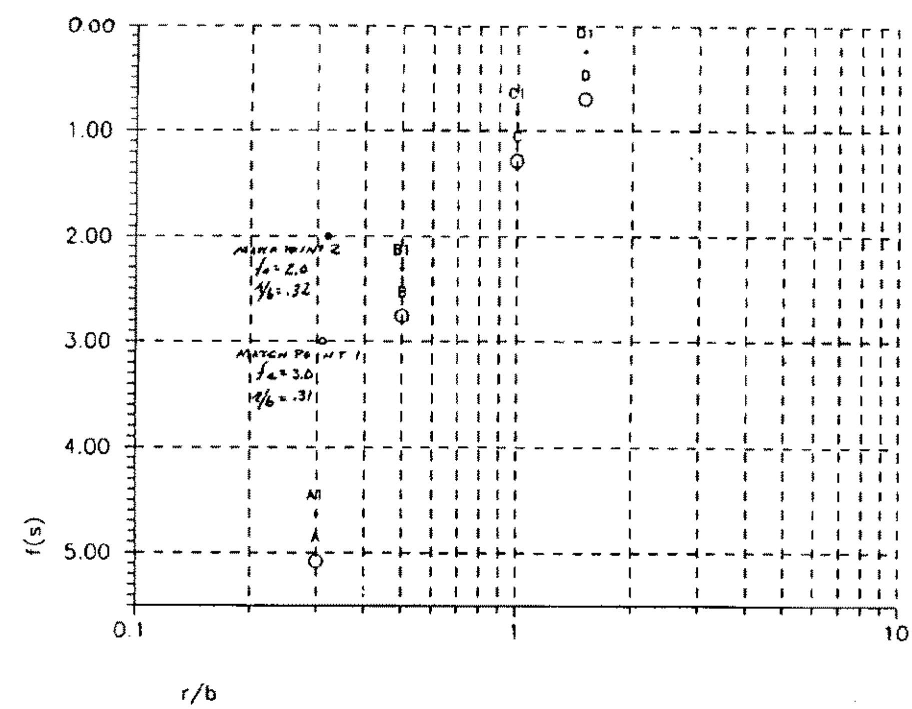


FIG. 8 Data Plot of fs, Dimensionless Drawdown Correction Factor, Versus r/b for Drawdown in Piezometers

axis. An example of such a plot is shown in Fig. 8.

8.3.2.5 Prepare a semilogarithmic-type curve by plotting values of f_s from Eq 3 or 4 or Table 1 on the arithmetic axis for various values of r_c/b plotted on the logarithmic axis. An example of such a plot is shown in Fig. 9.

8.3.2.6 Match the data plot to the type curve, keeping the coordinate axes of the two plots parallel, and select any convenient point common to both plots (see Figs. 8 and 9).

8.3.2.7 Determine for the selected match point, the coordinate value of r/b from the data plot and the value of r_c/b from the type-curve plot. Solve for K_r/K_z from the formula:

$$\frac{K_r}{K_z} = \left(\frac{r/b}{r_c/b}\right)^2 \tag{15}$$

8.3.2.8 For the selected match point, subtract the data-plot value of f_s (see Fig. 8) from the type-curve value of f_s (Fig. 9) and correct the data-plot values of f_s (see 8.3.2.4) by adding, algebraically, the amount to each f_s.

8.3.2.9 Replot data using corrected values of f_s and repeat 8.3.2.6 (Points A1, B1, C1, and D1 in Fig. 8); recalculate K_r/K_z.

8.3.2.10 If the calculated values of K_r/K_z differ by more than 10 %, repeat 8.3.2.8 and 8.3.2.9.

8.3.2.11 Correct straight-line plot in 8.3.2.2 (E–F, in Fig. 7) by adding, algebraically, $Q/4\pi T \cdot (f_s$ (type-curve) $- f_s$ (data-curve). Corrected line is G–H in Fig. 7.

8.3.2.12 Using the zero drawdown intercept of the redrawn straight-line plot, determine the coefficient of storage from Eq 14.

