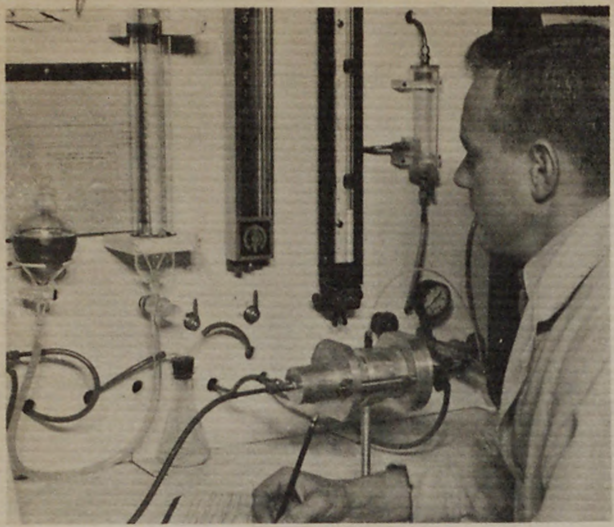


UNITED STATES

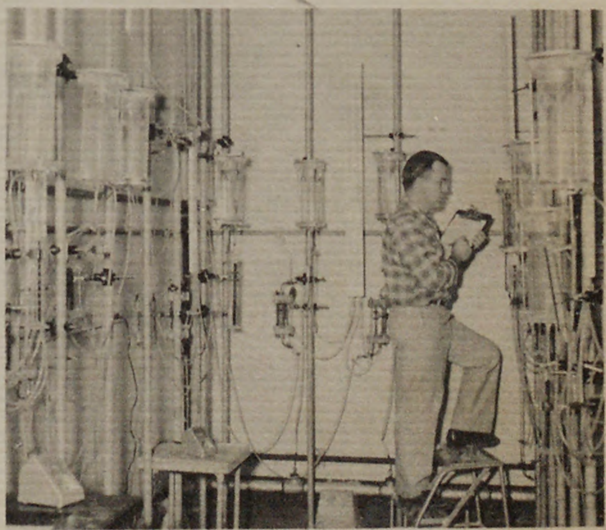
DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

APPLICATION OF LABORATORY PERMEABILITY DATA

HYDROLOGIC LABORATORY

Denver, Colorado



UNITED STATES
DEPARTMENT OF THE INTERIOR
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APPLICATION OF LABORATORY PERMEABILITY DATA

By A. I. Johnson

Open-File Report
63-67

U.S. Geological Survey.
Hydrologic Laboratory, Denver.
Denver, Colorado
1963

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By A. I. Johnson

INTRODUCTION

Some of the basic material contained in this report originally was prepared in 1952 as instructional handouts for ground-water short courses and for training of foreign participants. The material has been revised and expanded and is presented in the present form to make it more readily available to the field hydrologist. Illustrations now present published examples of the applications suggested in the 1952 material.

For small areas, a field pumping test is sufficient to predict the characteristics of an aquifer. With a large area under study, the aquifer properties must be determined at many different locations and it is not usually economically feasible to make sufficient field tests to define the aquifer properties in detail for the whole aquifer. By supplementing a few field tests with laboratory permeability data and geologic interpretation, more point measurements representative of the hydrologic properties of the aquifer may be obtained.

A sufficient number of samples seldom can be obtained to completely identify the permeability or transmissibility in detail for a project area. However, a few judiciously chosen samples of high quality, combined with good geologic interpretation, often will permit the extrapolation of permeability information over a large area with a fair degree of reliability. The importance of adequate geologic information, as well as the importance of collecting samples representative of at least all major textural units lying within the section or area of study, cannot be overemphasized.

PERMEABILITY DEFINED

Permeability is a measure of the capacity of a material to transmit water under pressure. It may be determined in the laboratory by observing the rate of percolation of water through samples of known length and cross-sectional area under a known difference in head.

The basic law for flow of fluids through porous materials was established by Darcy, who demonstrated experimentally that the rate of flow of water was proportional to the hydraulic gradient. Darcy's law may be expressed as

$$Q = kiA \tag{1}$$

in which $\underline{Q}$ is the quantity of water discharged in a unit of time, $\underline{A}$ is the total cross-sectional area through which the water percolates, $\underline{i}$ is the hydraulic gradient (the difference in head, $\underline{h}$, divided by the length of flow, $\underline{L}$) and $\underline{k}$ is the coefficient of permeability of the material for water, or

$$k = \frac{Q}{iA} \text{ or } \frac{QL}{hA} . \tag{2}$$

The coefficient of permeability, $\underline{P}$, used by the Ground Water Branch of the U.S. Geological Survey, is defined (Wenzel, 1942, p. 7) as the rate of flow of water in gallons per day, through a cross-sectional area of 1 square foot under a hydraulic gradient of 1 foot per foot at a temperature of 60°F.(this is sometimes known as a Meinzer). Other permeability units are used by other organizations and other disciplines and table 1 provides factors for converting between many common permeability units.

Coefficients of permeability, ranging from 0.00001 to 90,000 gpd per sq ft, have been determined in the Hydrologic Laboratory. The value depends in general upon the degree of sorting and upon arrangement and size of the particles. It is usually low for clay and other fine-textured or tightly cemented materials, and high for coarse, clean gravel. Most productive water-bearing materials have coefficients of permeability of 100 or above and usually above 1,000. In general, the permeability in a direction parallel to the bedding plane (for convenience, often designated as horizontal permeability) of sediments is greater than the permeability perpendicular to the bedding plane (often designated as vertical permeability).

Table 1.--Permeability conversion factors

(From Wenzel, L. K., 1942, p. 9, 10)

No.[a]	Method of expressing permeability unit	Factors for conversion of other units expressed for temperatures of 60° and 68° F. into Meinzer's unit at 60° F.		Factors for conversion of Meinzer's units for temperature of 60° F. into other units expressed for temperatures of 60° and 68° F.	
		68° F.	60° F.	68° F.	60° F.
1	$\frac{1 \text{ cm.}^3}{\text{sec. cm.}^2 \text{ (1 cm. } H_2O\text{/cm.)}}$	1.897×10^{4}	2.120×10^{4}	5.270×10^{-5}	4.716×10^{-5}.
2	$\frac{1 \text{cm.}^3}{\text{sec. cm.}^2 \text{ (gm./cm.}^2\text{) cm.}}$	1.894×10^{4}	2.118×10^{4}	5.280×10^{-5}	4.721×10^{-5}.
3	$\frac{1 \text{ cm.}^3}{\text{sec. cm.}^2 \text{ (dyne/cm.}^2\text{) cm.}}$	1.848 [b] $\times 10^{7}$	2.077×10^{7}	5.410×10^{-8}	4.814×10^{-8}.
4	$\frac{1 \text{ cm.}^3}{\text{sec. cm.}^2 \text{ (atmosphere/cm.)}}$	18.24 [b]	20.50	5.482×10^{-2}	4.877×10^{-2}.
5	$\frac{1 \text{ ft.}^3}{\text{min. ft.}^2 \text{ (1 ft. } H_2O\text{)/ft.)}}$	9.640×10^{3}	1.077×10^{4}	1.037×10^{-4}	9.283×10^{-5}.
6	$\frac{1 \text{ ft.}^3}{\text{sec. ft.}^2 \text{ (1/g ft. } H_2O\text{/ft.)}}$	1.861×10^{7}	2.079×10^{7}	5.374×10^{-8}	4.809×10^{-8}.
7	$\frac{1 \text{ in.}}{\text{hr. (1 ft. } H_2O\text{/ft.)}}$	13.39	14.96	7.470×10^{-2}	6.684×10^{-2}.
8	$\frac{1 \text{ in.}^3}{\text{min. in.}^2 \text{ (lb./in.}^2\text{) in.}}$	28.97	32.40	3.452×10^{-2}	3.086×10^{-2}.
9	$\frac{1 \text{ in.}^3}{\text{hr. ft.}^2 \text{ (lb./in.}^2\text{) 0.5 in.}}$	0.966	1.080	1.036	0.926.
10	$\frac{1 \text{ ft.}^3}{\text{sec. ft.}^2 \text{ (lb./ft.}^2\text{) ft.}}$	3.604×10^{7}	4.031×10^{7}	2.774×10^{-6}	2.481×10^{-6}.

[a] References used for permeability units.

1. P. W. Ketchum, A. E. R. Westman, and R. K. Hursh.—Cubic centimeters per second per square centimeter under a hydraulic gradient of 100 percent at a temperature of 77° F. Illinois Univ. Eng. Exper. Sta. Cir. 14, p. 22, 1926.
2. C. F. Barb and E. R. Branson.—Cubic centimeters per second per square centimeter under a pressure of 1 gram per square centimeter per centimeter length of material. Internat. Petroleum Technology, vol. 8, pp. 325–335, 1931.
3. P. G. Nutting.—Cubic centimeters per second per square centimeter under a pressure of 1 dyne per square centimeter per centimeter length of material and a viscosity of 1 centipoise. Am. Assoc. Petroleum Geologists Bull., vol. 14, p. 1348, 1930.
4. R. D. Wyckoff, H. G. Botset, Morris Muskat, and D. W. Reed.—Cubic centimeters per second per square centimeter under a pressure of 1 atmosphere per centimeter and a viscosity of 1 centipoise. The unit is called a darcy. Rev. Sci. Instruments, vol. 4, No. 7, pp. 394–405, 1933.
5. C. S. Slichter.—Cubic feet per minute per square foot under a hydraulic gradient of 100 percent. U. S. Geol. Survey Water-Supply Paper 140, p. 11, 1905.
6. O. W. Israelsen and E. R. Morgan.—Cubic feet per second per square foot for unit potential gradient at 60° F. Unit potential gradient was defined as 1/g foot per foot. Am. Geophys. Union Trans., 1937, pp. 568–574.
7. C. S. Slater and H. G. Byers.—Inches per hour under a hydraulic gradient of 100 percent (temperature not given). U. S. Dept. Agr. Tech. Bull. 232, p. 9, 1931.
8. C. M. Nevin.—Cubic inches per minute per square inch under a pressure of 1 pound per square inch per inch length of material at a temperature of 68° F. Am. Assoc. Petroleum Geologists Bull. vol. 16, No. 4, pp. 373–384, 1932.
9. D. W. Kessler.—Cubic inches per hour per square foot under a pressure of 1 pound per square inch per 0.5 inch length of material (temperature not given). Nat. Bur. Standards Tech. Paper 305, 1926.
10. H. D. Wilde and T. V. Moore.—Cubic feet per second per square foot under a pressure of 1 pound per square foot per foot length of material. Oil Weekly, vol. 67, No. 12, pp. 34–40, 1932.

