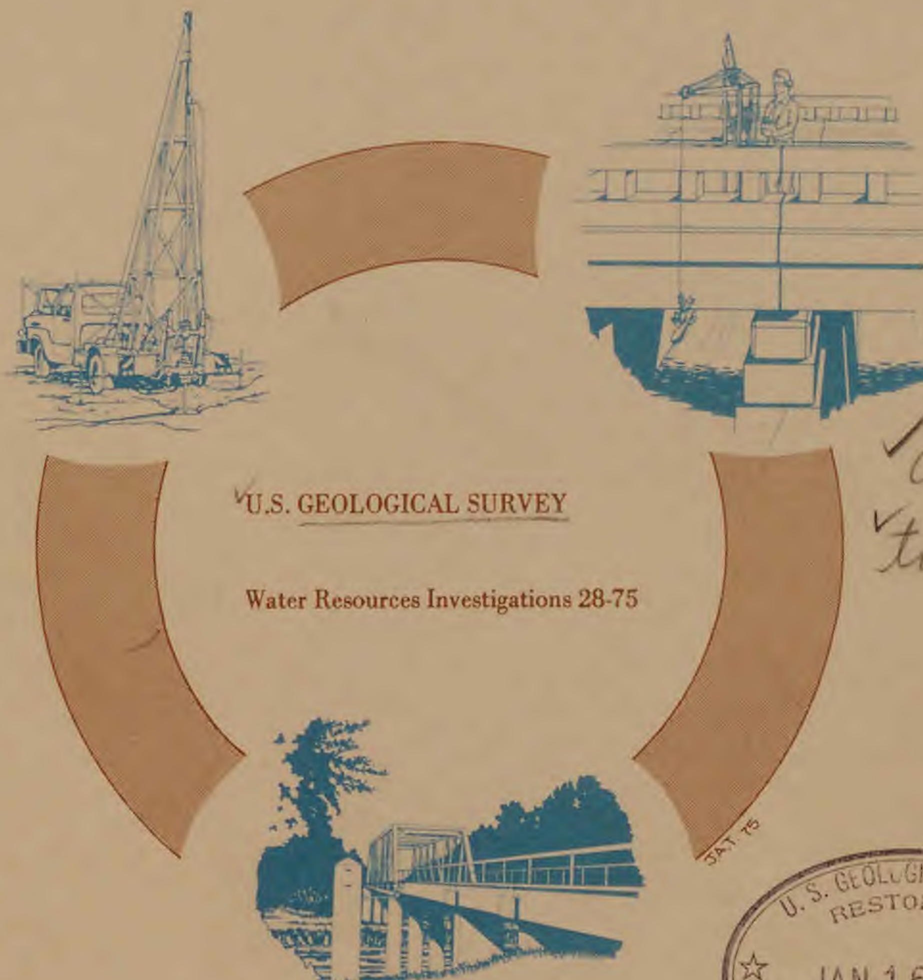
WRI 28-75

AQUIFER TESTS IN THE SUMMIT REACH OF THE PROPOSED CROSS-FLORIDA BARGE CANAL NEAR OCALA, FLORIDA



U.S. GEOLOGICAL SURVEY

Water Resources Investigations 28-75

Aquifer tests in the summit reach of the proposed Cross-Florida Barge Canal near Ocala, Florida

Prepared in cooperation with
U.S. DEPARTMENT OF THE ARMY,
CORPS OF ENGINEERS

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16. Abstracts

The Summit Pool reach of the proposed Cross-Florida Barge Canal will be excavated into the Floridan aquifer at least 12 feet below the water table. Particular areas of concern are "outflow" areas where water is expected to pass from the canal into the aquifer. The rate of outflow to the aquifer has important implications with regard to potential for ground-water contamination. Horizontal and vertical hydraulic conductivity of Floridan aquifer materials are determined by analyses of specially designed aquifer tests at three sites along the Summit Pool reach. Methods are described that deal with unique boundary conditions and aquifer anisotropy at two sites. Extreme aquifer heterogeneity precluded the determination of aquifer coefficients at the third site and probably affected the results of the tests at the other two sites; therefore, the calculated aquifer coefficients reported should be regarded only as estimates. If the aquifer test sites are representative of the entire Summit reach, most of the flow in the aquifer will pass beneath the canal in solution channels.

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August 1975

UNITED STATES DEPARTMENT OF THE INTERIOR

Kent Frizzell, Acting Secretary

GEOLOGICAL SURVEY

Vincent E. McKelvey, Director

For additional information write to:

U.S. Geological Survey
Suite F-240
325 John Knox Road
Tallahassee, Florida 32303

August 1975

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AQUIFER TESTS IN THE SUMMIT REACH OF THE PROPOSED CROSS-FLORIDA BARGE CANAL NEAR OCALA, FLORIDA

By C. H. Tibbals

ABSTRACT

Values for the horizontal and vertical hydraulic conductivity of Floridan aquifer materials are estimated by analyses of specially-designed aquifer tests at three sites along the Summit Pool reach of the proposed Cross-Florida Barge Canal for use in evaluating the exchange of water between the aquifer and the canal. Methods are described that deal with unique boundary conditions and aquifer anisotropy at two sites. Extreme aquifer heterogeneity precluded the determination of aquifer coefficients at one of the sites and probably affected the results of the tests at the other two. Therefore, the calculated aquifer coefficients reported should be regarded only as estimates. Calculated coefficients of horizontal hydraulic conductivity ranged from 0.025 to 3,500 gallons per day per square foot (0.0010 to 143 metres per day) and calculated coefficients of vertical hydraulic conductivity ranged from 0.05 to 23,000 gallons per day per square foot (0.0021 to 943 metres per day). Ratio of horizontal to vertical hydraulic conductivity ranged from 0.09 to 2.9.

INTRODUCTION

The rate, locations and directions of exchange of water between the Floridan aquifer and the Summit Pool (a part of which is shown on fig. 1 as that reach of the canal west of R.N. Dosh Lock) of the proposed Cross-Florida Barge Canal are of primary concern with regard to the effects of the canal on the ground-water regimen. Particular areas of concern are "outflow" areas where water is expected to pass from the canal into the aquifer. Knowledge of the probable water-exchange relationships between the canal and the aquifer in the Summit Pool reach is needed to predict, under any particular set of hydrologic conditions, the water level in the Summit Pool and in the aquifer in the vicinity of the pool. Also, the ability to predict the effects of different inflow-outflow rates is important to planning backpumping schedules from lower pools on either end of the Summit Pool to maintain the desired water level in the Summit Pool. The rate of outflow to the aquifer has important implications with regard to potential for ground-water contamination.

Flow-net analysis was used in an earlier intensive hydrogeologic investigation in the Ocala vicinity of the canal area (Faulkner, 1973) to determine quantitatively the hydrologic characteristics of the aquifer in the Summit reach of the canal. In that investigation, Silver Springs was likened to a continuously discharging well whose cone of depression was the entire drainage basin for the springs. Aquifer transmissivities derived from the flow-net analysis were then used to predict the water level in the Summit Pool under certain natural ground-water level conditions, and to identify areas of ground-water inflow to the canal and canal-water outflow to the aquifer. Inflow to the canal was expected along

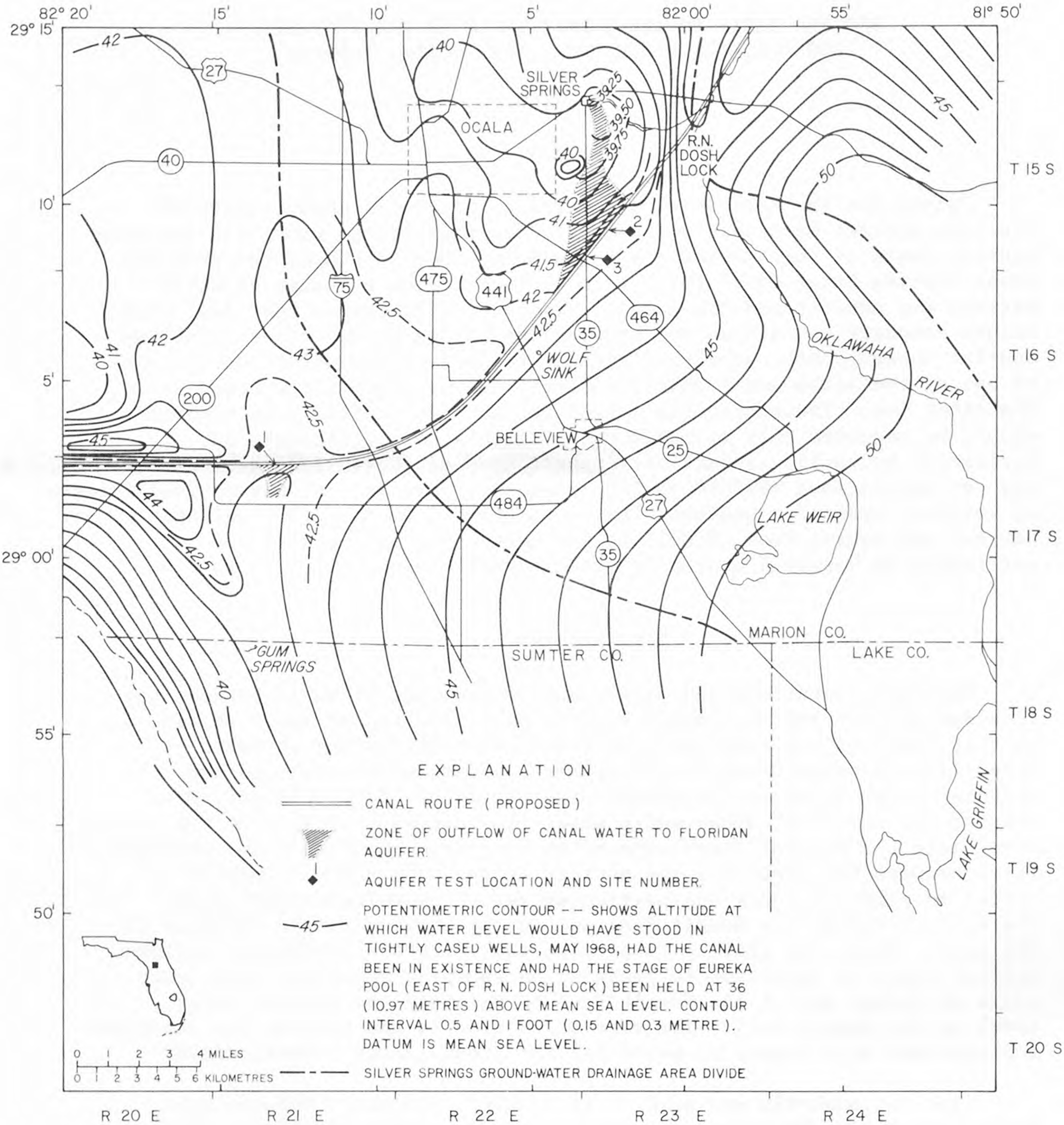

FIGURE 1.--LOCATIONS OF AQUIFER TESTS AND CONCEPTUAL MODEL OF POTENTIOMETRIC SURFACE OF UPPER PART OF FLORIDAN AQUIFER NEAR OCALA, (FROM FAULKNER, 1973, FIG. 32).

most of the Summit reach, but two comparatively narrow zones of outflow from the canal to the aquifer were identified. One was about 5 mi (miles) or 8 km (kilometres) south of Silver Springs, extending a length of about 4 mi (6 km) along the Summit reach; outflow was northward through the aquifer toward the springs. The other was centered some 12 mi (19 km) southwest of the edge of the larger outflow zone, extending a length of 1.25 mi (2.01 km); outflow was southward toward Gum Springs near the Withlacoochee River.

The flow-net analysis necessarily evaluated the entire thickness of the ground-water flow zone associated with spring discharge in the area. This flow zone in the vicinity of the Summit Pool was estimated to be the top 100 ft (feet) or 30 m (metres) of the Floridan aquifer. Although in the flow-net method used, lateral differences in hydraulic conductivity are determined, it is not possible to distinguish differences in hydraulic conductivity with depth. Therefore, at a given location in the Summit Pool, that part of the saturated zone penetrated by the canal was considered as having the same hydraulic conductivity as the underlying remaining part of the 100-ft (30-m) thick flow zone.

Because the canal would, on the average, penetrate less than one-fifth of the effective thickness of the aquifer, it was estimated the canal would intercept about one-fourth of the total ground-water flow moving through the canal's line of section. The flow would only be deflected or rerouted, but not necessarily prevented from ultimately reentering the aquifer and flowing on to the springs. The rate at which water would enter and then leave the canal on its way to Silver Springs was thus calculated to be equivalent to about 8 percent of the average discharge of the springs.

A report by Faulkner (1973) indicated that a series of large-scale aquifer tests needed to be made along the centerline of the Summit reach to better define the influence of the canal on the ground-water flow system in the Summit reach.

Throughout this report, measurements of length, depth, distance, well yield, and aquifer coefficients of transmissivity and hydraulic conductivity are expressed in English units. For convenience, the English units appearing in the text and on illustrations are followed by the equivalent metric value in parentheses. The metric equivalents for values expressed in English units in the tables may be computed using the following conversions:

English unit	Multiplied by	Metric unit
inches	2.54	centimetres
feet	.3048	metres
gallons per minute	3.785	litres per minute
gallons per day per foot	.01242	metres squared per day
gallons per day per foot squared	.04075	metres per day

PURPOSE AND SCOPE

The purpose of this investigation is to determine coefficients of horizontal and vertical hydraulic conductivity of Floridan aquifer materials in the saturated interval penetrated by the proposed barge canal. These coefficients should be helpful in determining the rates of exchange of water between the aquifer and the Summit Pool reach. Such coefficients cannot, however, take into account ground-water flow in large solution channel systems or cavities that may occur at random in the aquifer. The scope of the investigation is limited to conducting and analysing three specially-designed aquifer tests at selected locations in two canal "outflow" areas indicated from the earlier hydrogeologic investigation (Faulkner, 1973).