NOTE 8—The following is provided to complement the procedures for calculation of hydraulic properties using Deviation Method 2. Plot of drawdown in Fig. 7 is indicated to be greater than for an equivalent isotropic aquifer. Straight line E–F of slope $\Delta s = -2.3Q/2\pi T = (-2.3 \cdot 10\,000\ m^3\ d^{-1})/(2 \cdot \pi \cdot 1500\ m^2\ d^{-1}) = -2.44$ m/log cycle is drawn above drawdown values in Fig. 7.

Drawdown deviation, δs, for each piezometer is the observed drawdown minus the drawdown value for the straight-line plot, E–F, as shown in the accompanying table. The corresponding values of $f_s = 4\pi T\delta s/Q$ are calculated and a semilogarithmic graph of f_s on the arithmetic scale versus r/b (r of A = 30 m, B = 50 m, C = 100 m, and D = 150 m; b = 100 m) on the logarithmic scale as shown in Fig. 8.

	A	B	C	D
δs	2.70	1.47	0.68	0.37
f_s	5.08	2.76	1.28	0.70
r/b	0.3	0.5	1.0	1.50

A type curve is prepared plotting values of f_s versus r_c/b, shown in Fig. 9.

The plot of Points A, B, C, and D (see Fig. 8) are matched with the type curve (see Fig. 9). Match point 1, Figs. 8 and 9, are selected, and values of f_s and r/b from the data plot (see Fig. 8) are recorded and values of f_s and r_c/b from the type curve (see Fig. 9) are recorded. From the match point, determine:

$$K_r/K_z = [(r/b)/(r_c/b)]^2 = [0.31/0.1]^2 = 9.6$$

For the selected match point, subtract data point f_s from the type-curve f_s:

$$f_s \text{ (type curve)} - f_s \text{ (data plot)} = 2.55 - 3 = -0.45$$

Correct the data plot by adding, algebraically, this amount to the f_s (data plot) values, as shown below:

	A1	B1	C1	D1
f_s	4.63	2.31	0.83	0.35

Replot data in Fig. 8 using corrected values of f_s, match the type curve to the replotted data (Match Point 2), and recalculate K_r/K_z:

$$K_r/K_z = [(r/b)/(r_c/b)]^2 = [0.32/0.1]^2 = 10.2$$

Recalculate the drawdown deviation, $\delta s = f_s \cdot (Q/4\pi T)$:

	A	B	C	D
δs	2.45	1.22	0.44	0.13

Redraw straight-line plot using these values of drawdown deviation, as shown by Line G–H in Fig. 7.