[b] Determined for a viscosity of 1 centipoise, that is, for a temperature of approximately 68.4°F.

LABORATORY METHODS

Coefficients of permeability are determined in the laboratory in constant-head or variable-head permeameters (fig. 1). The constant-head permeameter is generally used for samples of medium to high permeability, the variable-head permeameter for samples of low permeability.

The constant-head permeability method requires observations on the rate of discharge of water through a sample where the difference in head of water at the top and bottom of the sample is maintained at a constant value. From Darcy's law, the basic formula for the constant-head permeameter is

$$k = \frac{QL}{Ath} C_T , \qquad (3)$$

where *k* is the coefficient of permeability, *Q* is the volume of percolation, *L* is the length of the sample, *A* is the area of the sample cylinder, *t* is the length of the time of flow, *h* is the difference in head at the top and bottom of the sample, and C_T is the ratio of the viscosity of water at the observed temperature to the viscosity at 60°F. Using Ground Water Branch units, equation (3) becomes

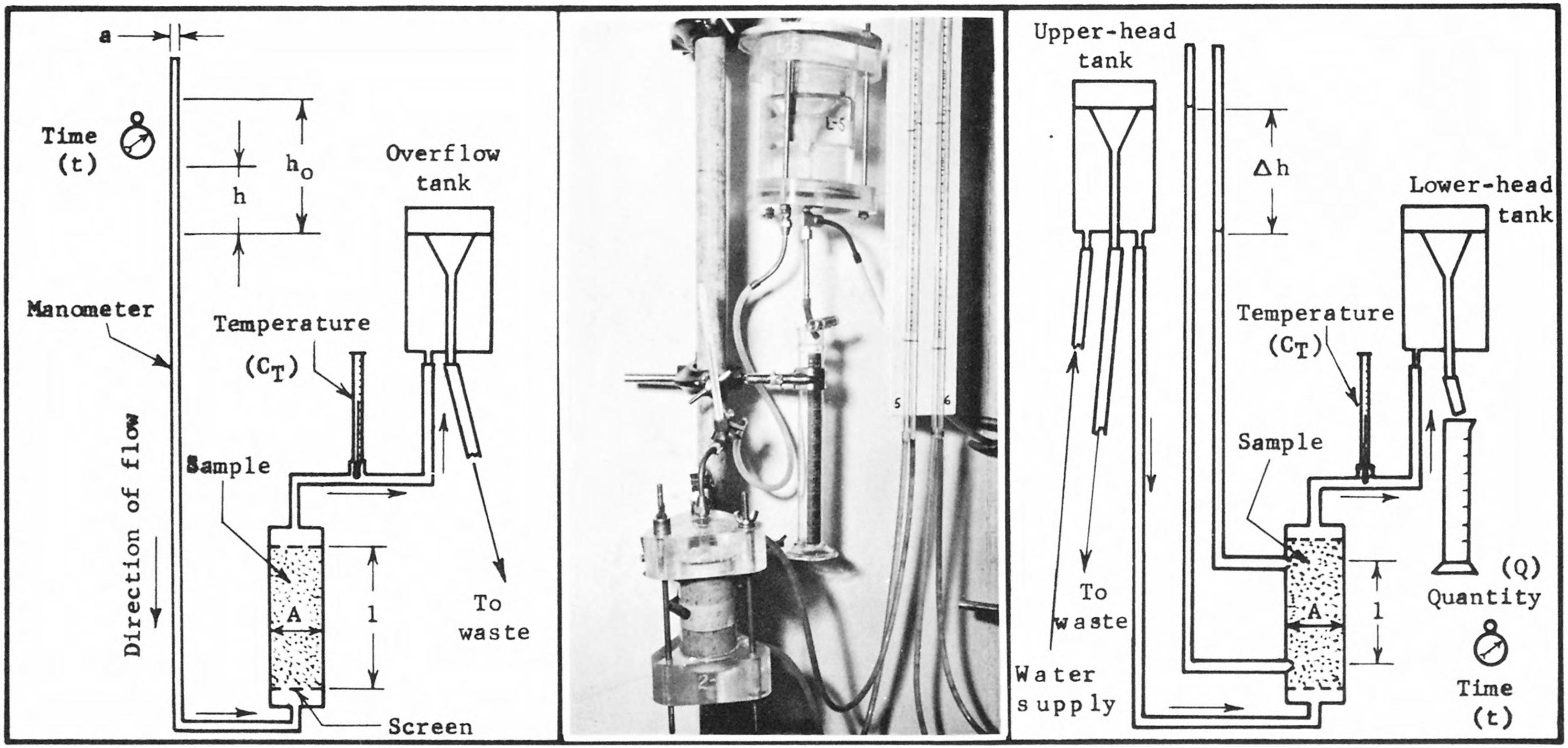
$$P = \frac{21{,}200\ QL}{Ath} C_T \qquad (4)$$

when *P* is in gallons per day per square foot, *Q* is in cubic centimeters, *L* and *h* are in centimeters, *A* is in square centimeters, *t* is in seconds, and C_T is dimensionless.

The variable-head permeability method requires the indirect measurement of the quantity of water percolating through the sample by observing the rate of fall of the water level in a manometer connected to the sample. By integrating Darcy's equation, the basic formula for use of the variable-head permeameter is

$$k = 2.3\frac{aL}{At}\log\frac{h_o}{h} C_T \qquad (5)$$

where *k* is the coefficient of permeability, h_o is the head in the manometer at zero time, *h* is the head at any given elapsed time, *t* is the elapsed time, *A* is the cross-sectional area of the sample, *a* is the area of the manometer, *L* is the length of the sample, and C_T is the temperature correction.



(a) Diagram of variable-head type,

where $k = 2.3 \frac{al}{At} \log \frac{h_o}{h} C_T$

(b) Photograph of apparatus

(c) Diagram of constant-head type,

where $k = \frac{Ql}{At(\Delta h)} C_T$

Figure 1.--Permeability apparatus.

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Using Ground Water Branch units, equation (5) becomes

$$P = 48{,}815 \frac{aL}{At} \log \frac{h_o}{h} C_T \qquad (6)$$

in which P is in gallons per day per square foot under a hydraulic gradient of one foot per foot at $60^{\circ}F$. A and a are in square centimeters, L is in centimeters, t is in seconds, h_o and h are in centimeters, and C_T is dimensionless.

In the above equations, the properties of the percolation fluid have been neglected. However, permeability is directly proportional to the unit weight (density), γ, and inversely proportional to the viscosity, μ.

Thus,

$$k_1 = k_2 \frac{\gamma_1}{\gamma_2} \qquad (7)$$

and

$$k_1 = k_2 \frac{\mu_2}{\mu_1} . \qquad (8)$$

Although special fluids, as well as air or other gases, are used by the Hydrologic Laboratory in the determination of permeability, most tests have used fairly pure water. (See Johnson and Morris, 1962, for the chemical analysis of Denver tap water.) Under the latter conditions, the unit weight of water, γ_w, is essentially constant at a value close to 1 g per cc, but the viscosity, μ, varies considerably with changes in temperature. From equation (7), it is obvious that permeability increases with an increase in temperature.

Because coefficients of permeability are reported from the laboratory for a water temperature of $60^{\circ}F$, they must be corrected for the temperature of the ground water before applying them to field problems. The permeability at some given field temperature, k_T, may be obtained from the equation

$$k_T = \frac{k_{60}}{C_T} . \qquad (9)$$

Table 2 provides the temperature corrections required for the most common ground-water temperatures.

Table 2.--Temperature corrections for laboratory permeabilities

Conversion factors for converting coefficients of permeability at water temperatures of 40°F - 90°F to coefficients of permeability at water temperature of 60°F.

$$k_{60} = k_T C_T$$

Water temperature (°F)	Conversion factor (C_T)	Water temperature (°F)	Conversion factor (C_T)
40	1.37	65	0.93
41	1.35	66	0.91
42	1.33	67	0.90
43	1.31	68	0.89
44	1.28	69	0.88
45	1.26	70	0.87
46	1.24	71	0.86
47	1.22	72	0.84
48	1.20	73	0.83
49	1.18	74	0.82
50	1.16	75	0.81
51	1.15	76	0.80
52	1.13	77	0.79
53	1.11	78	0.78
54	1.09	79	0.77
55	1.08	80	0.76
56	1.06	81	0.75
57	1.04	82	0.75
58	1.03	83	0.74
59	1.01	84	0.73
60	1.00	85	0.72
61	0.98	86	0.71
62	0.97	87	0.70
63	0.96	88	0.69
64	0.95	89	0.69
		90	0.68

Equations (7) and (8) show that permeabilities determined from flow of air or other gases theoretically can be converted to equivalent permeabilities for water. Although good agreement sometimes may be obtained (usually on fairly clean sands and gravels) from actual tests using either gas or water, the agreement more often is quite poor. The cases of disagreement usually can be explained by the fact that clay minerals in the sample may be affected by water but not by gas. Thus, the author recommends the use of water for most permeability measurements in connection with ground-water studies. However, for special problems--such as salt-water encroachment, the tests should be made with water of the same analysis as that found in the project area. When water is used for the permeability test, entrapped air in the sample may cause plugging of some of the pore space and greatly reduce the apparent coefficient of permeability. Thus, a specially-designed vacuum system (fig. 2) is used by the Hydrologic Laboratory to provide the de-aired water used as a percolation fluid. Such water has an affinity for soluble gas and any gases present in the pore space will thus tend to be dissolved and carried out of the sample, saturating the pore space during the process.