At each aquifer test site, a test well (hereinafter referred to as "pilot" hole) was drilled about 200 ft (61 m) into the limestone, test-pumped, and logged. In addition to a lithologic log, the logs include electric, gamma-ray, caliper, flowmeter, water temperature, and specific conductance logs. Water samples were taken at the pump discharge for standard complete chemical analysis. In addition, while the pilot hole was being pumped, water samples were taken at selected depths in the hole and analyzed for a few key parameters. Continuous rock cores were taken from all wells, including the observation wells. A few selected intervals of the rock core from wells at site 1 were submitted for laboratory testing of vertical and horizontal hydraulic conductivity.

At each site the "pumped" well (well that was pumped during the aquifer tests) was initially drilled to at least +26 ft (+8.0 m) msl (mean sea level), a depth at or near the design altitude of the bottom of the proposed barge canal (+28 ft or +8.5 m msl) and cased to the top of the limestone aquifer. The wells were test-pumped to determine yield and drawdown and water samples were collected for standard complete analysis. At all three sites, the pumped well had to be deepened to obtain enough water to conduct a meaningful aquifer test.

Observation wells were drilled and cased to selected depths at various distances from the pumped wells to determine the lateral and vertical influence of pumping during the tests.

Three drilling rigs were used at each aquifer test site. This allowed work to progress rapidly because it was possible to drill the pumped well and the observation wells while the pilot hole was being drilled and tested. Therefore, the locations of the observation wells and the pumped well were fixed before all of the information to be developed from the pilot hole could be evaluated. This resulted in less than the most desirable spacing of observation wells in a few instances.

ACKNOWLEDGMENTS

The author expresses his appreciation to the U.S. Army, Corps of Engineers' drilling crews for their helpfulness and many long hours of work that made possible the conducting of the aquifer tests. Lithologic logs by Joe Gentile, Corps of Engineers, were of major importance in interpreting hydrologic boundary conditions. Edwin Weeks, U.S. Geological Survey, helped formulate the conceptual models for the analysis of the aquifer test data and furnished a computer program to generate type curves. Technical advice and comments given by A. I. Foster and Harry Whitsett, Corps of Engineers, are appreciated.

WELL-NUMBERING SYSTEM

Each observation well is numbered according to its direction and approximate distance from the pumped well and to its depth relative to the other observation wells. For example, a well numbered SW50S indicates a shallow well that is about 50 ft (15 m) southwest of the pumped well. Similarly, SW50D1 and SW50D2 are about 50 ft (15 m) southwest of the pumped well but are deeper than SW50S, SW50D2 being the deeper.

NOTATION AND UNITS

Unless otherwise indicated, the following notation and units are used in the mathematical expressions and tables of the reports:

b = Aquifer thickness (ft)
b' = Thickness of real aquifer plus thickness of image aquifer (ft).
$f'(s)$ = Dimensionless function defined by Weeks (1969)

K_r = Horizontal hydraulic conductivity $(gal/d)/ft^2$

K_z = Vertical hydraulic conductivity $(gal/d)/ft^2$

Q = Discharge of pumped well (gal/min)
r = Radial distance from pumped well to observation well (ft)

$r_c = r(K_z/K_r)^{1/2}$ (ft)

s = Drawdown (ft)
S = Storage coefficient (dimensionless)
S_c = Storage coefficient calculated from intercept of semi-logarithmic distance-drawdown plot (dimensionless)
S_y = Specific yield (dimensionless)

t = Time (days)
t_o = Time intercept on semi-logarithmic distance-drawdown plot (days)
T = Transmissivity $(gal/d)/ft$
$u = 1.87\ r^2S/Tt$ (dimensionless)

In this report, depths and altitudes are referred to mean sea level. For example, if the altitude of the bottom of a well is 16 ft (4.9 m) below mean sea level, it is given as -16 ft (-4.9 m), msl. Conversely, if the altitude of the top of a cavern is 6 ft (1.8 m), above mean level, it is given as +6 ft (+1.8 m), msl.

AQUIFER TEST 1

The test site is shown on figure 1 and the pilot hole, pumped well, and observation wells are spaced as shown in figure 2 and finished at depths listed in table 1.

Geologist's logs (Corps of Engineers, written commun, 1974) and geophysical logging of the pilot hole indicated a highly permeable cavernous zone from -20.6 ft (-6.28 m), msl to -22.3 ft (-6.80 m), msl, (fig. 3). A few cavities were noted at higher altitudes during the drilling of some of the observation wells. The logs of water temperature, specific conductance, and a flowmeter traverse while the pilot hole was being pumped indicate that little ground-water circulation takes place below altitude -23 ft (-7 m), msl. The graph of specific conductance in figure 4 suggests that there is also an increase in the dissolved-solids concentration in water below about -23 ft (-7 m), msl. The degree of dissolved-solids concentration of water in the aquifer generally reflects the solubility of the rock materials and the length of time the water has been in contact with the materials. The comparatively high dissolved-solids concentration shown at depth in figure 4 indicates relatively sluggish ground-water circulation below about -23 ft (-7 m), msl. Therefore, on the basis of lithologic and other logs, the base of the aquifer tested is taken to be at altitude -20.6 ft (-6.28 m), msl, the top of the cavernous zone.

The boundary conditions used to analyse the test results are somewhat unusual because the water-table aquifer pumped during the aquifer test is bounded beneath by the cavernous zone that acts as a constant head boundary. Weeks (written commun., 1974) outlined a method by which image theory, applied to methods developed by Hantush (1961 a) and Weeks (1969), can be used to analyse the test data.

In an open-hole observation well of finite-depth the drawdown caused by constant discharge from a nearby partly-penetrating well tapping a homogeneous, anisotropic artesian aquifer (fig. 5) is given, after modification for effects of anisotropy, for periods greater than

$$t = (bS/2K_z), \qquad (1)$$

where:

t = time since pumping began (days);
b = aquifer thickness (ft);
S = storage coefficient (dimensionless);
K_z = vertical hydraulic conductivity (ft/d);

by the equation (Hantush, 1961a, p.90, eq. 8A modified for anisotropy by Weeks, 1969, p 200, eq. 2):

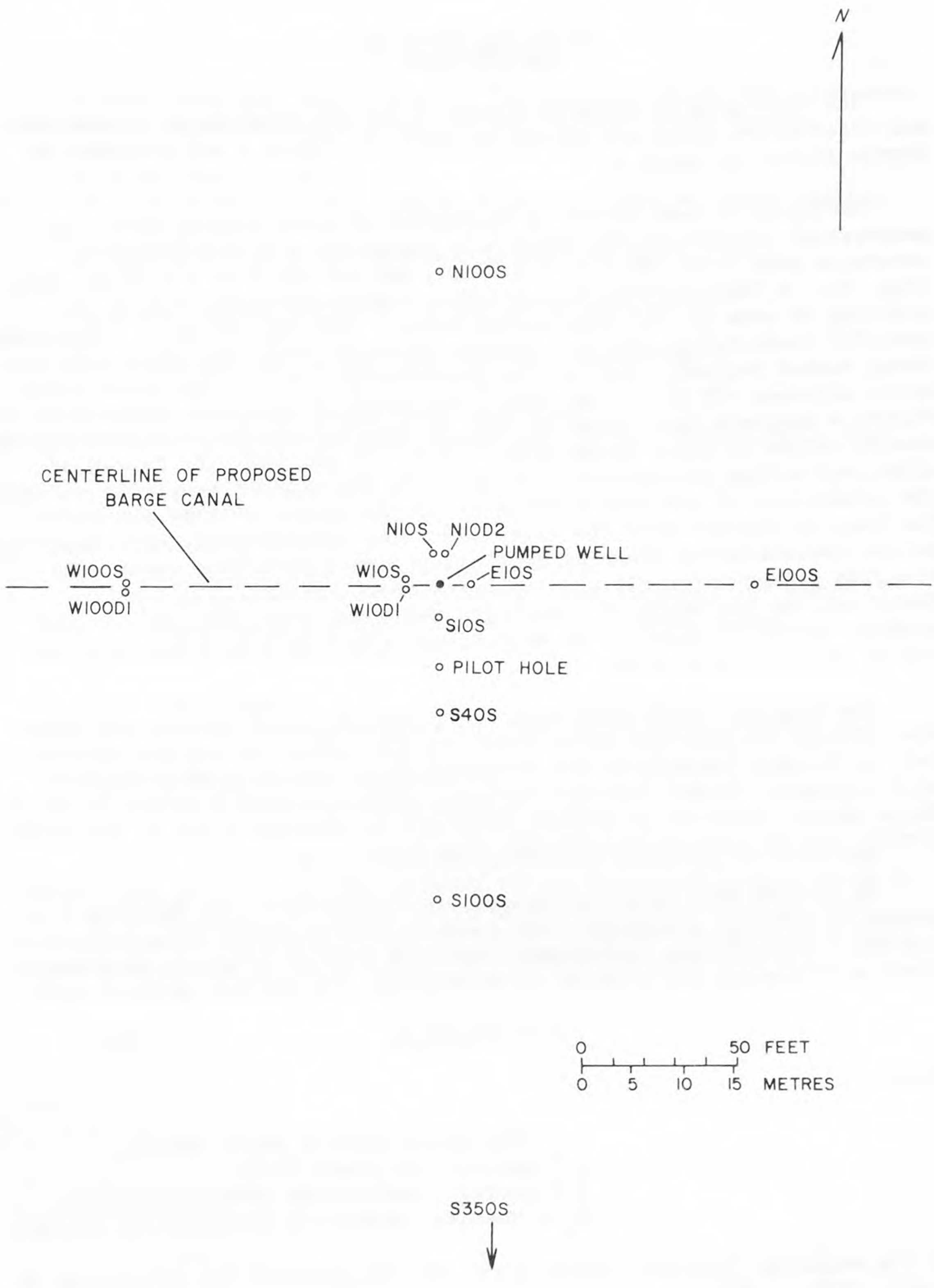

FIGURE 2.--LOCATIONS OF WELLS AT AQUIFER TEST SITE 1.

Table 1.--Physical description of wells at aquifer test site 1.

Well number or name	Diameter (inches)	Distance from pumped well (feet)	Altitude of land surface (feet)	Altitude of bottom of casing (feet)	Altitude of bottom of hole (feet)	Yield, (gallons per minute)	Drawdown,[a] (feet)
Pilot hole	13	25	75.4	41.1	-160.5	450 [b]	0.18 [b]
Pumped Well*	13	-	75.4	38.4	28.0	35 [b]	15.31 [b]
Pumped Well*		-	75.4	38.4	9.1	314	14
N10S	6	10.4	75.6	43.6	7.1	-	5.45
N10D2	6	10.1	75.5	-119.5	-138.0	-	0
S10S	6	9.8	75.3	36.3	27.3	-	7.09
E10S	6	9.8	75.6	37.8	9.6	-	6.54
W10S	6	10.1	75.3	34.8	8.3	-	8.25
W10D1	6	9.7	75.3	40.3	-26.7	-	0
S40S	6	40.2	75.4	36.6	9.4	-	0.96
N100S	6	99.8	75.5	44.6	9.0	-	1.04
S100S	6	100	75.3	32.8	9.8	-	0.11
E100S	6	97.6	78.0	44.1	10.0	-	0.68
W100S	6	99.8	73.2	42.7	8.7	-	0.86
W100D1	6	100	73.2	-19.8	-23.8	-	-
S350S	6	350	77.2	40.2	7.7	-	0

a/ Measured at end of pumping period of aquifer test unless otherwise noted.

b/ Measured during preliminary test pumping.

*Well was deepened after test pumping at shallower depth.

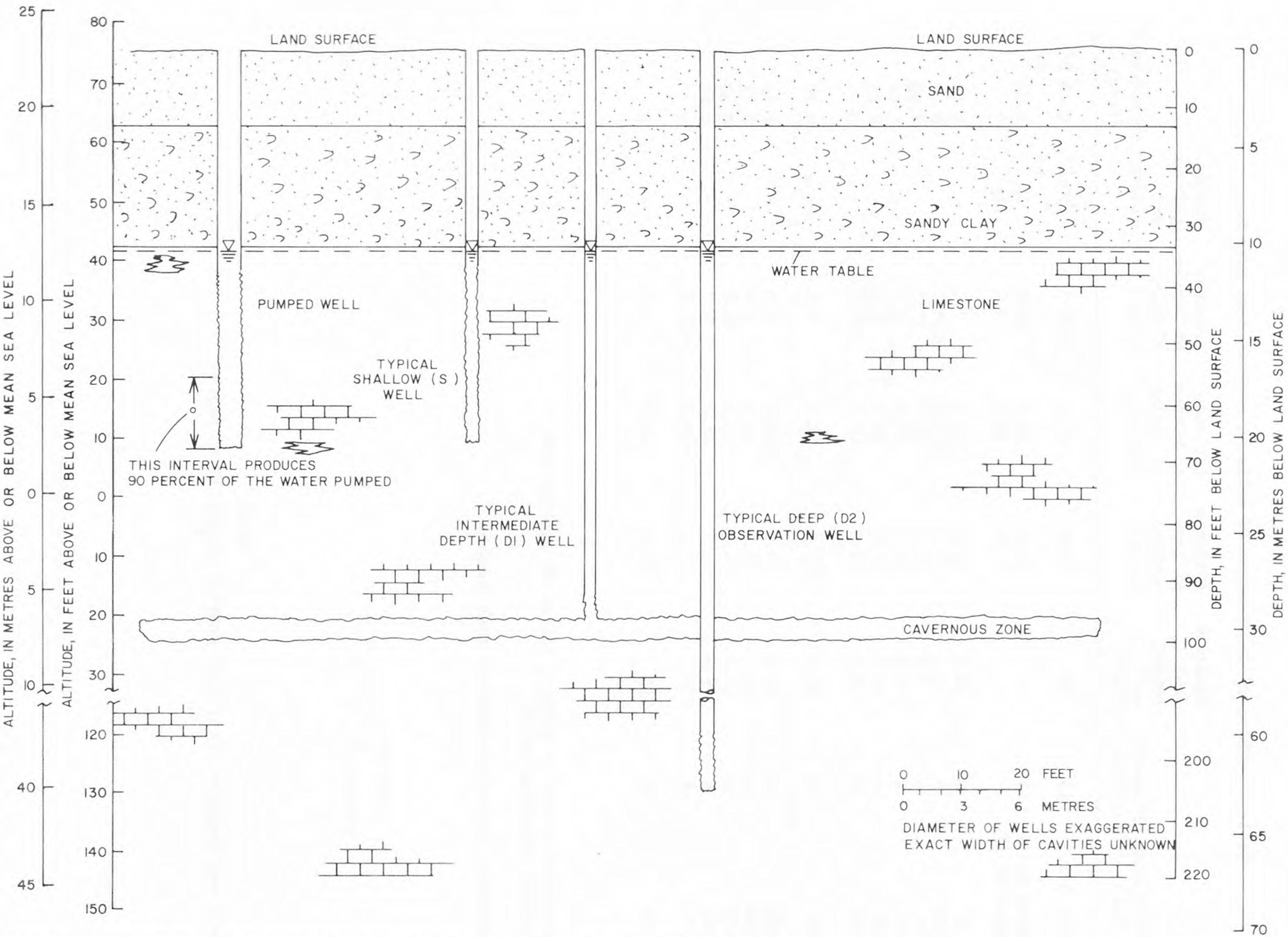

FIGURE 3.--SECTION SHOWING GENERALIZED GEOLOGY AND WELL CONSTRUCTION OF PUMPED WELL AND TYPICAL OBSERVATION WELLS AT AQUIFER TEST SITE 1.