8.3.2.13 Using the zero drawdown intercept, r, of the redrawn straight-line plot, determine the storage coefficient,

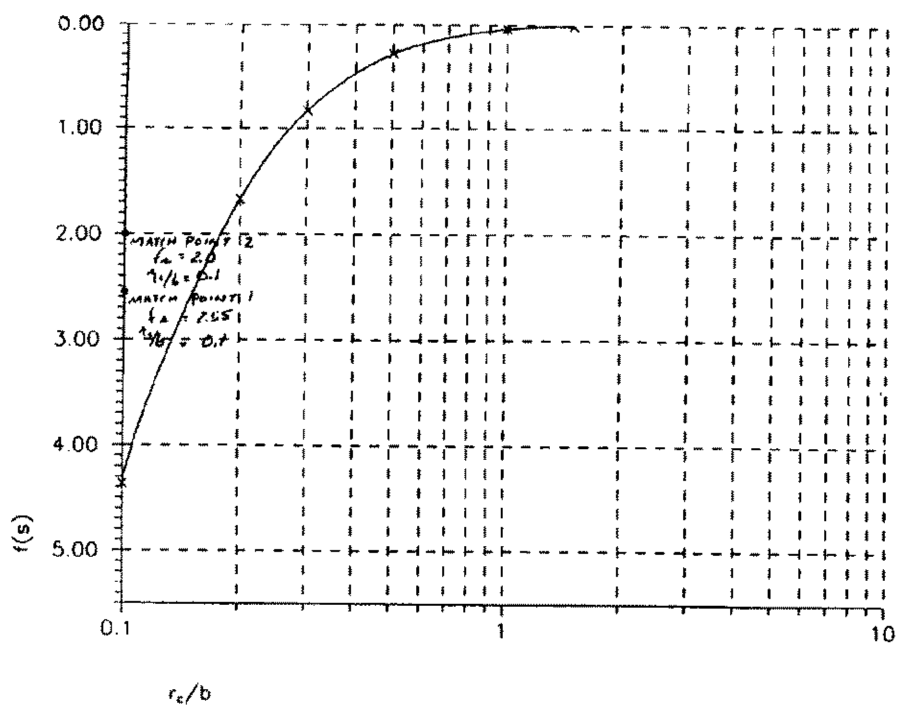


FIG. 9 Type Curve of f_s, Dimensionless Drawdown Factor, Versus r_c/b

$S = (2.25Tt)/r^2 = (2.25 \cdot 1500\ m^2 \cdot d^{-1} \cdot 1d)/(5400\ m)^2 = 1 \cdot 10^{-4}$

9. Report

9.1 Prepare a report including the following:

9.1.1 *Introduction*—The introductory section is intended to present the scope and purpose of this test method. Briefly summarize the field hydrogeologic conditions and the field equipment and instrumentation including the construction of the control well and observation wells or piezometers, or both, the method of measurement of discharge and water levels, and the duration of the test and pumping rate.

9.1.2 *Conceptual Model*—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 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 *Equipment*—Report the field installation and equipment for the aquifer test, including the construction, diameter, depth of screened and gravel packed intervals, and location of control well and pumping equipment, and the construction, diameter, depth, and screened interval of piezometers and observation wells.

9.1.4 *Instrumentation*—Describe the field instrumentation for observing water levels, pumping rate, barometric 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 and method of the last calibration, if applicable.

9.1.5 *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 piezometers and observation wells, and other environmental data recorded during the testing procedure.

9.1.6 *Presentation and Interpretation of Test Results:*

9.1.6.1 *Data*—Present tables of data collected during the test. Show methods of adjusting water levels for background water-level and barometric changes and calculation of drawdown and residual drawdown.

9.1.6.2 *Data Plots*—Present data plots used in analysis of the data. Show overlays of data plots and type curve with match points and corresponding values of parameters at match points.

9.1.7 Evaluate qualitatively the overall accuracy of the test, the corrections and adjustments made to the original water-level measurements, the adequacy and accuracy of instrumentation, accuracy of observations of stress and response, and the conformance of the hydrogeologic conditions and the performance of the test to the model assumptions.

10. Precision and Bias

10.1 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. No statement can be made about bias because no true reference values exist.

11. Keywords

11.1 anistroph; aquifers; aquifer tests; control wells; ground water; hydraulic conductivity; observation wells; storage coefficient; transmissivity

REFERENCES

(1) Weeks, E. P., "Determining the Ratio of Horizontal to Vertical Permeability by Aquifer-Test Analysis," *Water Resources Research*, Vol 5, No. 1, 1969, pp. 196–214.

(2) Hantush, M. S., "Drawdown Around a Partially Penetrating Well," American Society of Civil Engineers, *Proceedings*, Vol 87, No. HY4, 1961, pp. 83–98.

(3) Theis, C. V., *The Relation Between the Lowering of the Piezometric Surface and the Rate and Duration of Discharge of a Well Using Ground-Water Storage: American Geophysical Union Transactions*, Vol 16, Part 2, 1935, pp. 519–524.

(4) Jacob, C. C., "Determining the Permeability of Water-Table Aquifers," *in* Bentall, Ray, Compiler, *Methods of Determining Permeability, Transmissibility, and Drawdown*, U.S. Geological Survey Water-Supply Paper 1536-I, 1963, pp. 245–271.

(5) Reed, J. E., "Type Curves for Selected Problems of Flow to Wells in Confined Aquifers," *U.S. Geological Survey Techniques of Water-Resources Investigations*, Book 3, Ch. B3, 1980.

(6) Dawson, K. J., and Istok, J. D., *Aquifer Testing—Design and Analysis of Pumping and Slug Tests*, Lewis Publishers, Chelsea, Michigan, 1991.

(7) Kruseman, G. P., and DeRidder, N. S., *Analysis and Evaluation of Pumping Test Data*, International Institute for Land and Reclamation and Improvement, Bulletin 11, Wageningen, The Netherlands, 1979.