Once the sample is saturated, decreases in permeability usually will occur (fig. 3) if testing is continued. This decrease is due to (1) migration of some gas bubbles to points where they can plug a pore space and reduce flow, (2) solid matter of microscope size plugging pore channels, (3) small amounts of dissolved chemicals plug the filter disks on the permeameters or react with the clay minerals in the sample, (4) migration of fine particles of the sample plugging pore passages, and (5) growth of micro-organisms reducing the effective pore space. Figure 3 shows that the length of time and the amplitude of the changes for (1) the early period of rising permeability (to saturation), (2) the middle period of relatively constant permeability, and (3) the later period of reducing permeabilities varies with the texture of the material being tested. Figure 3 also shows, for a coarse sand, the difference in permeability obtained from use of ordinary tap water and de-aired water. The coefficient of permeability reported by the Hydrologic Laboratory is the maximum value obtained after several flow measurements, the peak values on the graphs of figure 3, and represents the permeability at saturation.

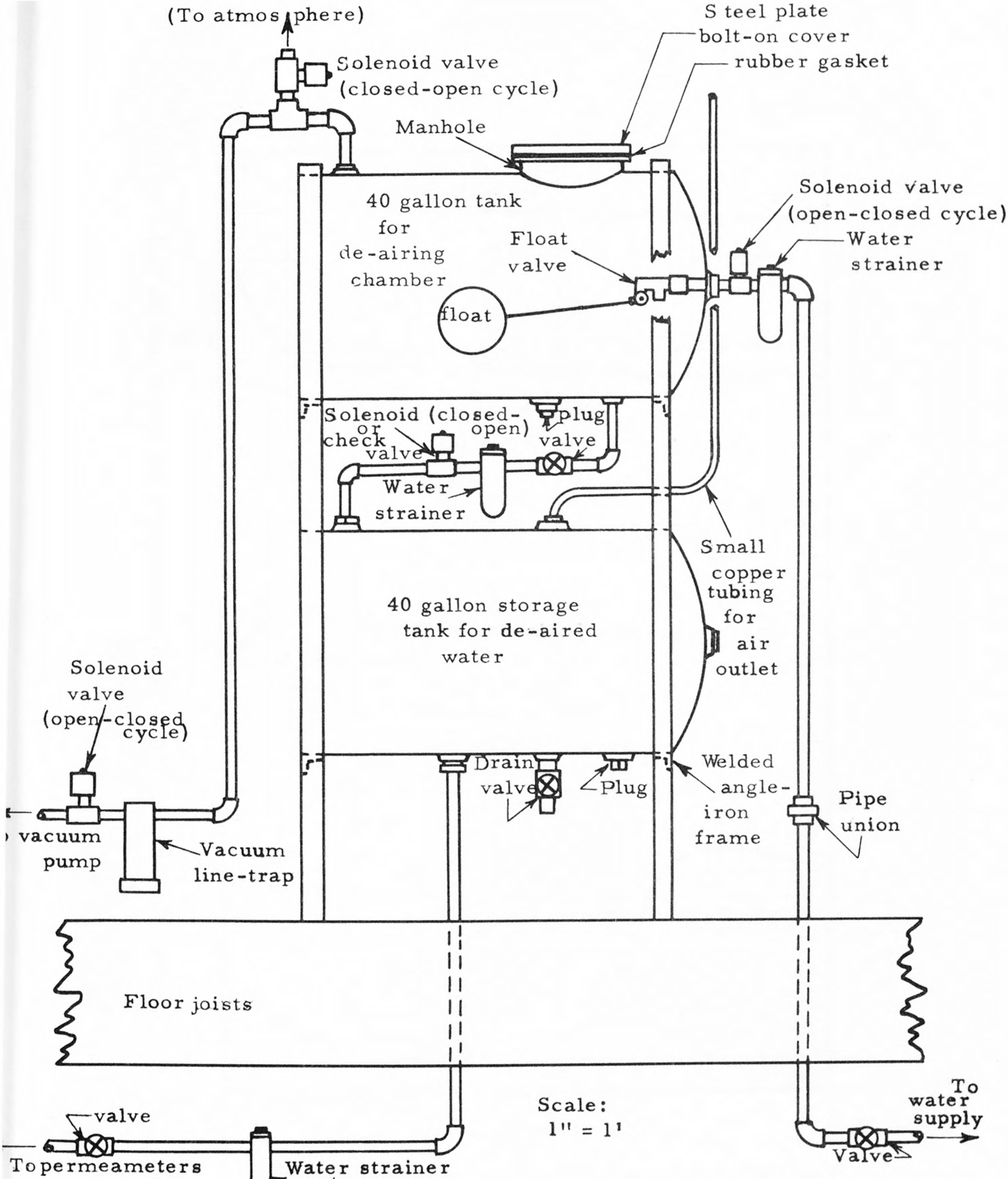


Figure 2.--De-aired water-supply system for permeability testing, Hydrologic Laboratory, Denver, Colo.

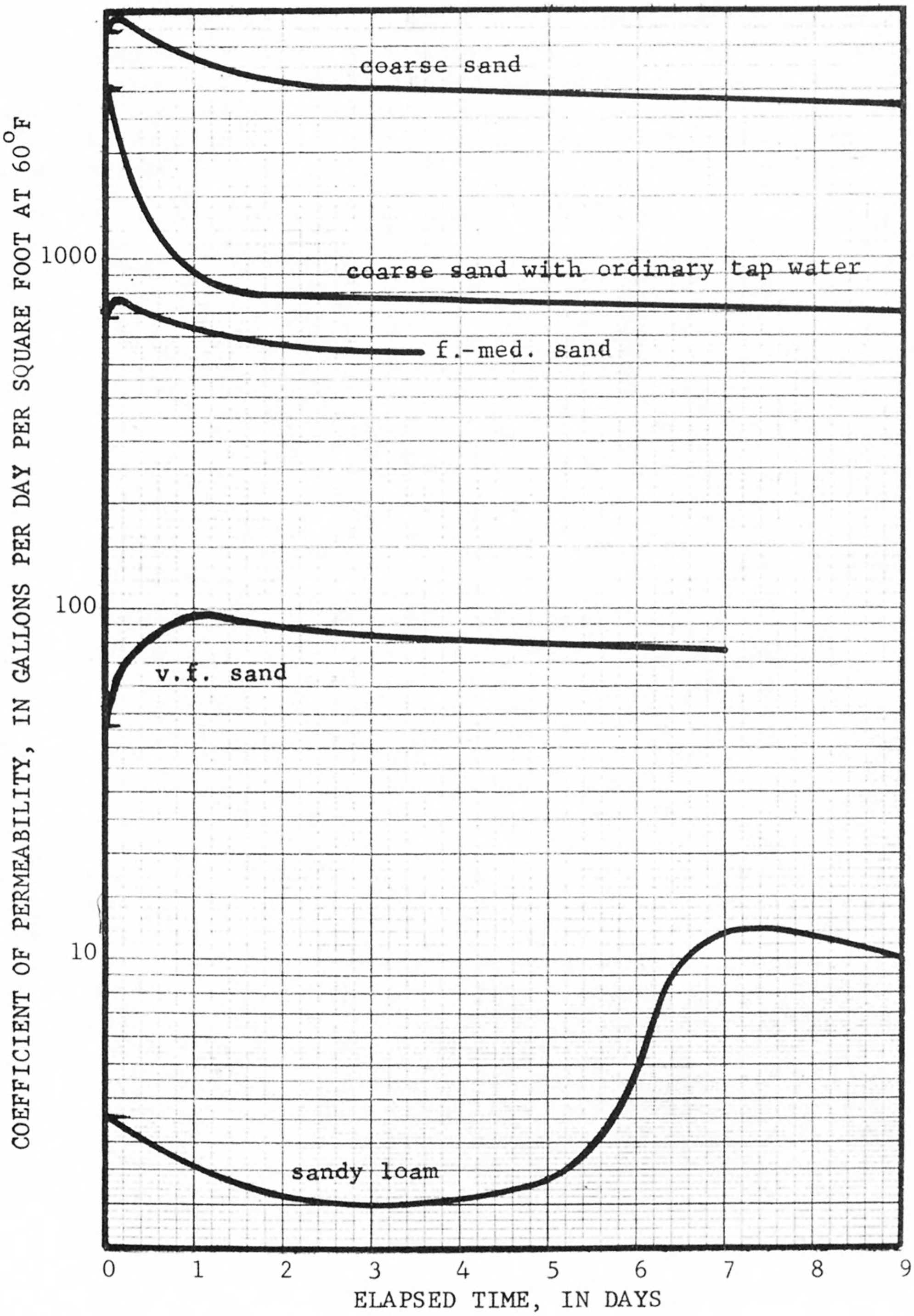


Figure 3.--Graph showing variation of permeability with elapsed time of testing.

For saturated permeability measurements, undisturbed cores of unconsolidated materials are retained in the cylinder liners of drive core barrels. Undisturbed cores of consolidated materials are sealed with sealing wax in the percolation cylinders. Disturbed samples of unconsolidated materials are packed in the percolation cylinders by means of a specially-designed packing machine (fig. 4). All cylinders are installed directly in the permeameter to serve as the percolation cylinder of the apparatus.

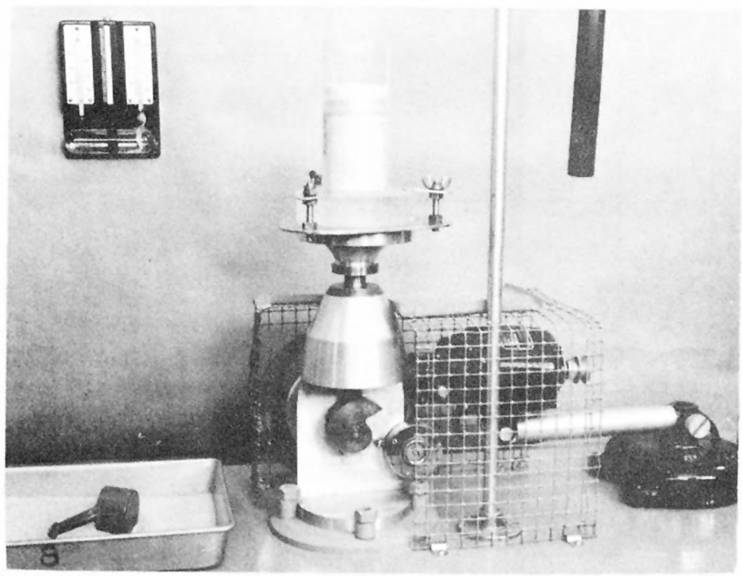


Figure 4.--Packing machine

Unsaturated permeability, or the variation of permeability with degree of saturation, is determined in the Hydrologic Laboratory by use of the pressure-plate outflow method (Gardner, 1956), for unconsolidated materials, and by use of a modified stationary-liquid method (Burdine, 1953; Corey, 1954; Hassler and others, 1936), for consolidated materials. The apparatus (bottom, cover photograph) used in the latter method holds the wetting phase (water) stationary within the sample by capillary forces while determining the permeability of the sample to the non-wetting phase (air) under very low pressure gradients. The unsaturated permeability to water (fig. 5) is then calculated from the measured air permeabilities using a mathematical procedure developed by Corey (1954).