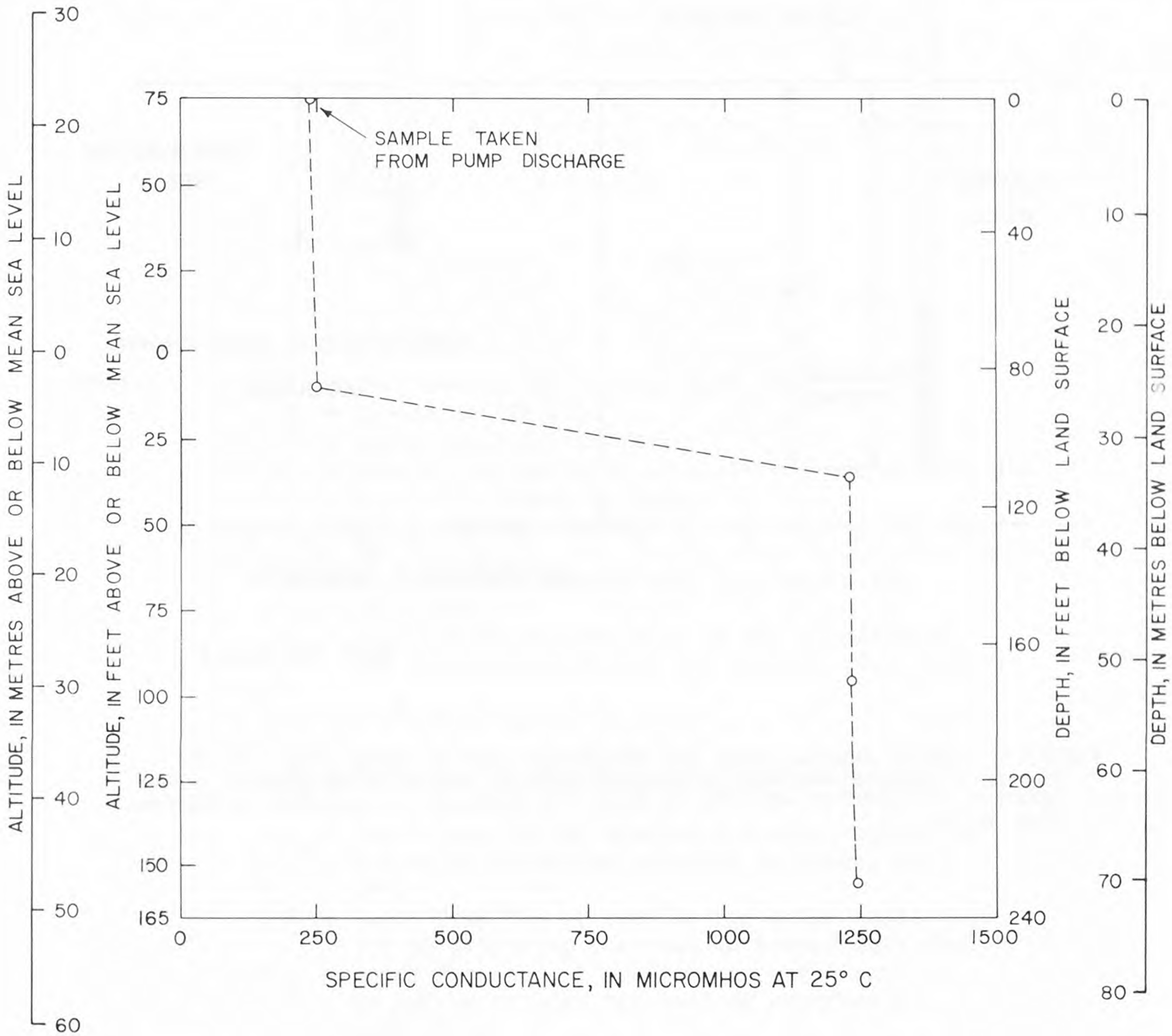

FIGURE 4.--SPECIFIC CONDUCTANCE OF WATER AT SELECTED DEPTHS IN PILOT HOLE AT AQUIFER TEST SITE 1.

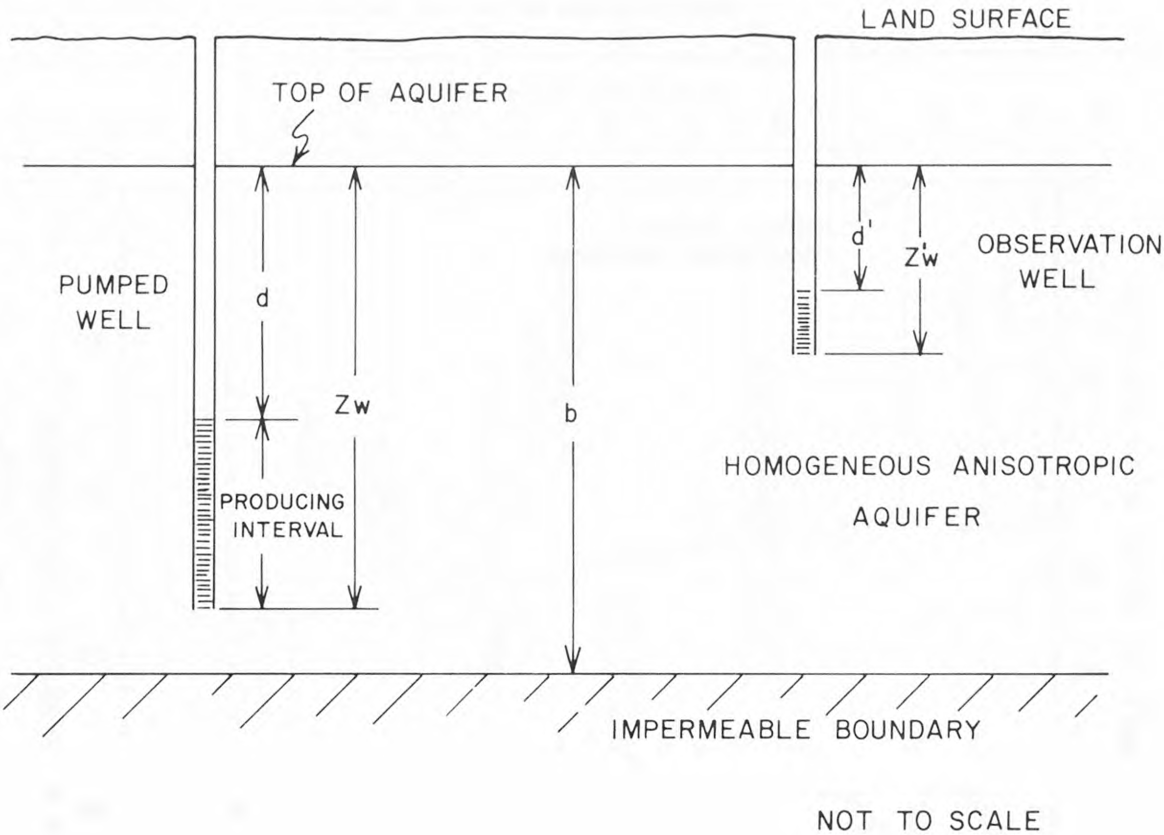

FIGURE 5.--SKETCH SHOWING MODEL AND PARAMETERS USED BY WEEKS (1969, P. 200, EQ. 2) TO DEVELOP ANALYSES OF AQUIFER TESTS OF PARTIALLY-PENETRATED, HOMOGENEOUS, ANISOTROPIC AQUIFERS IN WHICH THE DRAWDOWN IS MEASURED IN OBSERVATION WELLS.

$$s = \frac{Q}{4\pi T} \left\{ W(u) + \frac{4b^2}{\pi^2 (z_w - d)(z'_w - d')} \right.$$

$$\cdot \sum_{n=1,2,3,\ldots}^{\infty} 1/2\, K_o \left[\frac{n\pi r_c}{b}\right] \left(\sin \frac{n\pi z_w}{b} - \sin \frac{n\pi d}{b} \right)$$

$$\left. \cdot \left(\sin \frac{n\pi z'_w}{b} - \sin \frac{n\pi d'}{b} \right) \right\} \qquad (2)$$

where:

s = drawdown in observation well (ft);
Q = discharge (ft^3/d);
T = transmissivity (ft^2/d);
$W(u)$ = exponential integral of u (Ferris and others, 1962, p. 96-97) (dimensionless);
u = $\frac{r^2 S}{4Tt}$, (dimensionless);
r = distance from pumped well to observation well (ft);
K_o = modified Bessel function of the second kind and zero order (Ferris and others, 1962, p.115);
r_c = $r\,(K_z/K_r)^{1/2}$ (ft);
K_r = horizontal hydraulic conductivity (ft/d);
z_w = depth from top of aquifer (or water table) to bottom of producing interval in pumped well (ft);
d = depth from top of aquifer (or water table) to top of producing interval in pumped well (ft);
z'_w = depth from top of aquifer (or water table) to bottom of open interval in observation well (ft);
d' = depth from top of aquifer (or water table) to top of open interval in observation well (ft).
b = aquifer thickness (ft).

If the second, or summation term of eq. 2 is represented by f'(s), the equation can be written

$$s = \frac{Q}{4\pi T} \cdot \left[W(u) + f'(s) \right] \qquad (3)$$

The cavernous zone (fig. 3) acts as a constant head boundary for the water-table aquifer tested. The effects of the boundary can be treated by applying the theory of images (Ferris and others, 1962, p. 144-147) in the vertical plane (fig. 6).

According to the theory of images, the drawdown at any given point in the dual-aquifer system represented in figure 6 is equal to the algebraic sum of the drawdown, s_r, caused by discharge from the real well and the negative drawdown, s_i caused by recharge through the image well. Thus

$$s = s_r - s_i = \frac{Q}{4\pi T} \bullet \left[(W(u) + f'(s)_r) - (W(u) + f'(s)_i) \right]$$

$$= \frac{Q}{4\pi T} \bullet \left[f'(s)_r - f'(s)_i \right] \qquad (4)$$

where $f'(s)_r$ and $f'(s)_i$ are the components due to the real and image well, respectively.

When transmissivity is expressed in (gal/d)/ft (gallons per day per foot) and Q in gal/min (gallons per minute) then eq. 4 can be written

$$s = \frac{114.6Q}{T} \bullet \left[f'(s)_r - f'(s)_i \right] = \frac{114.6Q}{T} \bullet \sum f'(s) \qquad (5)$$

Type curves of $\sum f'(s)$ versus r_c/b', obtained by computing the two components $f'(s)_r$ and $f'(s)_i$ (using eq. 2 but with b being replaced by b') and summing them algebraically are shown in figure 7. These curves are used to obtain values of the transmissivity and r_c/b' by superposing on them logarithmic plots of observed drawdown versus r/b' in a manner similar to that of the Theis matching procedure (see for example Ferris and others 1962, p. 94-98). The transmissivity of the real half of the dual-aquifer system of figure 6 and the conductivity ratio K_z/K_r are computed from the relations

$$T = 1/2 \left[114.6Q \bullet \frac{\sum f'(s)}{s} \right]$$

and

$$K_z/K_r = (r_c/r)^2$$

where values of $\sum f'(s)$ corresponding to s and values of r_c corresponding to r are obtained from the matched positions of the drawdown plot on the type curves of figure 7.