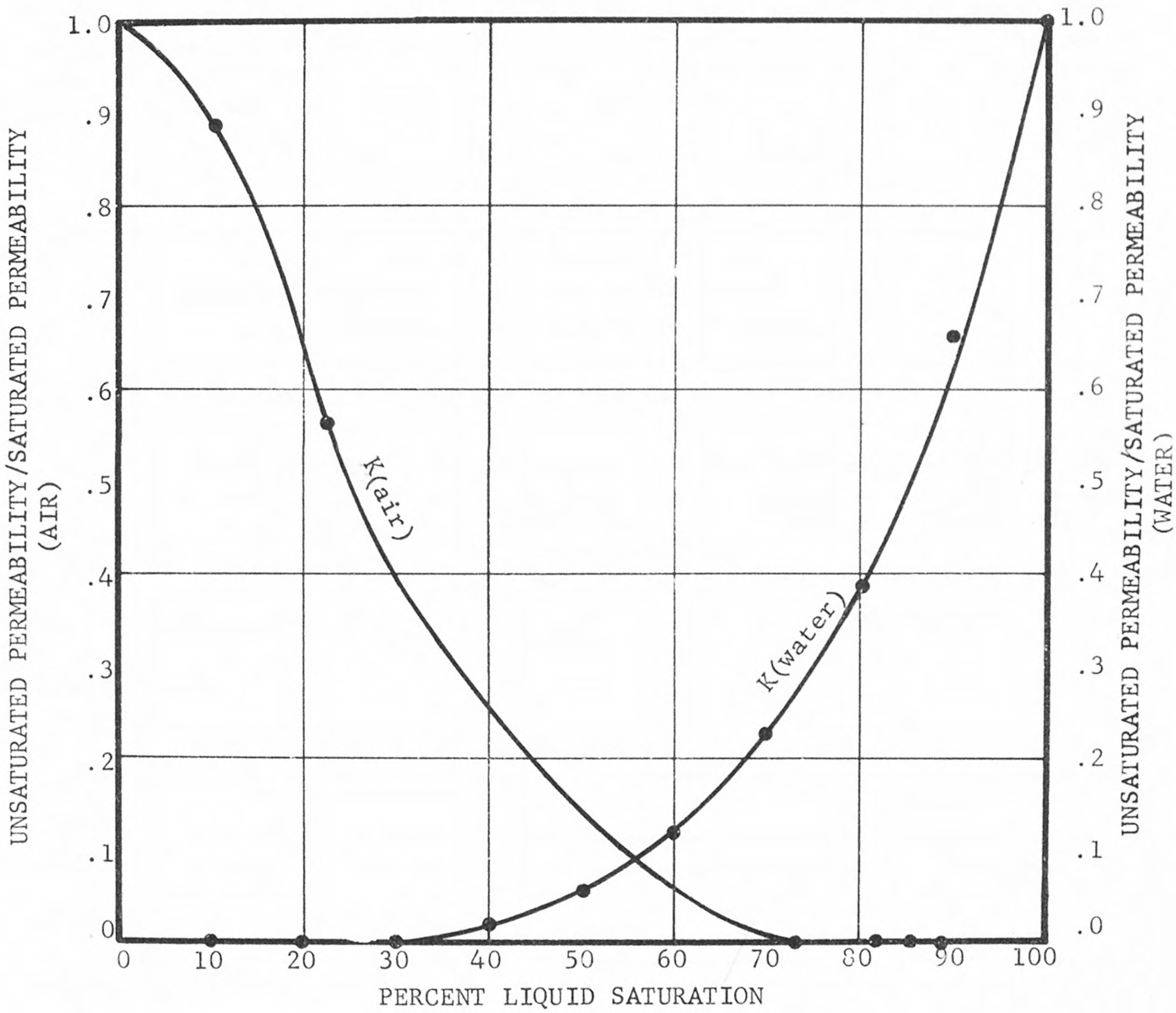


Figure 5.--Relative permeability curves for Bandelier tuff.

USE OF LABORATORY DATA

Application to Test-Hole Logs

Aquifers usually consist of lithologic units or layers, which have different texture and consequently different permeability. To determine the average permeability of the section under study, good quality samples (preferably undisturbed cores) should be obtained from each of the layers and analyzed for their permeability. Once the permeabilities are known for the individual units, the average permeability may be calculated by the following equation:

$$k = \frac{1}{m_T}\left[k_1m_1+k_2m_2+ \ . \ . \ . \ k_nm_n\right] \qquad (10)$$

where k = average coefficient of permeability parallel to the bedding planes of the layers,

m_T = total thickness of section under study,

m_1, m_2, . . . m_n = thickness of each unit or layer,

k_1, k_2, . . . k_n = coefficient of permeability of each unit or layer.

Table 3 demonstrates the method of making such calculations.

Table 3.--Application of laboratory permeability data to test-hole logs

Test-hole log	Thickness (feet)	Coefficient of permeability (gpd per sq ft)	Weighted permeability or unit transmissibility (gpd per ft)
		Surface	
Unsaturated materials	25		
		Water table	
Very fine sand	10	100	1,000
Sandy silt	5	10	50
Silty clay	15	1	15
Medium sand	10	2,000	20,000
Coarse sand-fine gravel	15	5,000	75,000
Medium-crs gravel with cobbles	20	8,000	160,000
		Base of aquifer	

Note: Saturated thickness (ft): 75. Aquifer transmissibility (gpd per ft): 256,000. Average permeability (gpd per sq ft): 256,000÷75=3,400.

Once permeabilities have been obtained for the lithologic units or textures found in the project area, driller's or geologist's (preferably) logs may be used in conjunction with that data to obtain the average permeability or transmissibility at many specific locations.

Maps of Transmissibility or Permeability

Once transmissibilities, or average permeabilities, have been determined from aquifer tests or by calculation from laboratory and test-hole data, they may be plotted at the location of the well or test hole. Contours of equal transmissibility, or permeability, then may be drawn in a manner similar to the preparation of topographic maps (fig. 6). Different patterns also may be drawn between contours to indicate ranges of transmissibility or permeability. Figures 7 through 15 present examples of areal maps showing patterns of transmissibility or permeability.

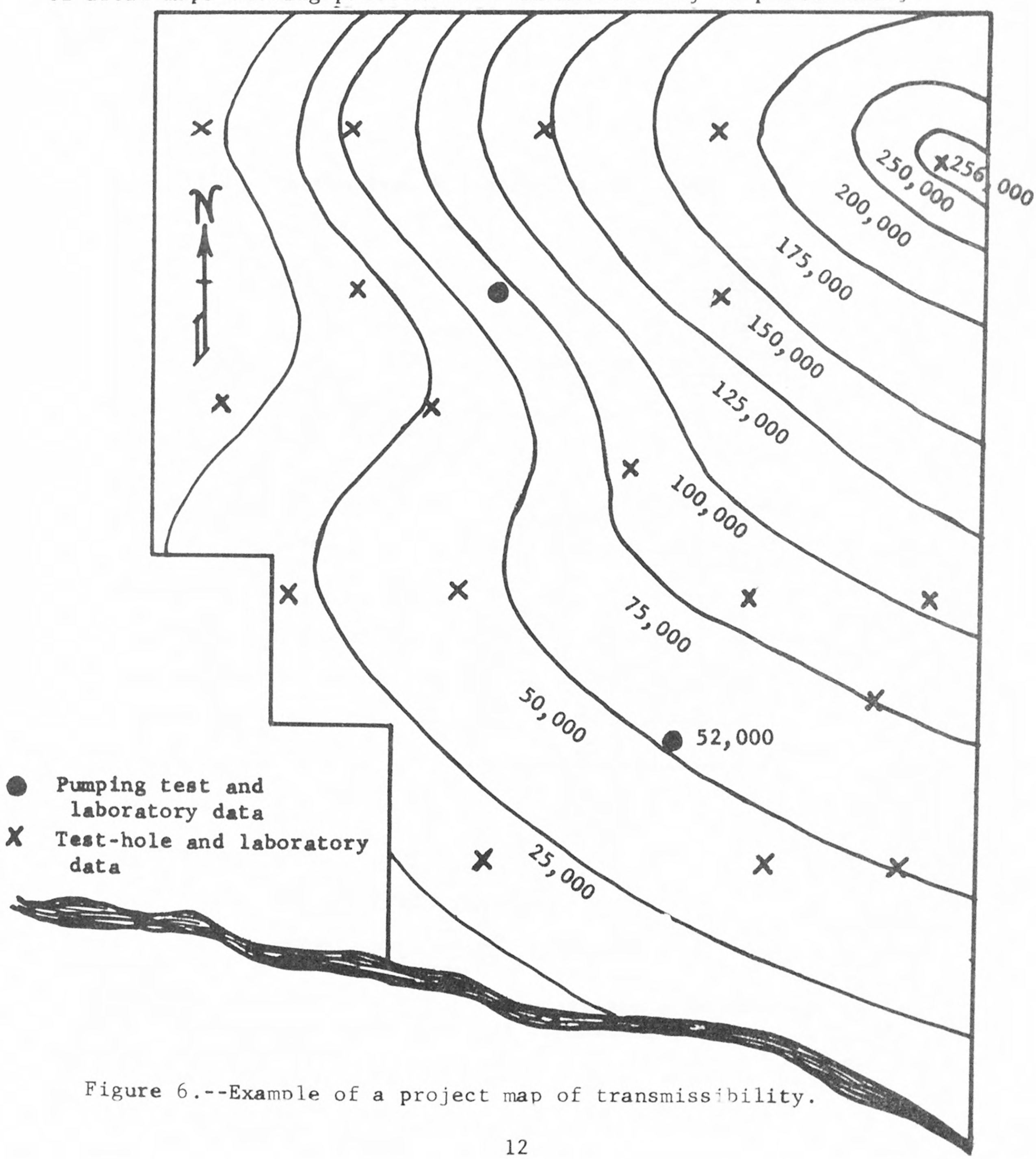
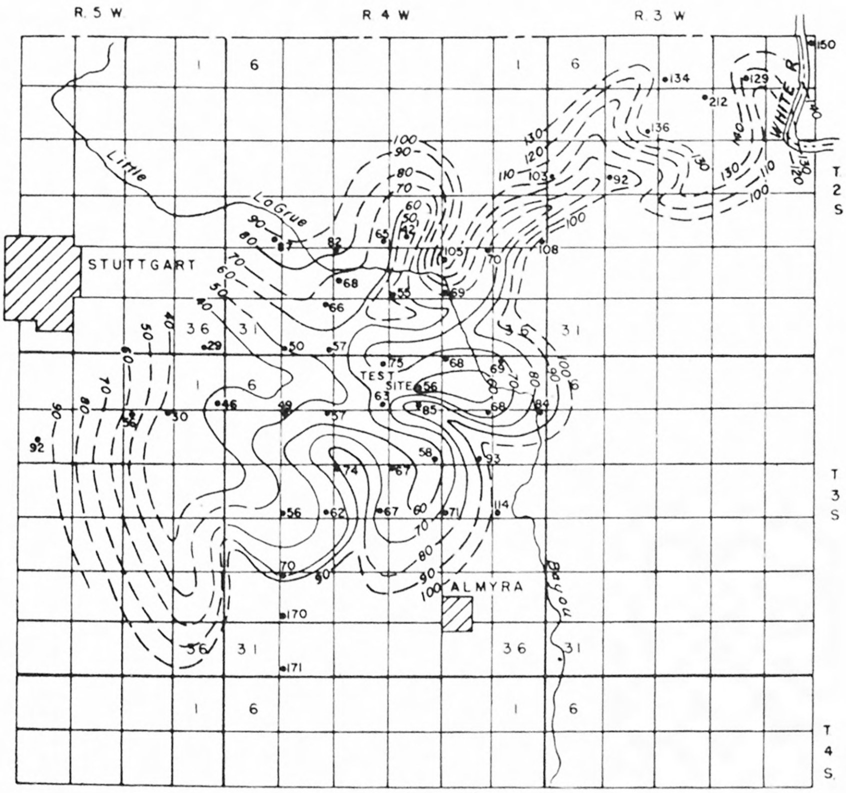