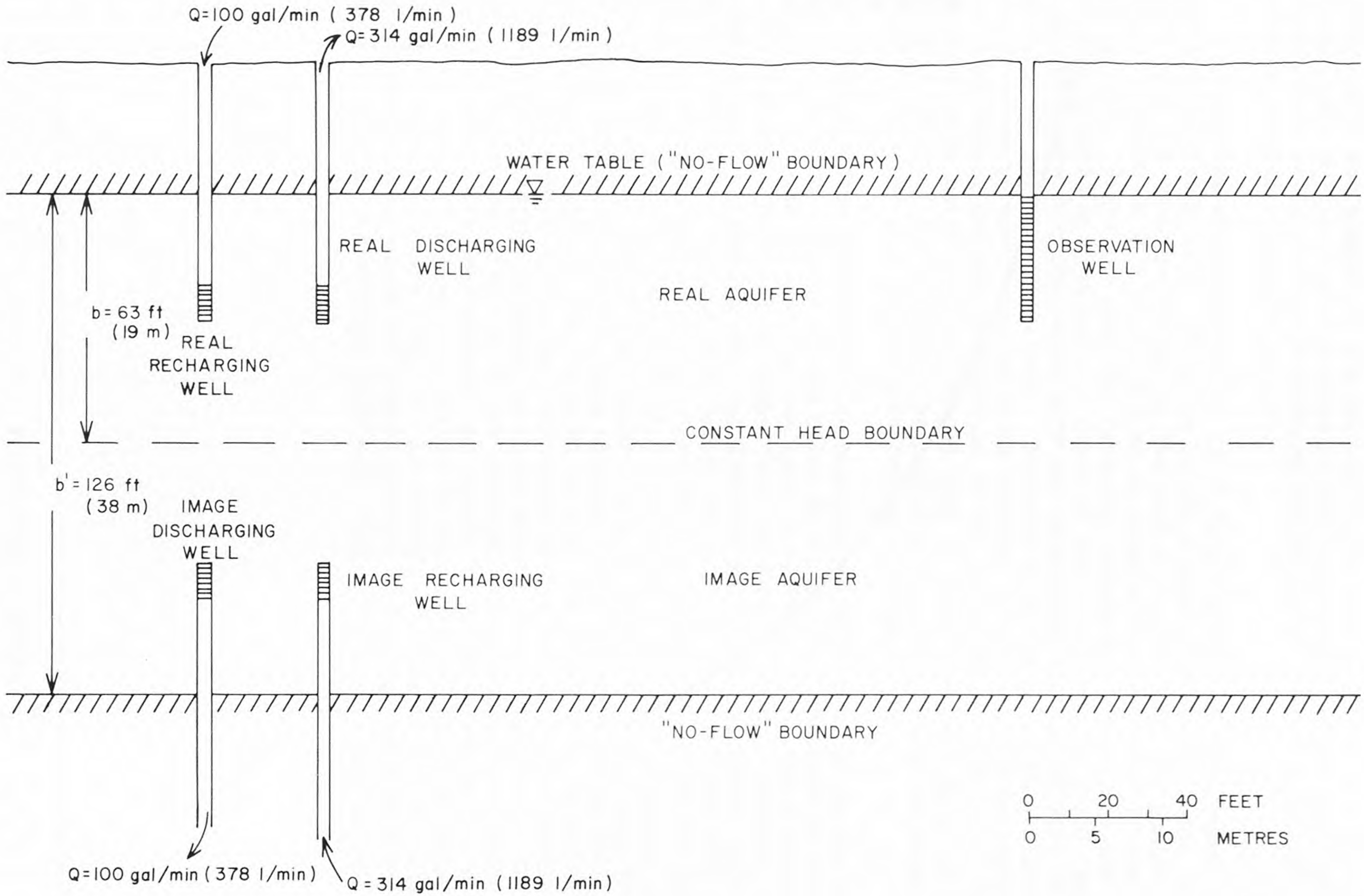

FIGURE 6.--SKETCH SHOWING BOUNDARY CONDITIONS AND CONCEPTUAL MODEL USED IN ANALYSIS OF DATA FROM AQUIFER TEST 1.

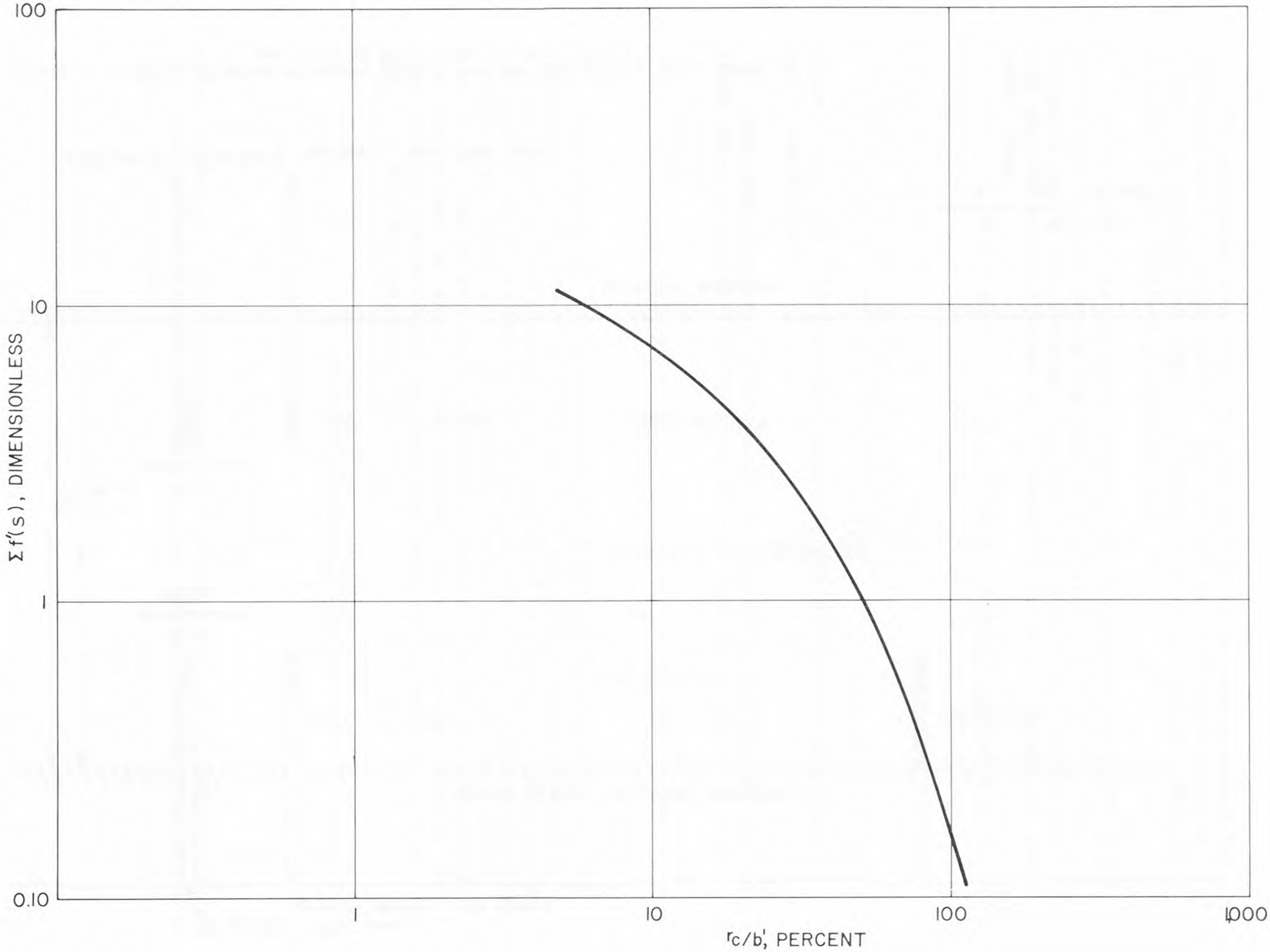

FIGURE 7.--TYPE CURVE USED IN ANALYSIS OF DATA FROM AQUIFER TEST 1.

Aquifer test 1 began at 1000 h (hours), October 25, 1974. The pumped well was pumped at 314 gal/min (1,189 l/min) for 24 h. Water levels were measured periodically in the pumped well, pilot hole and observation wells during the pumping period and for about 8 h after pumping stopped (recovery period).

During the aquifer test the pilot hole was open to the pumped zone and the cavernous zone. Drawdown in the pumped zone caused water to move from the cavernous zone, up the well bore, and into the pumped zone. As much as 0.04 ft (0.012 m) of drawdown was measured in the pilot hole. Since the specific capacity (discharge, in gallons per minute, divided by drawdown, in feet) of the pilot hole is 2,500 (gal/min)/ft {31,000 (l/min)/m}, the pilot hole was recharging the pumped zone as much as 100 gal/min (379 l/min). Recharge from the pilot hole diminished the drawdown primarily in the south quadrant of the cone of depression but some effect was had on drawdown in the other three quadrants. It is assumed water moved into the pumped zone in about the same interval that produced most of the water in the pumped well. This being the case, the pilot hole acted as a partly-penetrating recharge well.

The drawdown measured in the observation wells must be corrected for the recharge effects of the pilot hole. A first estimate of transmissivity and K_r/K_z is made by applying the type-curve (fig. 7) matching procedure and formulas as outlined by Weeks (written commun. 1974). However, the type curve is matched to only the drawdown data from the north, east, and west lines of shallow observation wells (fig. 8). The distance of each observation well from the pilot hole is divided by twice the thickness of the real aquifer. For each of these values a value of drawdown is obtained from the dashed type-curve trace of figure 8. To obtain the drawdown correction factor, each obtained value of drawdown is multiplied by 0.316, the ratio of the recharge rate of the pilot hole to the discharge rate of the pumped well. The correction factor for each observation well is added to the drawdown measured during the aquifer test. The corrected drawdown (fig. 8) is the drawdown that would have occurred if the pilot hole had been plugged and unable to recharge the pumped zone. The type-curve of figure 7 is fitted to the corrected drawdown data (solid type-curve trace, fig. 8), matchpoint coordinates are obtained and aquifer coefficients of transmissivity, horizontal hydraulic conductivity (K_r), and vertical hydraulic conductivity (K_z) are calculated.

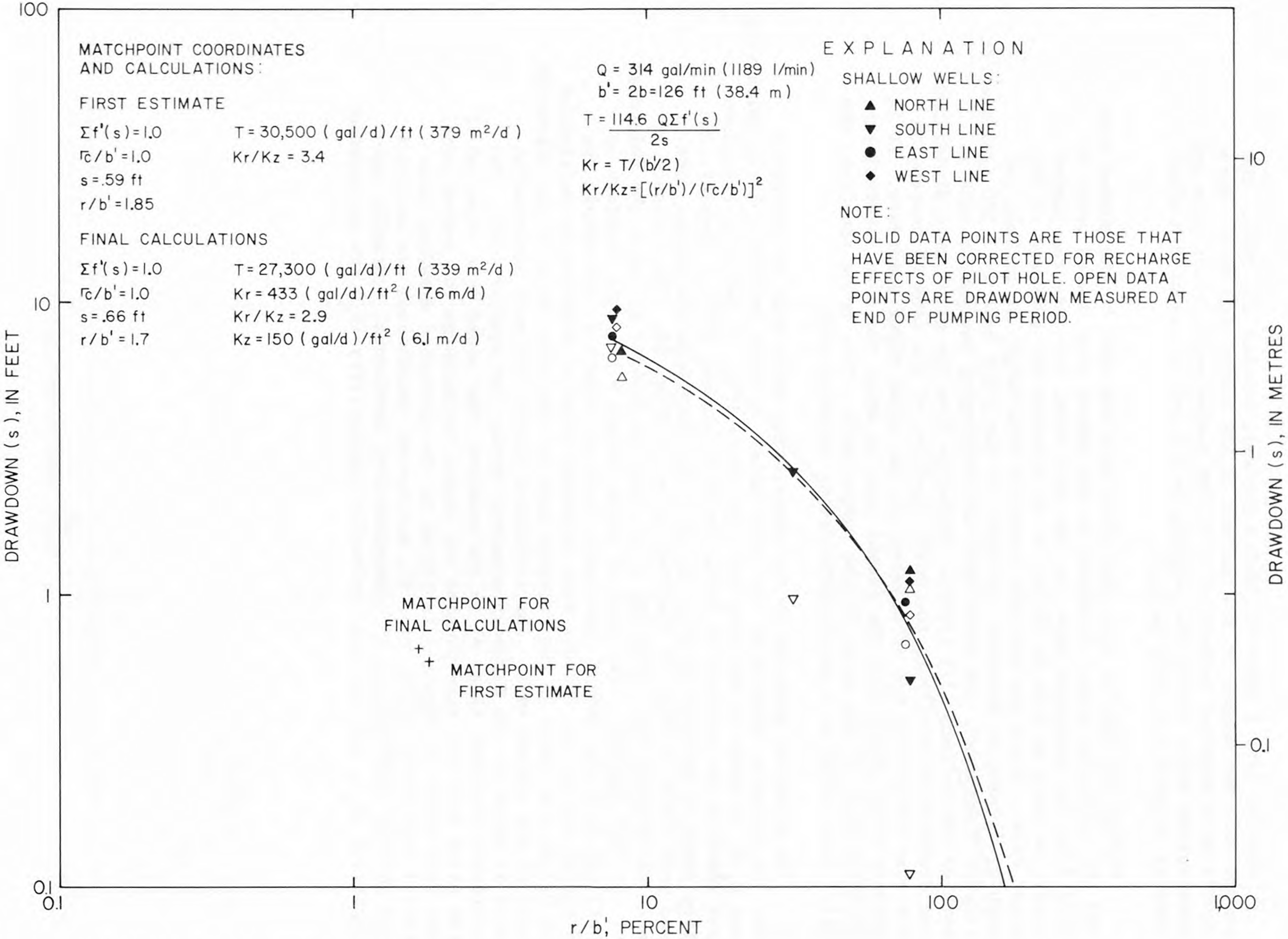

FIGURE 8.--DRAWDOWN DATA FROM AQUIFER TEST 1.

AQUIFER TEST 2

The test site is shown on figure 1 and the pilot hole, pumped well, and observation wells are spaced as shown in fig. 9 and finished at depths listed in table 2.

Geologist's logs and geophysical logging indicated a 12.5-ft (3.8-m) thick highly permeable cavernous zone from +3.3 ft (+1.01 m), msl to -9.2 ft (-2.80 m), msl (fig. 10) that acts as a constant head boundary (fig. 11) at the base of the aquifer in which the pumped well and observation wells are finished. Thus, the boundary conditions for aquifer test 2 are similar to those of aquifer test 1 so the drawdown data from the second test can be analyzed by the same procedure used in the first test.

Aquifer test 2 began at 1000 h, January 9, 1975. The pumped well was pumped at 105 gal/min (397 l/min) for 24 h. Water levels were measured periodically in the pumped well and in the observation wells during the pumping period and for about 2 h after pumping stopped (recovery period).

Distance-drawdown data are plotted (fig. 12) and analyzed by the type-curve matching procedure similar to that used in aquifer test 1. See type curves, fig. 13. The aquifer coefficients of transmissivity, and of horizontal and vertical hydraulic conductivity derived for the observation wells of shallow and intermediate depth are fairly consistent, but the values determined using data from the deep observation wells are much higher. The data indicate that the pumped zone functions as though it consists of two layers. These include an upper, less permeable layer tapped by the shallow and intermediate-depth wells, and a lower, more permeable layer tapped by the deep observation wells. If the more permeable zone were of about the same permeability of the cavernous zone, the effect of the indicated more permeable layer could be accounted for in the analysis by assuming the effective distance (Ferris and others, 1962, p. 129-130) from the water table to the underlying constant-head boundary is less than that to the cavernous zone. Basically, this procedure would replace the lower, more permeable layer of the pumped zone with a thinner layer of material having the same permeability as the upper material so the effective distance from the water table to the cavernous zone would be about 24.5 ft (7.5 m), rather than the 29.5-ft (9.0-m) value obtained from logs of the pilot hole.

Faulkner's (1973, fig. 34 and table 2) flow-net analysis indicated that, in the vicinity of aquifer test 2, the transmissivity of the full effective aquifer thickness is about 43.9 x 10^6 (gal/d)/ft (0.54 x 10^6 m^2/d). The current-meter survey of the pilot hole indicated that almost all of the water yielded came from the 12.5-ft (3.8-m) thick cavernous zone. Assuming then, that in the vicinity of test site 2, the effective

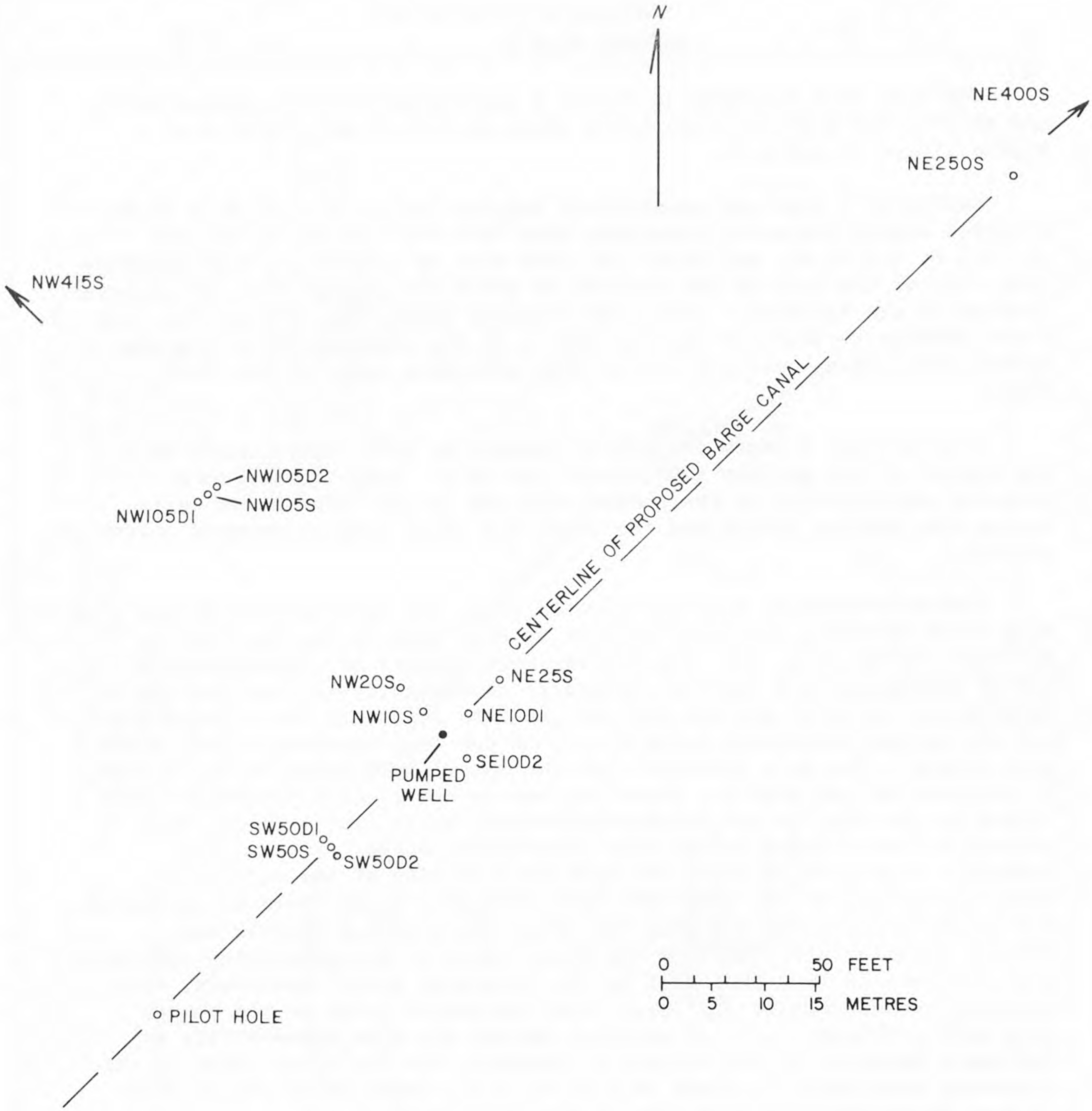

FIGURE 9.--SKETCH SHOWING LOCATIONS OF WELLS AT AQUIFER TEST SITE 2.

Table 2.--Physical description of wells at aquifer test site 2.

Well number or name	Diameter (inches)	Distance from pumped well (feet)	Altitude of land surface (feet)	Altitude of bottom of casing (feet)	Altitude of bottom of hole (feet)	Yield (gallons per minute)	Drawdown a/ (feet)
Pilot hole	13	148	71.3	25.3	-186.7	475 b/	0.10 b/
Pumped Well*	24	-	67.3	31.5	26.0	3.5 b/	12.40 b/
Pumped Well*	24	-	67.3	31.5	18.0	105	13.23
NW10S	6	11.4	71.0	26.0	23.0	-	7.12
NE10D1	6	10.2	72.6	17.9	16.9	-	7.54
SE10D2	6	10.2	71.6	9.0	8.0	-	0.11
NW20S	6	20.0	71.0	26.0	8.0	-	8.02 c/
NE25S	6	25.1	70.7	27.0	24.5	-	0.16 d/
SW50S	6	49.6	71.1	29.3	24.1	-	0.26
SW50D1	6	50.0	71.0	18.0	16.0	-	0.245
SW50D2	6	49.6	71.0	9.0	5.0	-	0.035
NW105S	6	105	69.3	32.3	26.0	-	0.045
NW105D1	6	105	69.4	17.9	16.9	-	0.01
NW105D2	6	104	69.5	9.0	8.0	-	0
NE250S	6	250	72.8	27.8	25.8	-	0
NE400S	6	399	68.8	31.7	26.7	-	0
NW415S	6	413	69.0	25.3	21.7	-	0

a/ Measured at end of pumping period of aquifer test unless otherwise noted.

b/ Measured during preliminary test pumping.

c/ Not used in analysis - open hole interval does not match that of other shallow wells.

d/ Not used in analysis - well partly plugged.

*Well was deepened after test pumping at shallower depth.

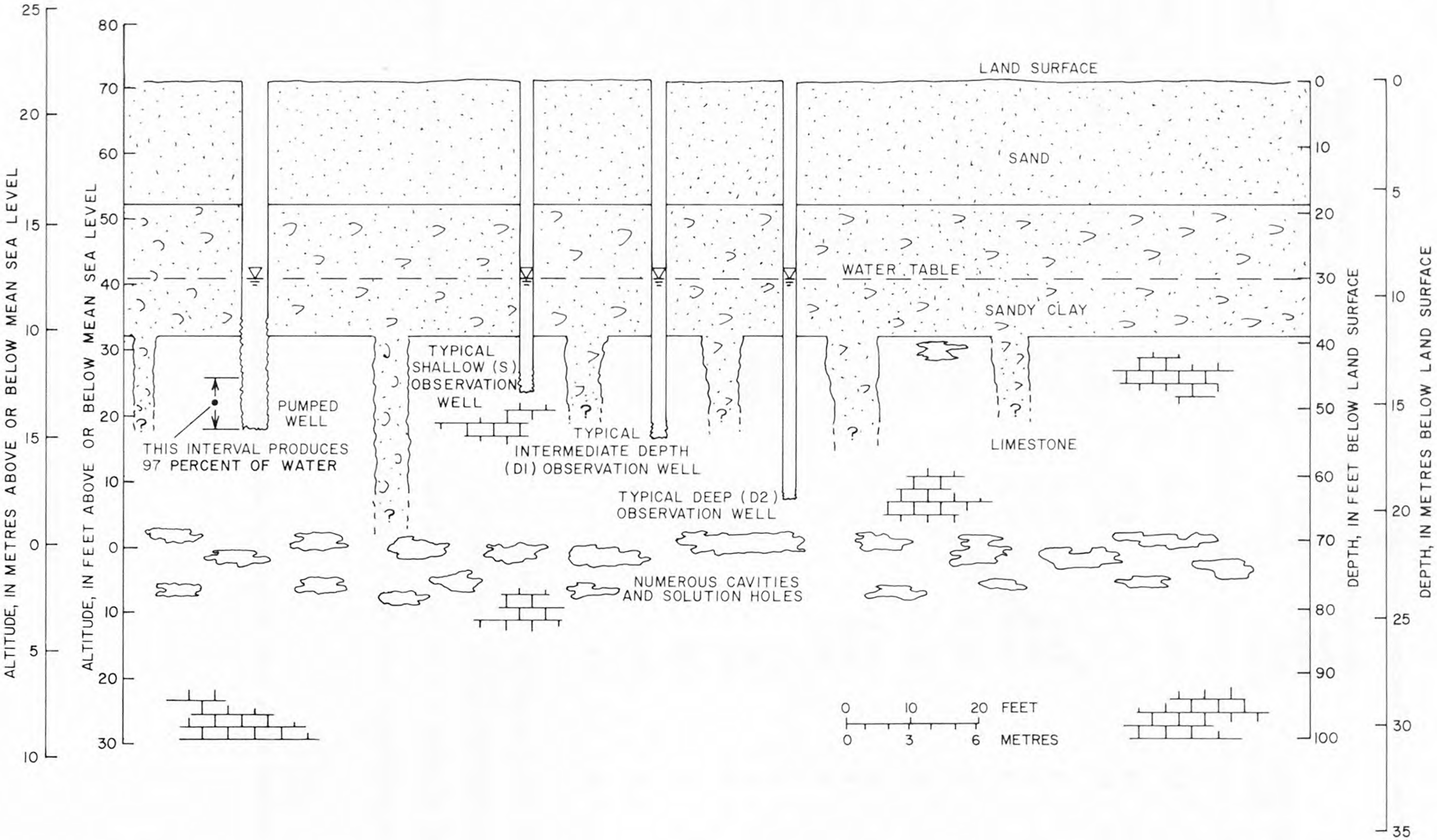

FIGURE 10.--SECTION SHOWING GENERALIZED GEOLOGY AND WELL CONSTRUCTION OF PUMPED WELL AND TYPICAL OBSERVATION WELLS AT AQUIFER TEST SITE 2.

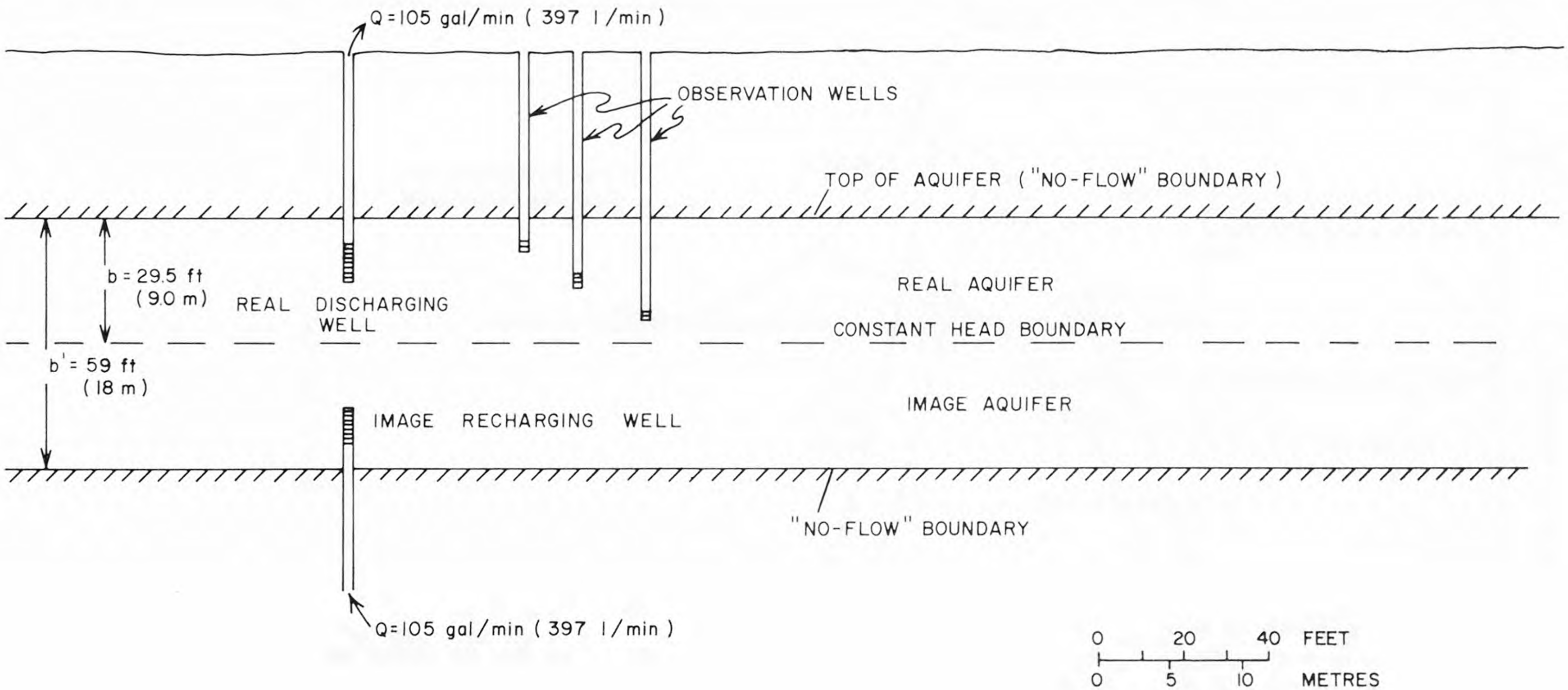

FIGURE 11. --SKETCH SHOWING BOUNDARY CONDITIONS AND CONCEPTUAL MODEL USED IN ANALYSIS OF DATA FROM AQUIFER TEST 2.