Figure 6.--Example of a project map of transmissibility.

(Illustration from Sniegocki, R. T., 1964)



EXPLANATION

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Test hole showing transmissibility estimated from well logs, in thousands of gallons per day per foot

——60— —

Line of equal coeffiecient of transmissibility, in thousands of gallons per day per foot. Dashed where inferred. Interval is 10 (10,000 gpd per foot)

Figure 7.--Map of the artificial-recharge area showing approximate lines of equal transmissibility, summer 1954.

(After Sniegocki, R. T., 1955, U.S. Geol. Survey Water-Supply Paper 1327)

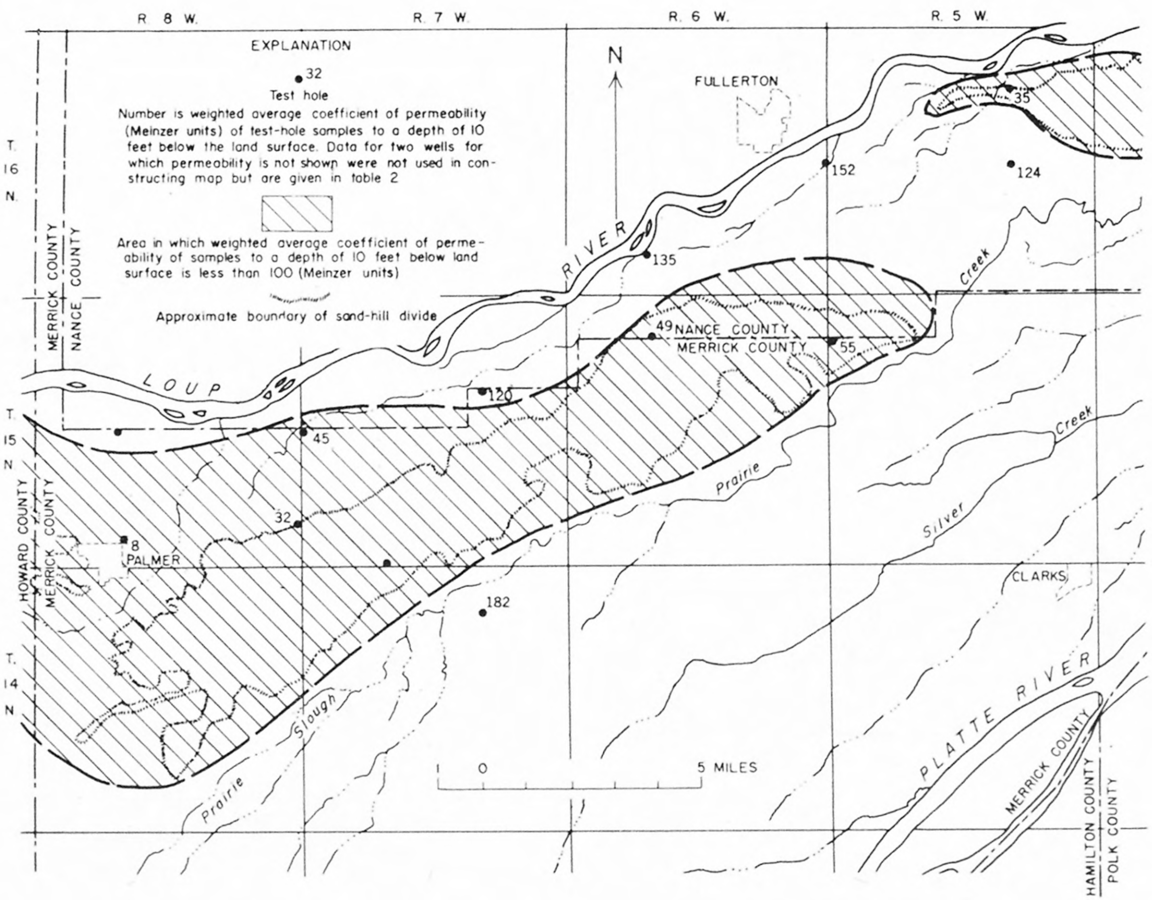

Figure 8.--Map of part of the Prairie Creek unit showing location of test holes and weighted average coefficient of permeability of test-hole samples to a depth of 10 feet below land surface.

(Illustration from Cardwell, W. D. E., and Jenkins, E. D., 1963)

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PLATE 7

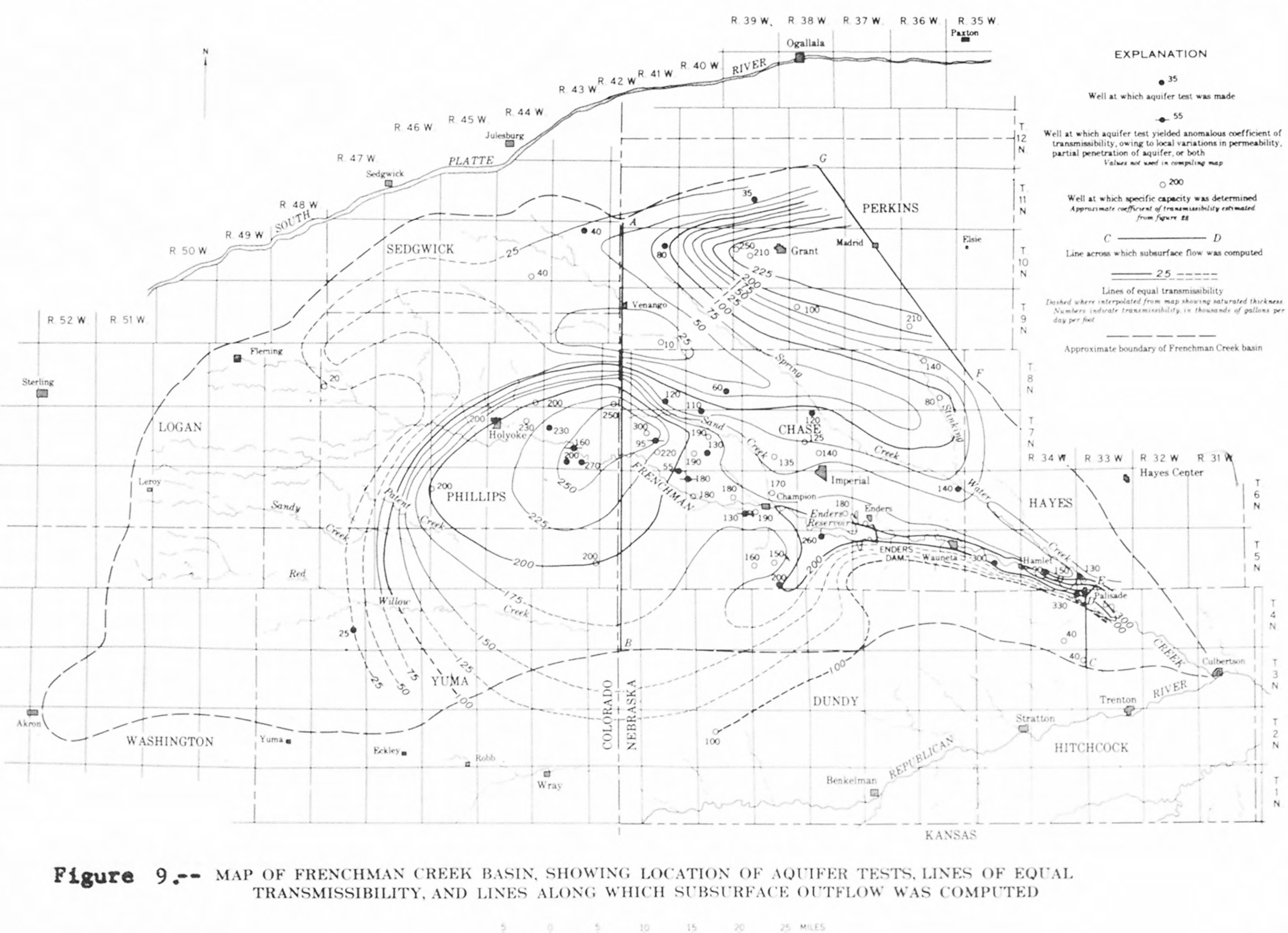

Figure 9.-- MAP OF FRENCHMAN CREEK BASIN, SHOWING LOCATION OF AQUIFER TESTS, LINES OF EQUAL TRANSMISSIBILITY, AND LINES ALONG WHICH SUBSURFACE OUTFLOW WAS COMPUTED