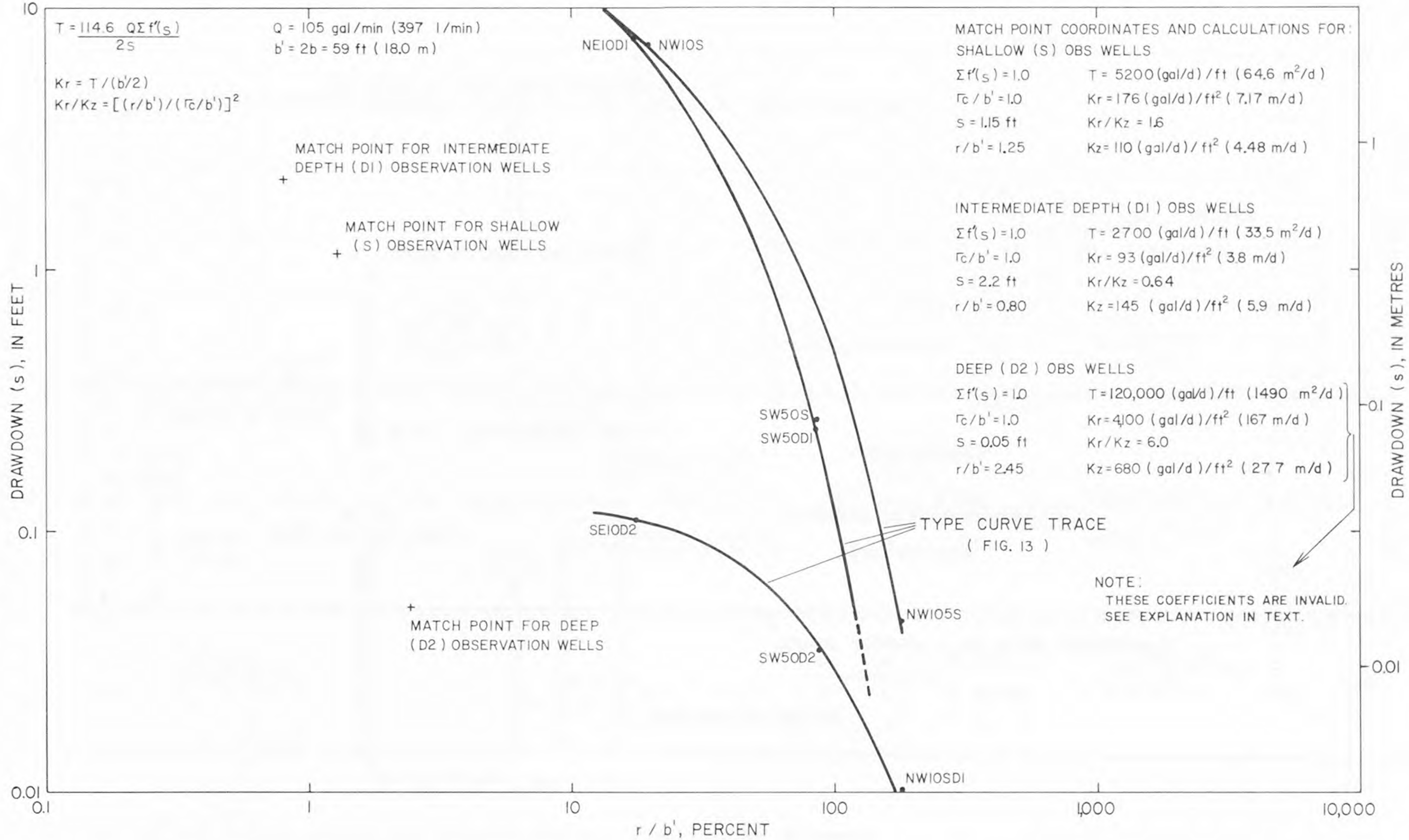

FIGURE 12.--DRAWDOWN DATA FROM AQUIFER TEST 2.

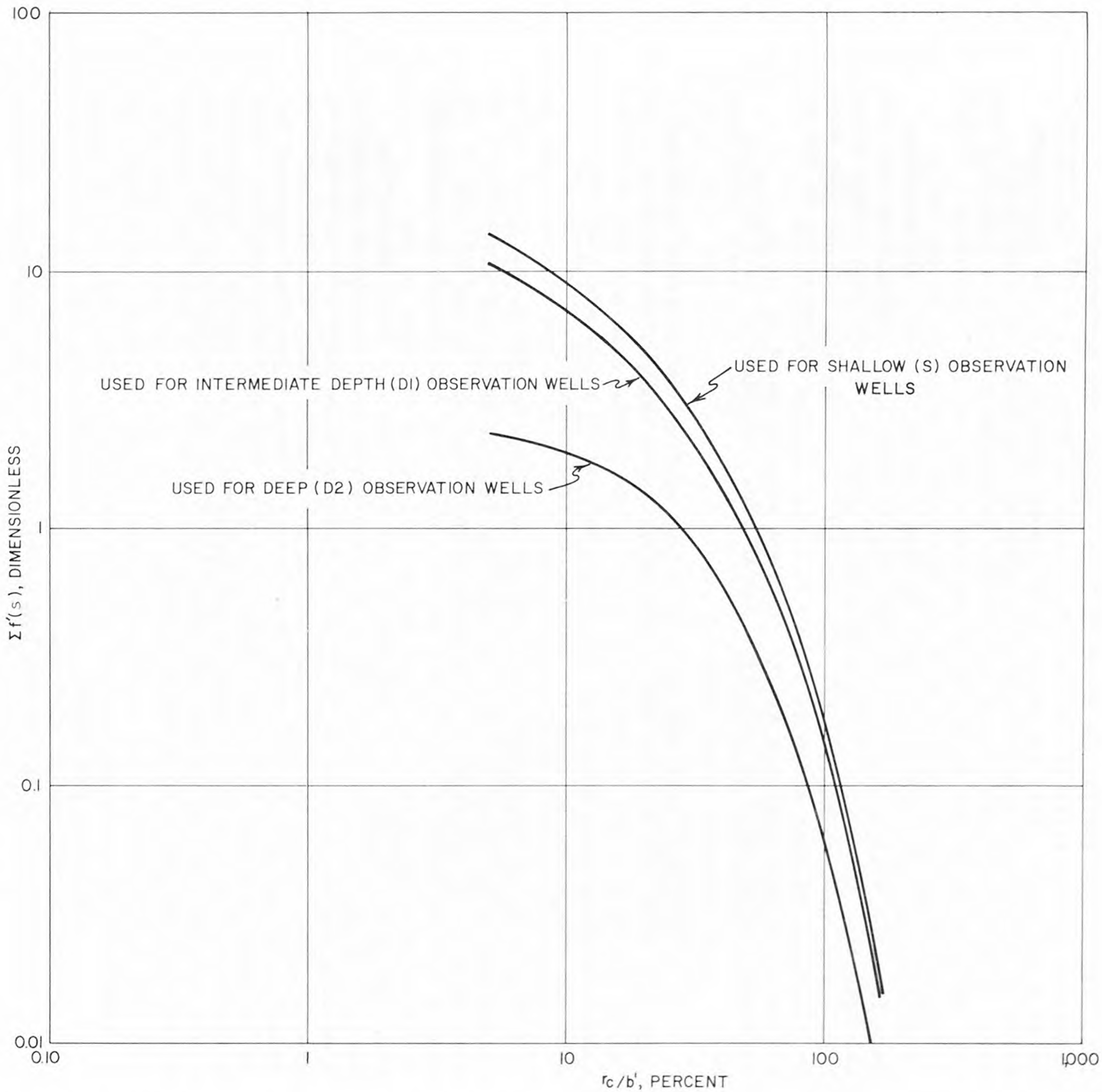

FIGURE 13.--TYPE CURVES USED IN ANALYSIS OF DATA FROM AQUIFER TEST 2.

thickness of the aquifer is about 12.5 ft (3.8 m), the horizontal hydraulic conductivity of the cavernous zone is about 3.5 x 10^6 (gal/d)/ft^2 (0.14 x 10^6 m/d). This is nearly 1,000 times greater than the calculated value of horizontal hydraulic conductivity of the lower, more permeable layer (fig. 12) of the pumped zone. This precludes an exact accounting for the effects of the lower, more permeable zone on the calculated aquifer coefficients derived from the analysis of drawdown in the wells of shallow and intermediate depth. However, as an exercise, the drawdown data from the shallow and intermediate depth wells were analysed as if the effective thickness of the pumped zone were 24.5 ft (7.5 m). The type curves used to analyse the data are not shown but the methodology is identical to that shown in figure 12. The aquifer coefficients derived from this analysis are in the same general range as those determined based upon an effective pumped zone thickness of 29.5 ft (9.0 m).

It is probable that the average of the aquifer coefficients obtained from data from the shallow and intermediate depth observation wells is fairly representative of the upper part of the pumped zone but the values obtained from data from the deep observation wells are questionable and should not be used for further interpretation.

The ratio of horizontal to vertical hydraulic conductivity is calculated to be about 1.6 for the shallow line of wells and slightly less than 1 for the line of intermediate depth wells. Values of less than 1 for the ratio K_r/K_z do not usually occur in undisturbed sedimentary rocks. Geologist's logs of auger holes drilled in addition to the observation wells (Corps of Engineers, written commun., 1975) showed the surface of the limestone aquifer to be very irregular. The depth to the limestone varies as much as 21 ft (6 m) between holes only 5 ft (1.5 m) apart. Thus, it is possible that during the aquifer test, sand-filled solution "pipes" within the cone of depression either acted as conduits to increase vertical hydraulic conductivity or the sand fill retarded horizontal flow causing relatively low horizontal conductivity. This would account for the unexpected value for K_r/K_z determined from the observation wells of intermediate depth.

AQUIFER TEST 3

The test site is shown on figure 1 and the pilot hole, pumped well, and observation wells are spaced as shown in fig. 14 and finished at depths listed in table 3.

Geologist's and geophysical logs of the pilot hole did not identify any cavernous zones. A flowmeter traverse while the pilot hole was being pumped indicated that most of the water was produced in two zones; from -104 ft (-31.7 m) msl to -64 (-19.5 m) msl and from +6 ft (+1.8 m) to +16 ft (+4.9 m) msl.

Geologist's logs of the observation wells showed that, with one exception, cavities, where encountered, occurred above the water table (fig. 15). The one cavity found below the water table extended from +22.7 ft (+6.92 m), msl to +11.2 ft (+3.41 m), msl and was penetrated while drilling observation well NE50D. The pumped well penetrated no cavities.

The specific capacity of the pilot hole at site 3 is 30.9 (gal/min)/ft or 384 (l/min)/m while at sites 1 and 2 the specific capacities of the pilot holes are 2,500 (gal/min)/ft or 31,000 (l/min)/m and 4,750 (gal/min)/ft or 59,000 (l/min)/m respectively. Cavernous zones were penetrated by the pilot holes at sites 1 and 2 and, undoubtedly, this is the reason why the pilot holes at those sites are more productive than at site 3.

The absence of a cavernous zone (or constant-head boundary) in the saturated section at aquifer test site 3 results in a different set of geohydrologic boundary conditions than at sites 1 and 2. Therefore, the method of analysis outlined by Weeks (written commun., 1974) and used for aquifer tests 1 and 2 could not be used for aquifer test 3. Weeks (1969) outlined three methods that can be used to determine the ratio of horizontal to vertical hydraulic conductivity by aquifer-test analysis for an aquifer bounded above and below by "no-flow" boundaries. At aquifer test site 3 the free surface of the water table acts as the overlying no-flow boundary, but an underlying no-flow boundary could not be identified. However, on the basis of caliper and electric logs, two zones of low permeability are tentatively located. They are at altitudes -20 ft (-6 m), msl and -60 ft (-18 m), msl. Since the water table stands at about +43 ft (+13 m), msl, two possible values for effective aquifer thickness (b) are 63 ft (19 m) and 103 ft (31 m).

Aquifer test 3 began at 1100 h, January 29, 1975. The pumped well was pumped at 255 gal/min (965 l/min) for 23 h and water levels in the observation wells were measured periodically during the pumping period and for about 4 h after pumping stopped (recovery period).

FIGURE 14.--SKETCH SHOWING LOCATIONS OF WELLS AT AQUIFER TEST SITE 3.

Table 3.--Physical description of wells at aquifer test site 3.

Well number or name	Diameter (inches)	Distance from pumped well (feet)	Altitude of land surface (feet)	Altitude of bottom of casing (feet)	Altitude of bottom of hole (feet)	Yield, (gallons per minute)	Drawdown a/ (feet)
Pilot hole	13	200	96.0	51.0	-144.0	138 b/	4.46 b/
Pumped Well*	13	-	88.4	40.4	26.0	30 b/	11.14 b/
Pumped Well*	13	-	88.4	40.4	4.5	255	-
NW10S	6	12.6	88.1	41.1	26.1	-	1.94
NE10D	6	10.6	88.0	6.0	3.6	-	0.88
NE20S	6	20.4	87.5	41.5	26.0	-	1.28
NW30S	4	29.6	87.5	67.5	26.0	-	0.77
NW30D	6	27.0	87.5	6.0	2.0	-	0.71
NE50S	6	51.6	86.2	51.2	26.2	-	0.69
NE50D	6	51.8	86.2	6.2	4.2	-	0.74
NW100S	6	101	86.1	39.3	26.0	-	0.24
NE100S	6	101	84.9	57.9	24.9	-	0.60
NE200S	6	200	83.0	54.6	25.0	-	0.20
NW400S	6	401	83.0	53.0	26.0	-	0.01

a/ Measured at end of pumping period of aquifer test unless otherwise noted.
b/ Measured during preliminary test pumping.

*Well was deepened after test pumping at shallower depth.

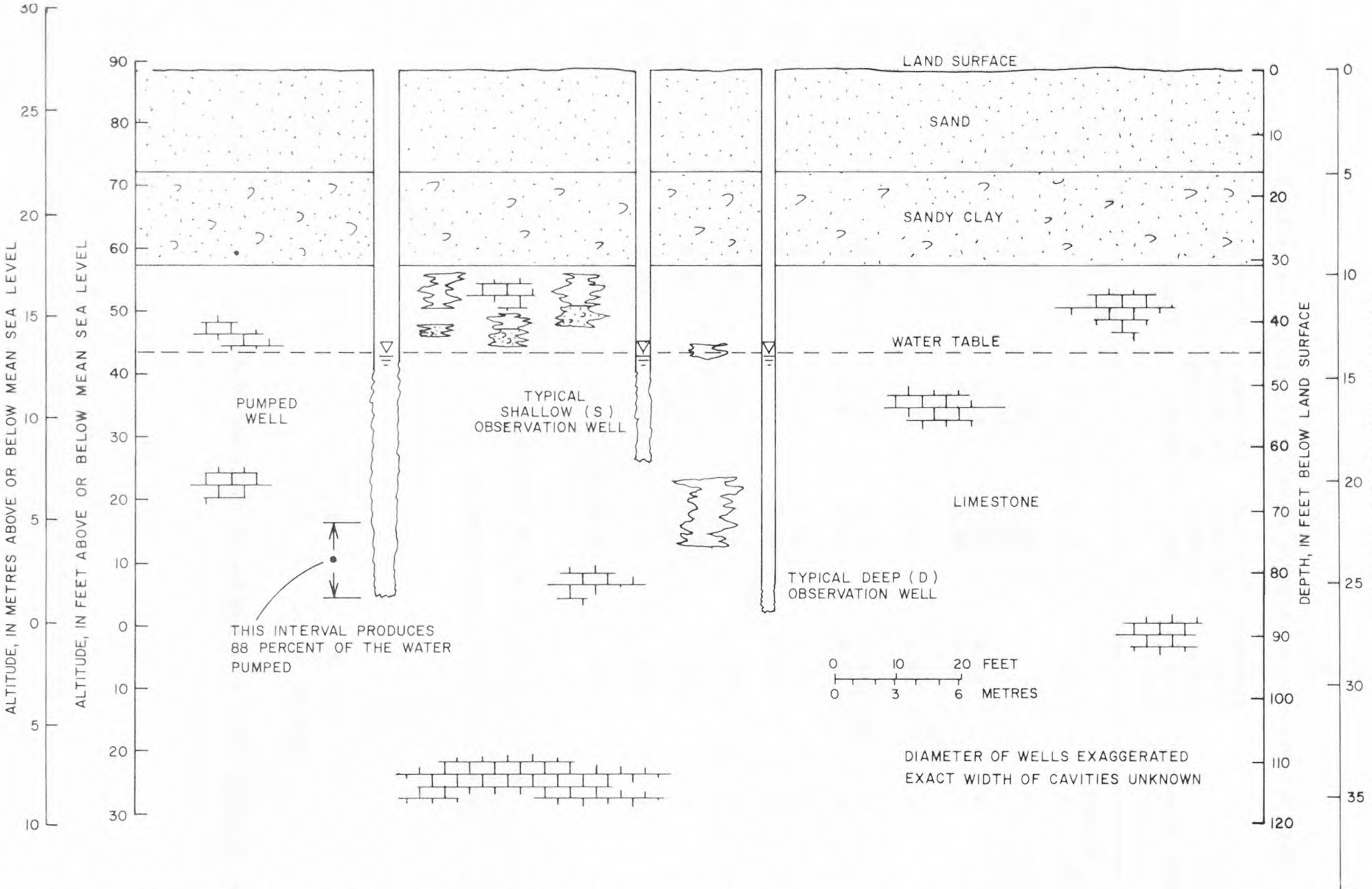

FIGURE 15.--SECTION SHOWING GENERALIZED GEOLOGY AND WELL CONSTRUCTION OF PUMPED WELL AND TYPICAL OBSERVATION WELLS AT AQUIFER TEST SITE 3.

The equations and methods derived by Weeks (1969) are for analysis of aquifer test data for artesian aquifers. Because of the effects of drainage at the free surface of a water-table aquifer during pumping, the rate of drawdown in a water-table aquifer would not coincide with that of an artesian aquifer. However, if the pumping period is long enough, the effects of drainage at the free surface become negligible. The pumping time that must elapse (Weeks, 1969, p.209, 210) is given by

$$t = 7.48\ (bS_y/K_z)$$

for values of

$$r/b\ (K_z/K_r)^{\frac{1}{2}} < .4$$

and by

$$t = 7.48\ (bS_y/2K_z) + 1.25\ r/b(K_z/K_r)^{\frac{1}{2}}$$

for values of

$$r/b\ (K_z/K_r)^{\frac{1}{2}} > .4.$$

If $S_y \approx 0.28$, $K_z \approx 100\ (\text{gal/d})/\text{ft}^2$, $b = 63$ ft and $(K_z/K_r)^{\frac{1}{2}} = 1/2$ then, even for the closest observation wells, the pumping time that must elapse before Weeks' (1969) methods can be applied is about 1.32 days, or about 32 hours. A difficulty in the calculation of minimum pumping time required to apply this analytical method is that one must assume values for the aquifer coefficients that are to be determined by the aquifer test. It was judged on the basis of estimated reasonable values for the aquifer coefficients and the effective thickness of the aquifer that 23 h of pumping (as during aquifer test 3) would be sufficient.

Distance-drawdown data for the shallow and deep observation wells are plotted in figure 16. Such data for a homogeneous anisotropic aquifer should plot on two smooth curves, one for the shallow observation wells and one for the deep observation wells. Lack of homogeneity results in the scatter of the data points. Lack of homogeneity is also shown by the time-drawdown data plots of figure 17. The time-drawdown data plots show a sharp reduction in slope about 130 to 250 minutes after pumping started. The aquifer is unconfined so the reduction in slope is not caused by induced downward leakage through confining beds. There are no surface-water bodies in the area so the reduction in slope is not caused by a classical "recharge boundary." More likely, the change in slope of the time-drawdown data plots is caused by a large increase in the permeability of the aquifer materials at some distance

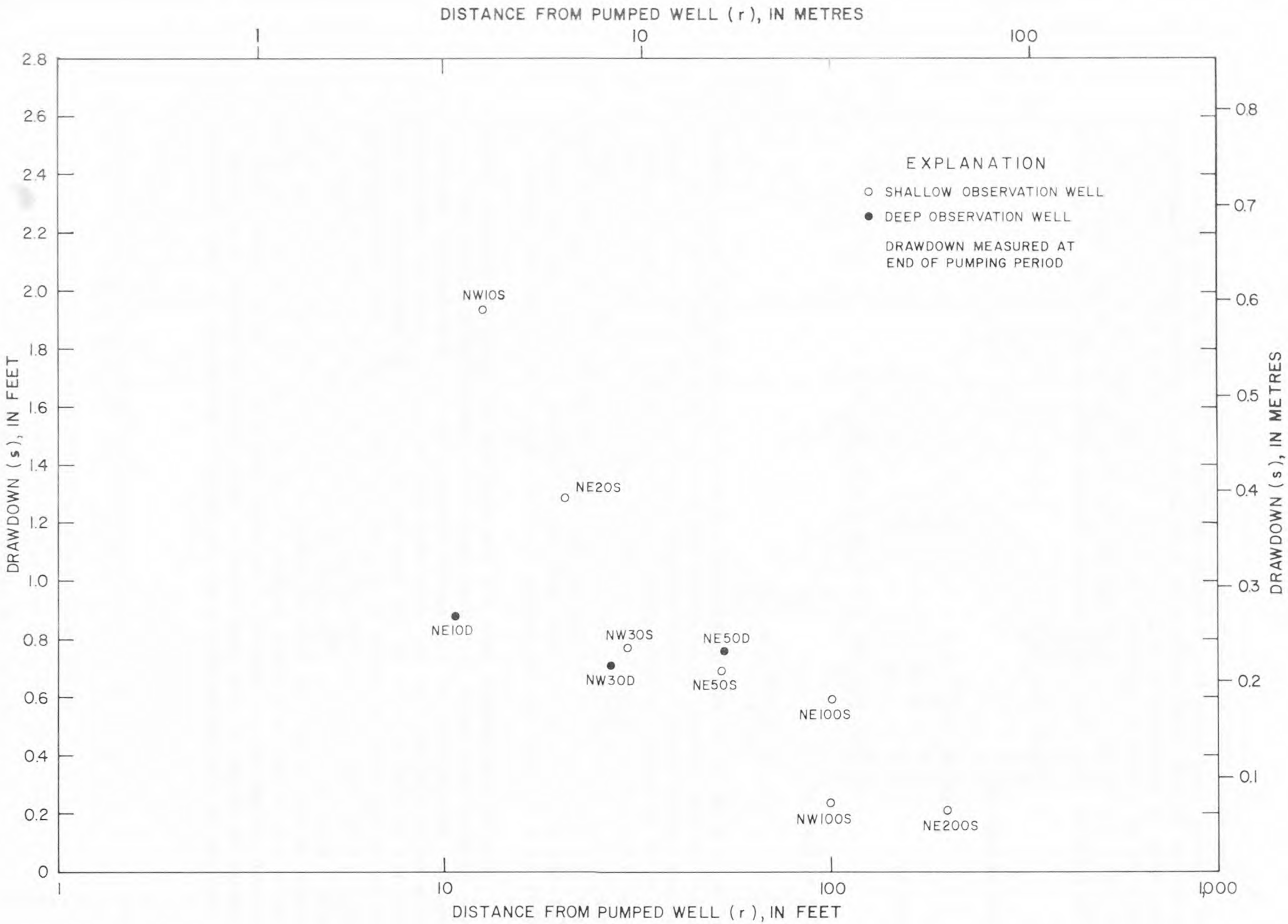

FIGURE 16.--DISTANCE-DRAWDOWN DATA FROM AQUIFER TEST 3.

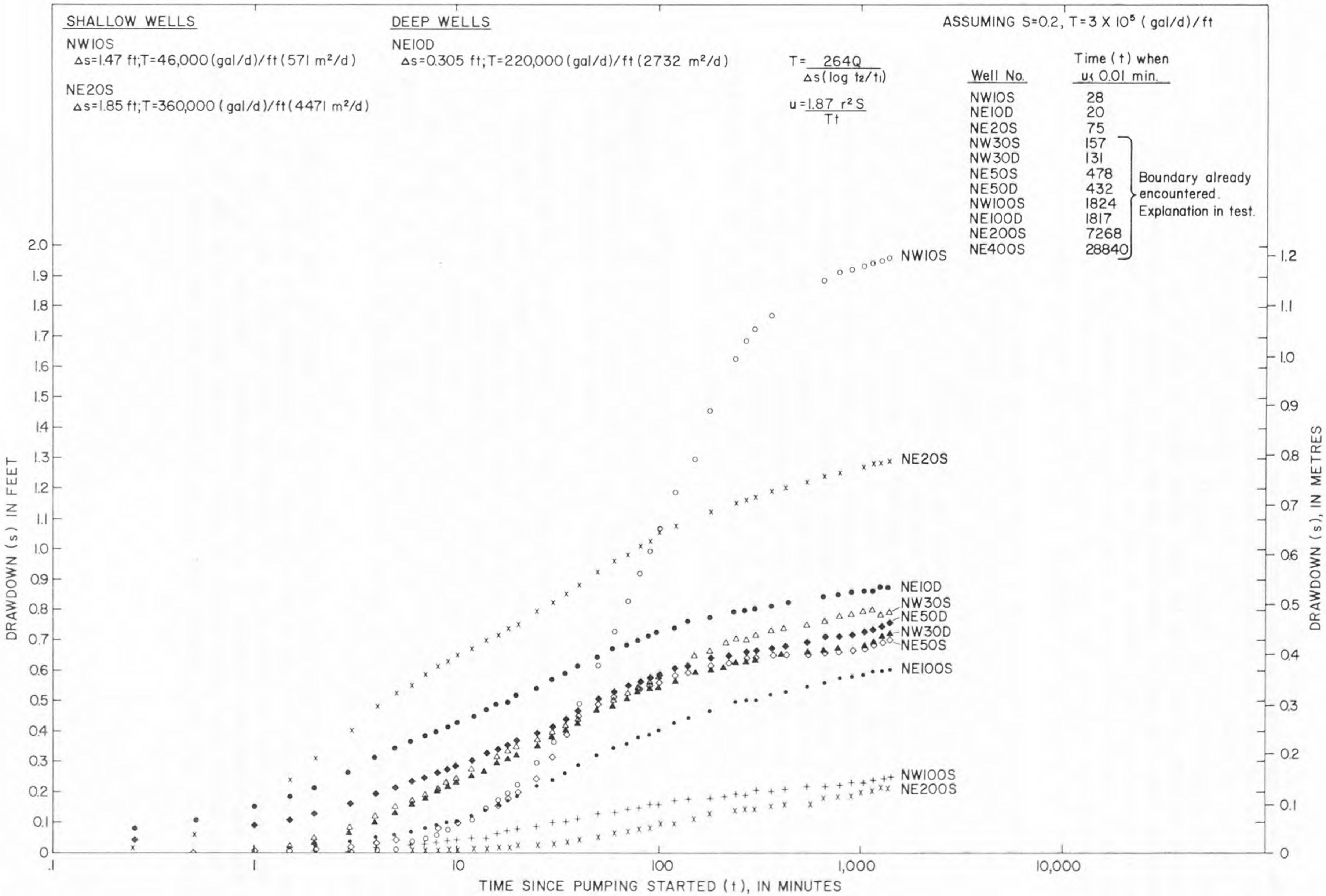

FIGURE 17.--TIME-DRAWDOWN DATA FROM AQUIFER TEST 3.

from the pumped well. The large cavity penetrated by NE50D might be indicative of such an increase in permeability. The calculated coefficients of aquifer transmissivity range over an order of magnitude. Since the modified nonequilibrium formula cannot be used until enough time has elapsed so the value of u is less than about 0.01 (fig. 17), the time-drawdown data for wells more than 30 ft (9 m) from the pumped well cannot be used to determine accurate transmissivity values. Weeks' methods 1 and 2 (1969) use a combination of distance-drawdown and time-drawdown data and, in the case of aquifer test 3, neither set of data is suitable for analysis so methods 1 and 2 could not be used.

Weeks (1969) described a third method by which the ratio of horizontal to vertical hydraulic conductivity can be estimated even if data are available for only one observation well. However, the aquifer storage coefficient must be known. Assuming the length of pumping time is sufficient so the effects of drainage at the free surface of the water table are negligible, the third method is applied to data from observation wells NW10S, NE10D, and NE20S. For these wells the straight-line segment of the time-drawdown curve is unaffected by the apparent nonhomogeneity of the aquifer materials yet enough pumping time has elapsed so u is less than 0.01 (fig. 17) and the modified nonequilibriun formula can legitimately be used. Values for transmissivity (T) in gallons per day per foot are calculated using $T = 264Q/\Delta s$ where Q is the discharge in gallons per minute and Δs is the change in slope (in feet) of the straight-line segment of the time-drawdown plot over one log cycle.