(Illustration from Bedinger, M. S., Tanaka, H. H., and others, 1960)

REPORT ON GROUND-WATER GEOLOGY AND HYDROLOGY OF THE LOWER ARKANSAS AND VERDIGRIS RIVER VALLEYS

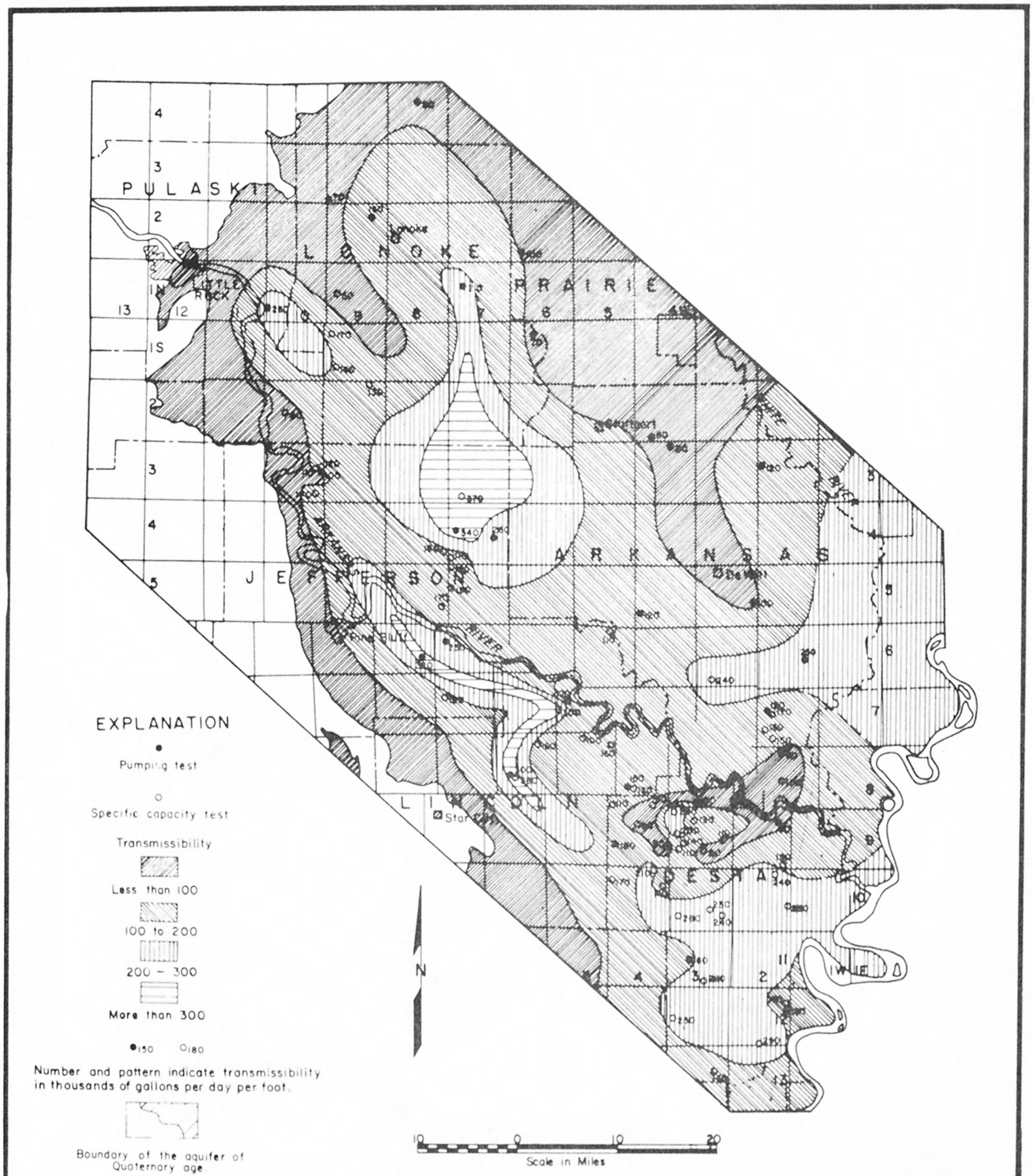

Figure 10 - Map showing transmissibility of the aquifer of Quaternary age in and near the project area from Mississippi River to Little Rock.

(Illustration from Kazmi, A. H., 1961)

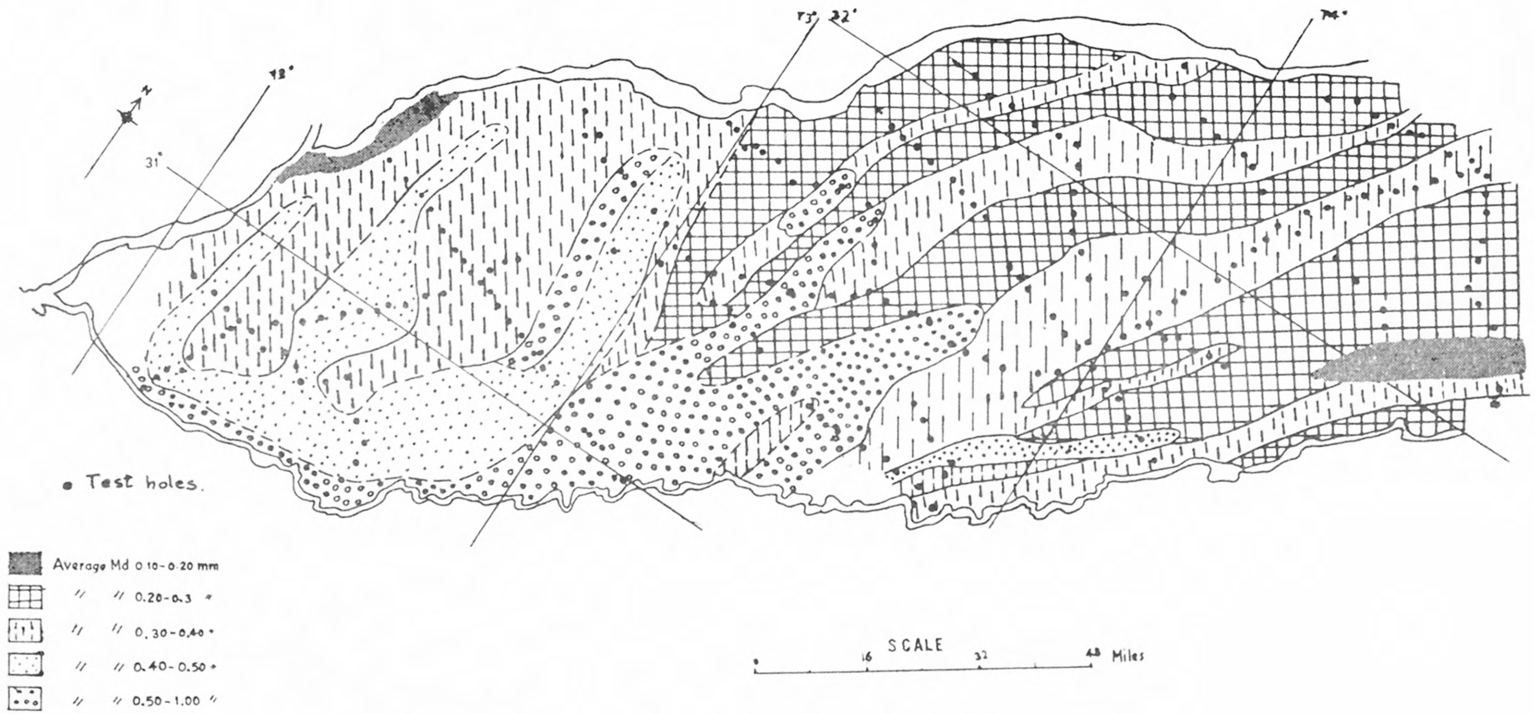

Figure 11.--Map of Rechna Doab, West Pakistan, showing median diameter of sediments.

(Illustration from Kazmi, A. H., 1961)