Values for storage coefficient (S_c) are calculated using $Sc = 0.301\,T(t_o/r^2)$ where T is as previously defined, r is the distance, in feet, from the pumped well, and t_o is the zero-drawdown intercept of the extended straight-line segment of the time-drawdown plot, in days.

Values of f'(s) are calculated from the equation given by Hantush (1961 b), $f'(s) = \ln S/S_c$ where ln is the natural logarithm, S is the known storage coefficient, and S_c is the calculated storage coefficient. Although S is not accurately known, a reasonable value is about 0.20 (Faulkner, oral commun., 1975). Curves of f'(s) versus r_c/b (fig. 18) are generated for an equivalent isotropic aquifer using the equations developed by Weeks (1969). From these curves the value of r_c/b at which the calculated f'(s) term would occur is determined and K_r/K_z is calculated from $K_r/K_z = \{(r/b)/(r_c/b)\}^2$.

The calculations are performed twice for each of the three observation wells; once for an effective aquifer thickness (b) of 63 ft (19.2 m) and again for an effective thickness of 103 ft (31.4 m). The results of the calculations (table 4) are inconclusive. Values of K_r/K_z were not determined for well NE20S because for both values of b the calculated value for f'(s) was outside the range of values for the curves f'(s) versus r_c/b, hence, r_c/b could not be determined. The same is true for NW10S where b = 103 ft (31.4 m). Values of K_r/K_z for wells NW10S and NE10D are quite different and the fact the calculated ratio K_r/K_z for NW10S is reasonable may be fortuitous.

Extreme aquifer heterogenity precludes the determination of reliable aquifer coefficients from data gathered during aquifer test 3.

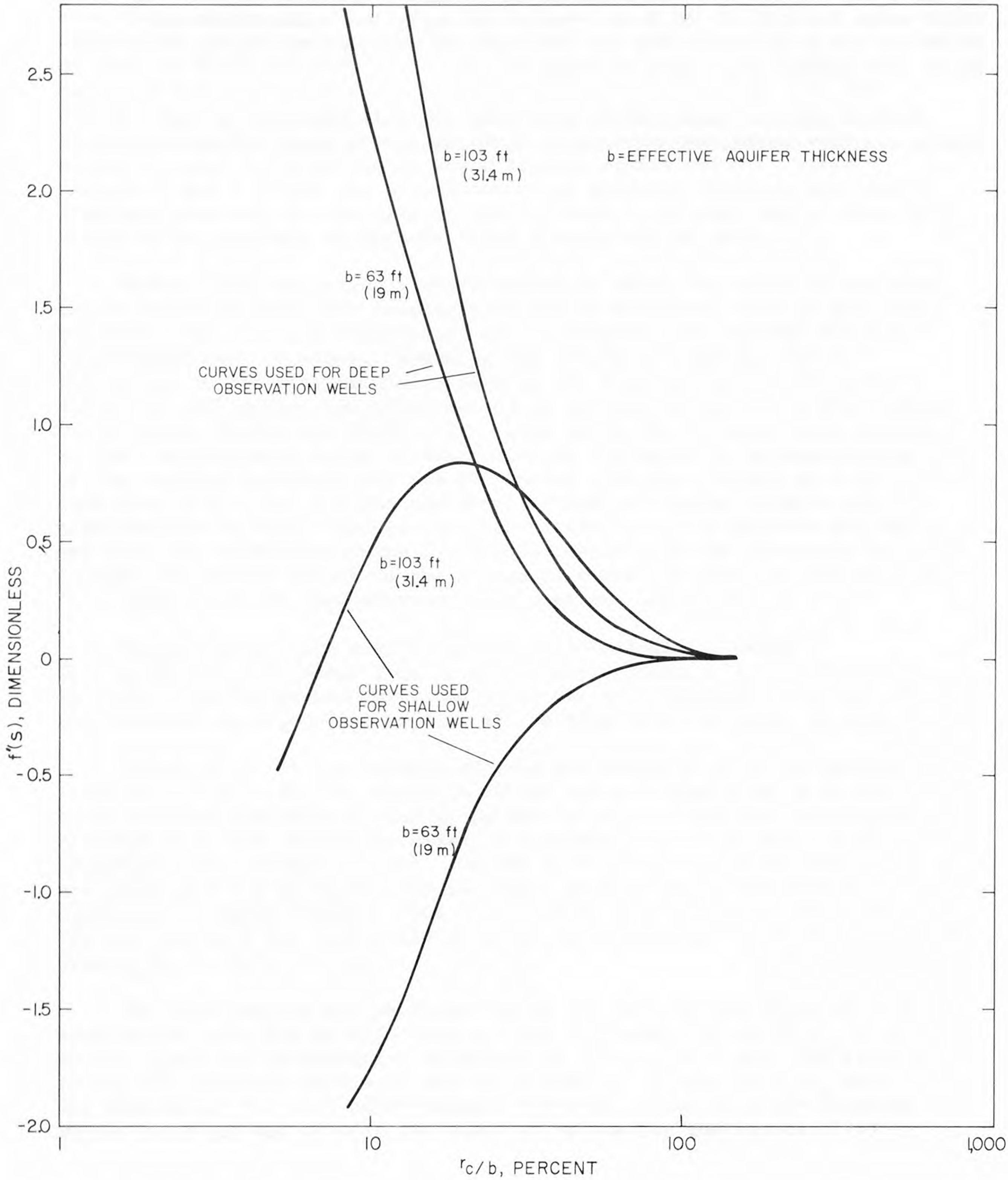

FIGURE 18.--GRAPHS OF f' (s) VERSUS r_c/b FOR SHALLOW AND DEEP OBSERVATION WELLS AT AQUIFER TEST SITE 3.

Table 4.--Results of calculations for aquifer test 3.

				b = 63 feet			b = 103 feet		
Well No.	Trans-missiv-ity (T) {(gal/d)/ft}	Calcu-lated storage coeffi-cient (Sc)	Cal-culated f'(s), di-mensionless	r_c/b from curve (percent)	r/b for well (percent)	Kr/Kz	r_c/b from curve (percent)	r/b for well (percent)	Kr/Kz
NW10S	46,000	1.21	-1.46	12.5	20.0	2.56	-	12.2	-
NE10D	220,000	.172	.49	26.0	16.8	.42	35	10.3	0.09
NE20S	160,000	.025	2.416	-	32.4	-	-	19.8	-

SUMMARY AND DISCUSSION OF RESULTS

Aquifer test results (table 5) together with geologists' logs and geophysical logs, show that, in outflow areas along the Summit Pool reach of the proposed Cross-Florida Barge Canal, the permeability of Floridan aquifer materials is highly variable in the horizontal plane as well as in the vertical. At sites 1 and 2, most solution channels and cavities were found in the upper 100 ft (30 m) feet of the aquifer (figs. 3 and 10) but most occur below +28 ft (8.5 m), msl, the planned altitude of the canal bottom. Therefore, after the canal is excavated, at sites 1 and 2 most of the flow in the aquifer would pass beneath the canal. However, this does not take into account the possible existence of open vertical solution pipes or fractures that could allow an intimate hydraulic connection between the canal and deeper, principal zones of lateral flow in the aquifer. Also, it is possible that vertical solution pipes, presently filled with sand, such as those apparently present at site 2, might become unplugged during or after excavation.

At site 3, most of the cavities encountered while drilling were at or above the water table. Since the water level in the canal would ideally be maintained at or near the natural seasonal ground-water level, cavities above the water table (fig. 15) would not convey water to or from the canal except when the water table is at about +52 ft (+16 m), msl, 9 ft (3 m) higher than at the time of the aquifer test. Faulkner (1973) states that if the canal is constructed it may be possible to control the canal stage in the Summit Pool within a range of about 10.5 ft (3.2 m), with a maximum stage of +51.5 ft (+15.7 m), msl. Therefore, the cavities found above the water table at site 3 would be above the anticipated maximum stage of the canal and would not convey water to or from the canal. However, one large cavity was encountered at site 3 between +22.8 ft (+6.95 m), msl and +11.2 ft (+3.41 m), msl (fig. 15) and the analysis and interpretation of the time-drawdown data (fig. 16) suggest that additional permeable zones might exist in the immediate vicinity of the canal alignment and at about the same altitude to which the canal would be excavated.

Table 5.--Summary of aquifer test and laboratory test results.

Aquifer test number	Well or well group	Interval tested by laboratory core analysis, (feet above or below msl)	Trans-missivity (T) {(gal/d)/ft}	Horizontal hyd-raulic conductivity (Kr), {(gal/d)/ft²}	Vertical hyd-raulic conductivity (Kz), {(gal/d)/ft²}	Kr/Kz
	Shallow wells	-	27,300	433	150	2.9
	-	39.0 to 38.0[a]	-	-	27	-
	-	31.8 to 30.8[a]	-	-	83	-
1	-	30.6 to 29.2[b]	-	-	22	-
	-	24.4 to 23.4[a]	-	-	4.9	-
	-	17.1 to 16.1[a]	-	200	146	1.4
	-	11.7 to 10.9[a]	-	-	127	-
	-	8.8 to 8.0[a]	-	-	350	-
	-	3.3 to 2.4[a]	-	.025	.05	.50
	-	-7.6 to -8.3[a]	-	-	15	-
	-	-7.8 to -8.6[b]	-	-	40	-
	-	-17.8 to -18.7[a]	-	3.82	14.2	.27
	Shallow wells	-	5,200 (3500)[c]	176 (143)[c]	110 (102)[c]	1.6 (1.4)[c]
2	Intermediate depth wells	-	2,700[d] (1400)[c]	93[d] (57)[c]	145[d] (67)[c]	.64 (.85)[c]
	Deep wells	-	120,000[d]	4100[d]	680[d]	6.0[d]
	NW10S, b = 63 ft		46,000	730	285	2.56
	NW10S, b = 103ft		46,000	450	-[e]	-[e]
3	NE10D, b = 63 ft		220,000	3500	8,300	.42
	NE10D, b = 103ft		220,000	2100	23,000	.09
	NE20S, b = 63 ft		160,000	2500	-[e]	-[e]
	NE20S, b = 103ft		160,000	1600	-[e]	-[e]

[a] Core samples from pilot hole.

[b] Core samples from observation well W100D.

[c] Values in parentheses are based upon pumped zone effective thickness of 24.5 ft.

[d] Invalid - see explanation in text.

[e] Could not be calculated - see explanation in text.

CONCLUSIONS

The extremely heterogeneous nature of the aquifer at all three test sites, especially at site 3, requires that all aquifer coefficients derived from the tests be regarded only as estimates. The three aquifer tests analyzed indicate that the vertical and horizontal hydraulic conductivity of the saturated materials that the canal would penetrate at the test sites is low compared to the average hydraulic conductivity determined by flow-net analysis (Faulkner, 1973) for the full effective thickness of the aquifer (about 100 ft or 30 m) in the vicinity of the Summit Pool. For example, flow-net analysis indicates that the average transmissivity of the upper part of the Floridan aquifer in the 2-mi^2 (5-km^2) area surrounding test sites 2 and 3 is 43.9 (Mgal/d)/ft ($0.54 \times 10^6 m^2/d$) (Faulkner, 1973). Whereas, the highest transmissivity determined from aquifer test 3 is 0.20 (Mgal/d)/ft ($0.0024 \times 10^6 m^2/d$). This suggests that the depth to which the canal would significantly influence the natural ground-water flow regime would not be great at the test sites, and that most ground-water flow would pass beneath the canal in solution channels.

The transmissivity of the full effective thickness of the aquifer, as determined from flow-net analysis, represents all types of hydraulic conductivity including intergranular, fracture, and solution-channel conductivity--solution channels probably are responsible for conveying most of the water. The analyses of the aquifer tests, especially test 1 and 2, treat important solution-channel systems as constant-head boundaries and, therefore, account only for the transmissivity due to intergranular and possible fracture conductivity.

If the aquifer-test sites are considered representative of the entire Summit reach (about 28 mi or 45 km) or, most importantly, the full length of the outflow zones (about 6 mi or 10 km), then the depth of influence on the natural ground-water flow regime of the Summit reach would not be great. If the depth of influence is not great, and the hydraulic conductivity in the part of the saturated zone penetrated by the canal is low, then exchange of water between the aquifer and the canal should be considerably less than indicated from the flow-net analysis (Faulkner, 1973).

It is not known how representative are the sites of the three aquifer tests of ground-water conditions along the entire Summit reach. At the test sites good vertical hydraulic connections between the top of the aquifer and horizontal solution channels in the lower part of the full effective thickness of the aquifer (about 100 ft or 30 m) are uncommon. It is reasonable to assume that sand-filled vertical solution pipes, such as those encountered at test site 2, are near the top of the aquifer. Vertical solution pipes in the area probably result from vertical flow in the unsaturated zone or where the vertical flow component in the saturated zone near the water table is dominant due to local recharge.

The canal would probably intersect some solution channels below the water table somewhere along the Summit reach. Time-drawdown data suggest that solution channels may exist in the immediate vicinity of the canal alignment near test site 3 at or about the design depth (+28 ft (+8.5 m) msl, of the canal. Open solution channels are known to occur near the design depth of the canal at Wolf Sink (fig. 1), about 1 mile (2 km) south of the canal alignment and about 3 miles (5 km) southwest of test site 3.

If, as indicated by the apparent conditions at the test sites, both vertical and horizontal solution channels are only sparsely distributed in that part of the saturated zone that would be penetrated by the canal, artificial blockage of such openings, if possible, when encountered during the canal excavation, could result in a much lower rate of water exchange between the canal and the aquifer than would be the case if cavities were left open. This would result in the minimal disruption of the natural ground-water flow regime as the large volume of natural flow along most parts of the Summit reach is apparently in solution channels below the design depth (+28 ft or +8.5 m, msl) of the Summit reach.

If some large solution channels were encountered during canal excavation and could be blocked off, especially in the outflow zones, some exchange would still take place between the canal and the aquifer by way of intergranular and possibly fracture conductivity in the aquifer. Where flow is mostly through intergranular pores, the filtration capability of the aquifer would be superior to that where appreciable flow is through solution channels.

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