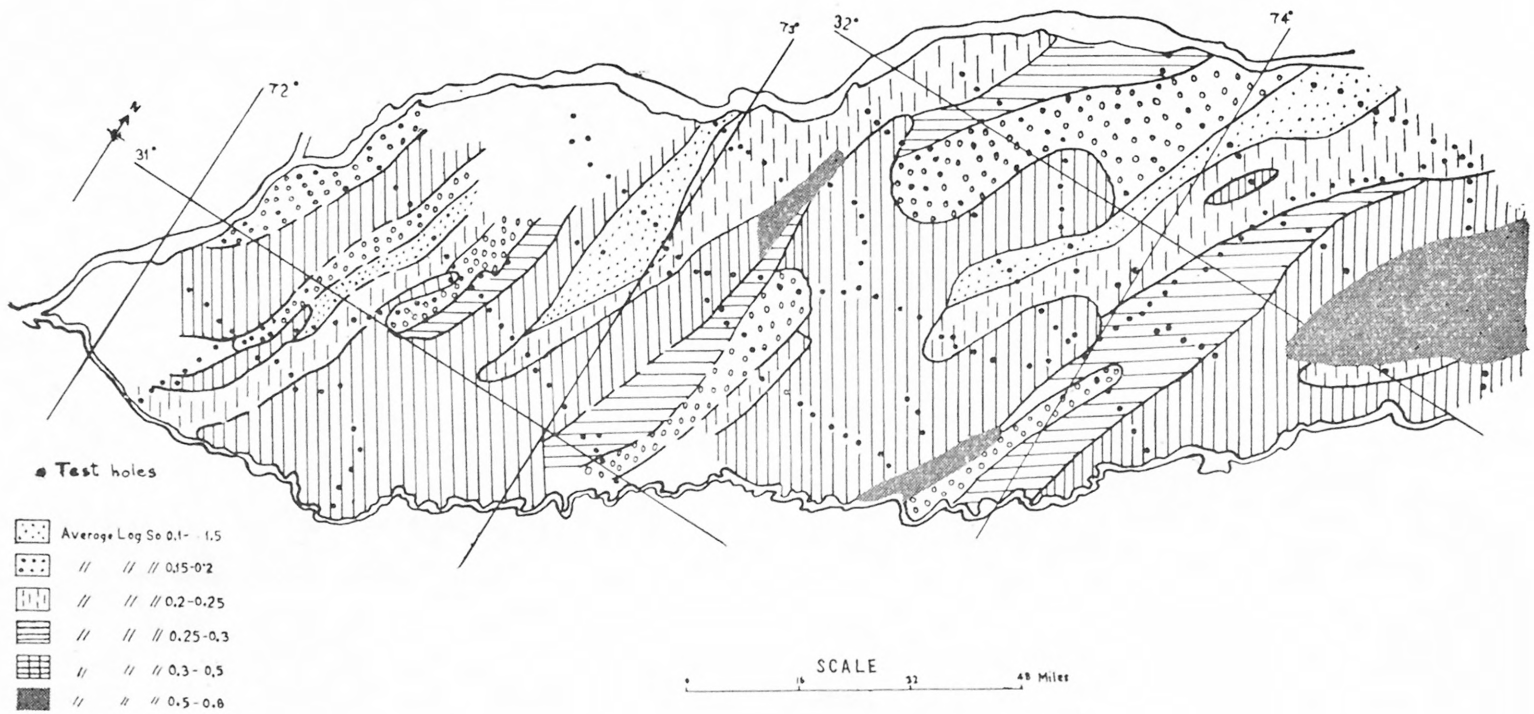

Figure 12.--Map of Rechna Doab, West Pakistan, showing a log of sorting coefficient.

(Illustration from Kazmi, A. H., 1961)

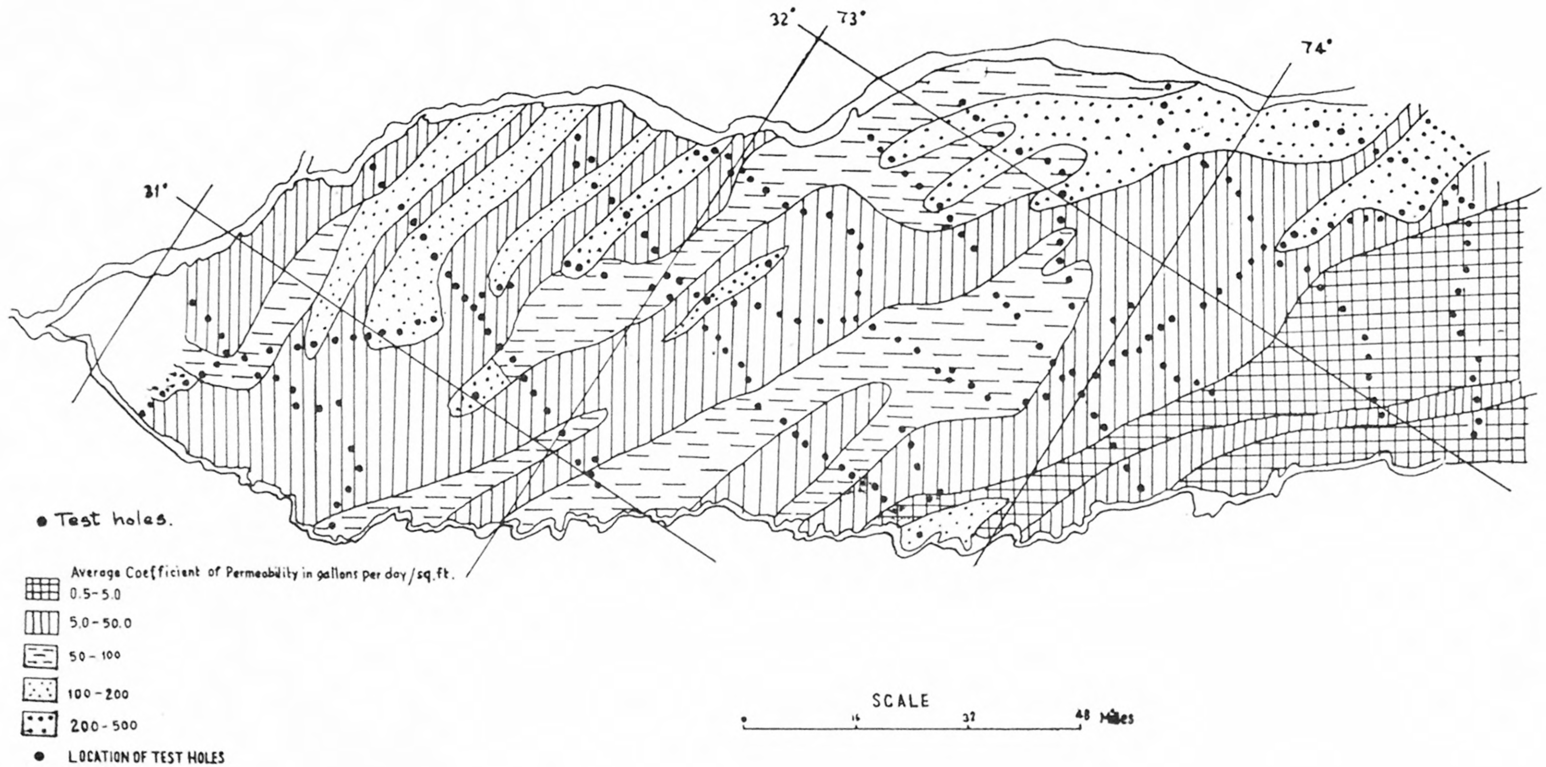

Figure 13.--Map of Rechna Doab, West Pakistan, showing average coefficient of permeability.

(Illustration from Kazmi, A. H., 1961)

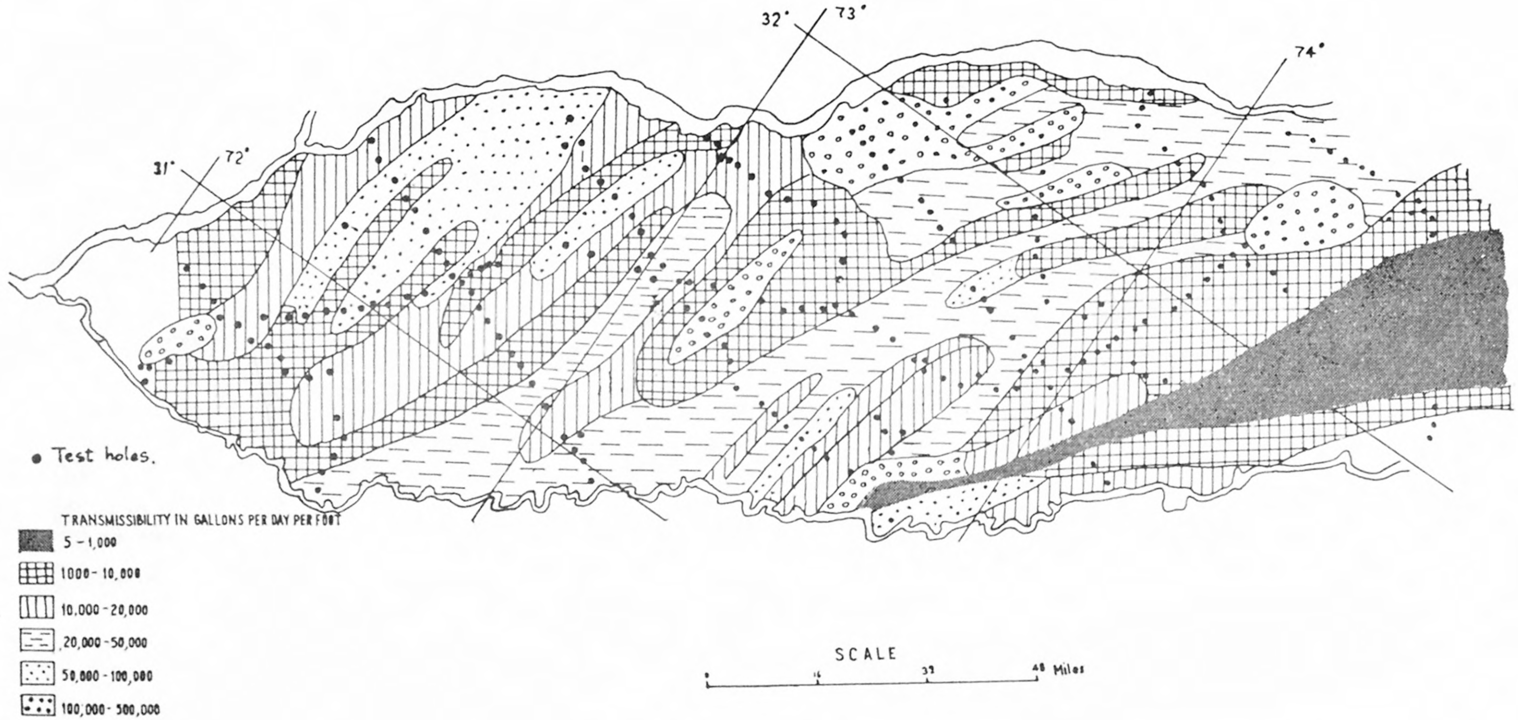

Figure 14.--Map of Rechna Doab, West Pakistan, showing transmissibility.

(Illustration from Kazmi, A. H., 1961)

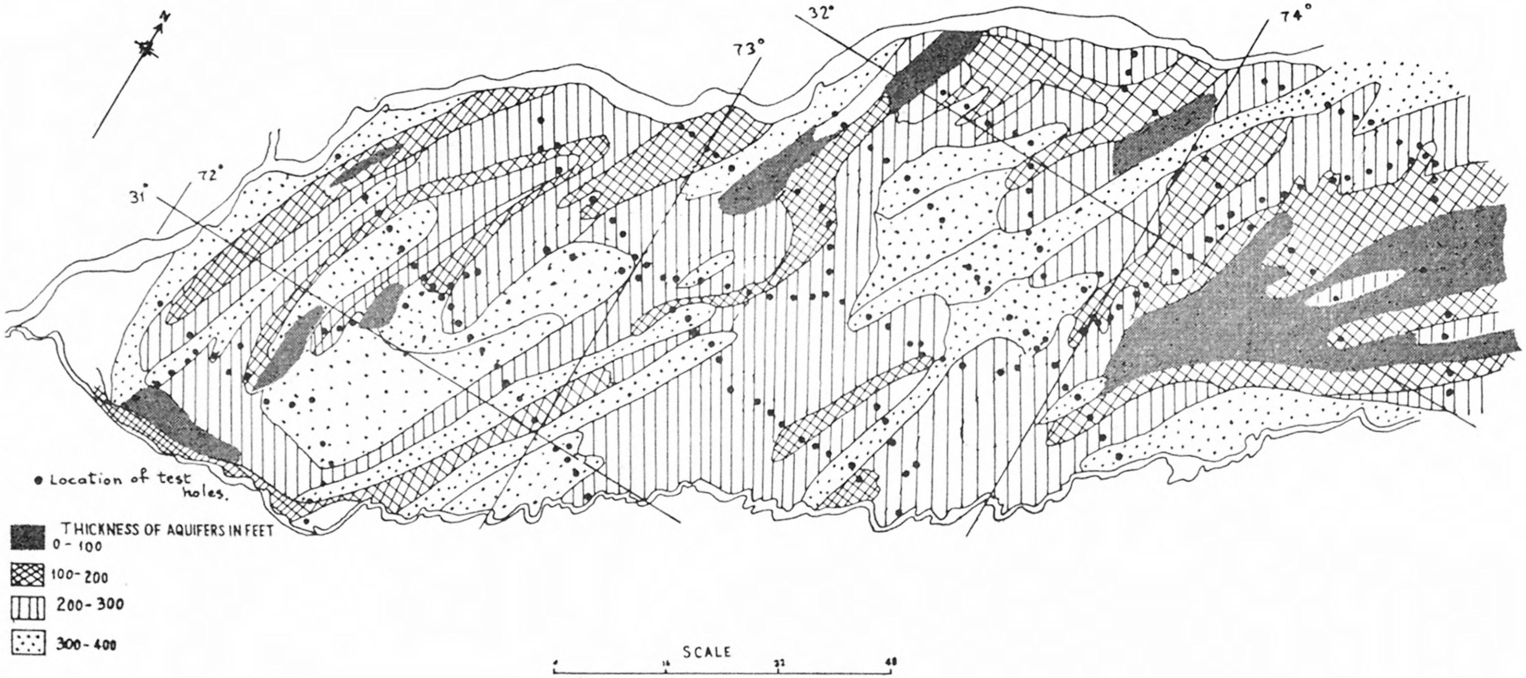

Figure 15.--Map of Rechna Doab, West Pakistan, showing thickness of aquifers.

Geohydrologic Cross-Sections

To completely understand subsurface hydraulic conditions, a geohydrologic cross-section is valuable. The cross-section is based on test-hole logs and laboratory and aquifer-test data and the interpretation of the geology. Patterns may indicate the hydrologic properties or permeability values at specific sample locations may be shown by the test hole or within the lithologic unit. In any case, it becomes obvious that there is little difference between a geologic and a geohydrologic cross-section, except for putting quantitative numbers on the geology. Figure 16 demonstrates the principle and figures 17 through 19 present examples of published applications.

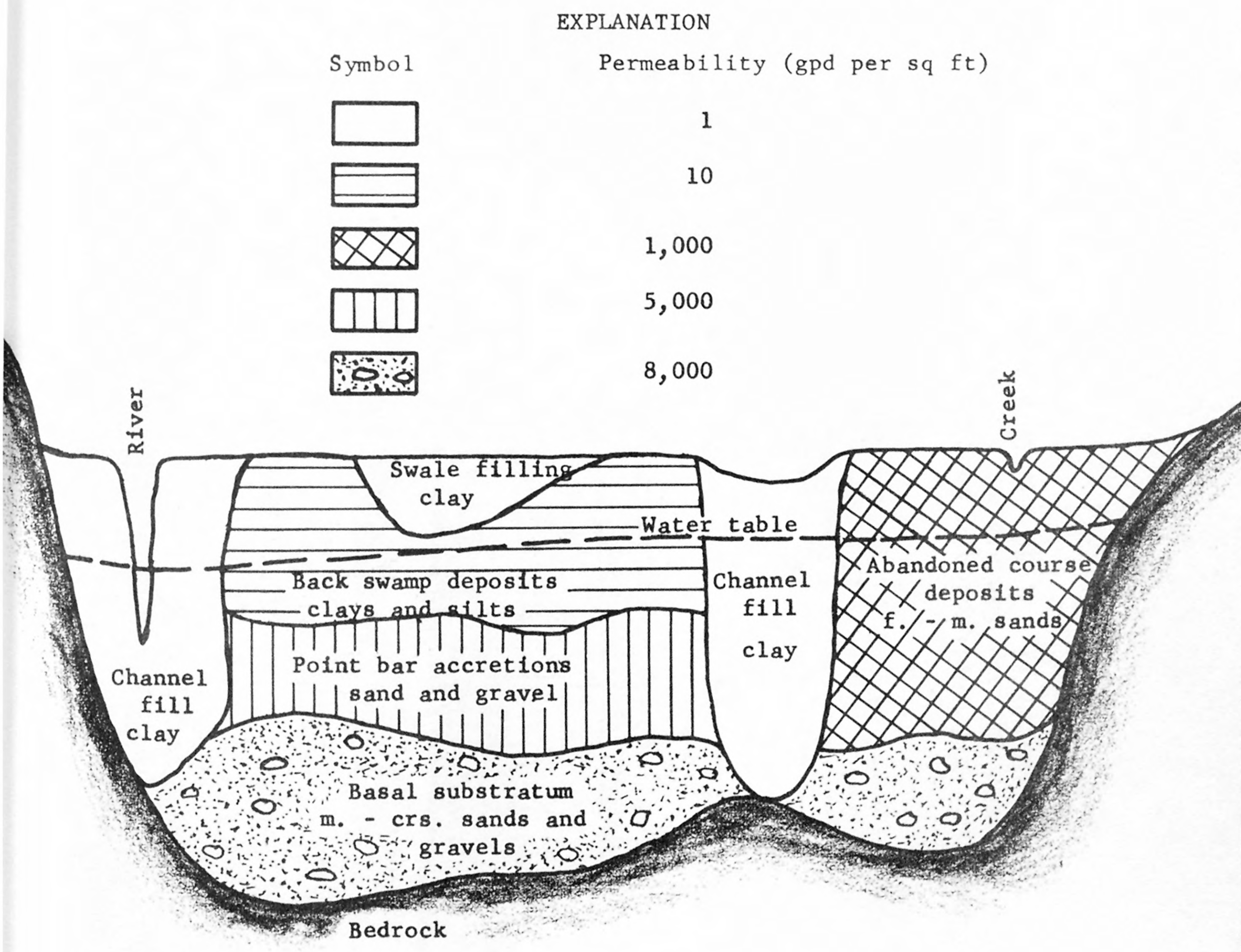

Figure 16.--Geohydrologic cross-section of alluvial deposits.

(Illustration from DeRidder, N. A., 1961)

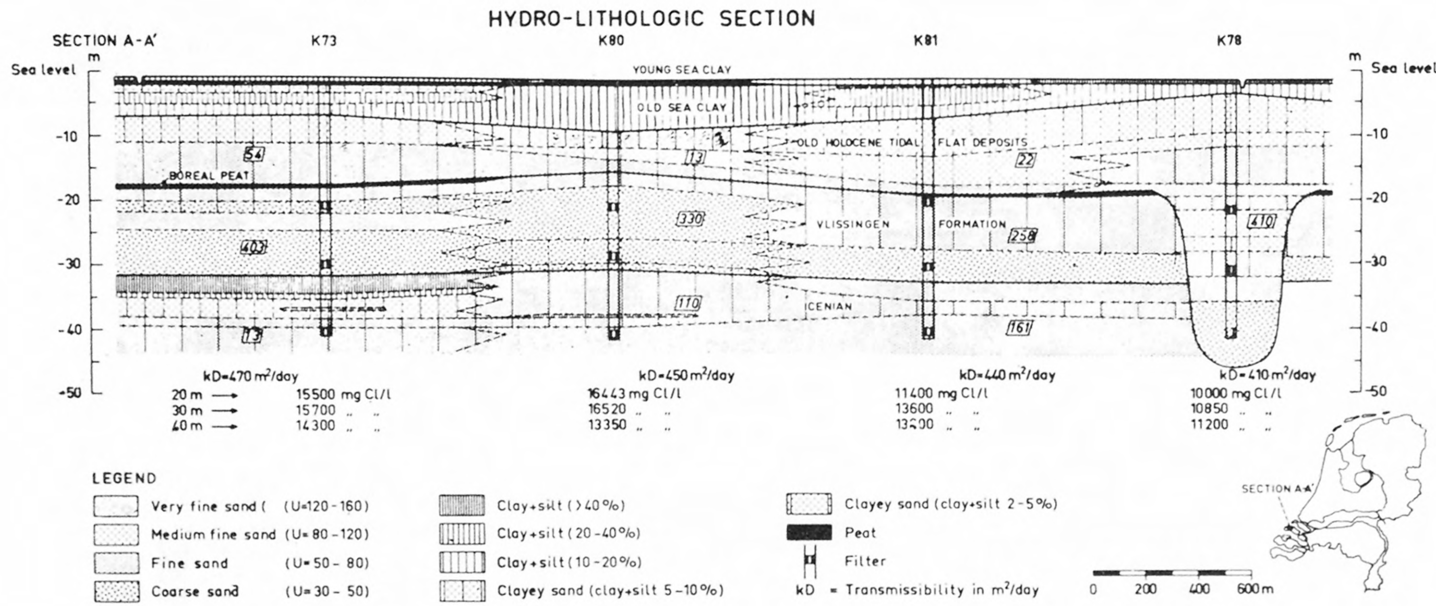

Figure 17.--Hydro-lithologic section showing lithologic units and transmissibility of the various formations and the chloride content in mg/l of the deep groundwater at 20, 30 and 40 m below soil surface.

(Illustration from Bedinger, M. S., Tanaka, H. H., and others, 1960)

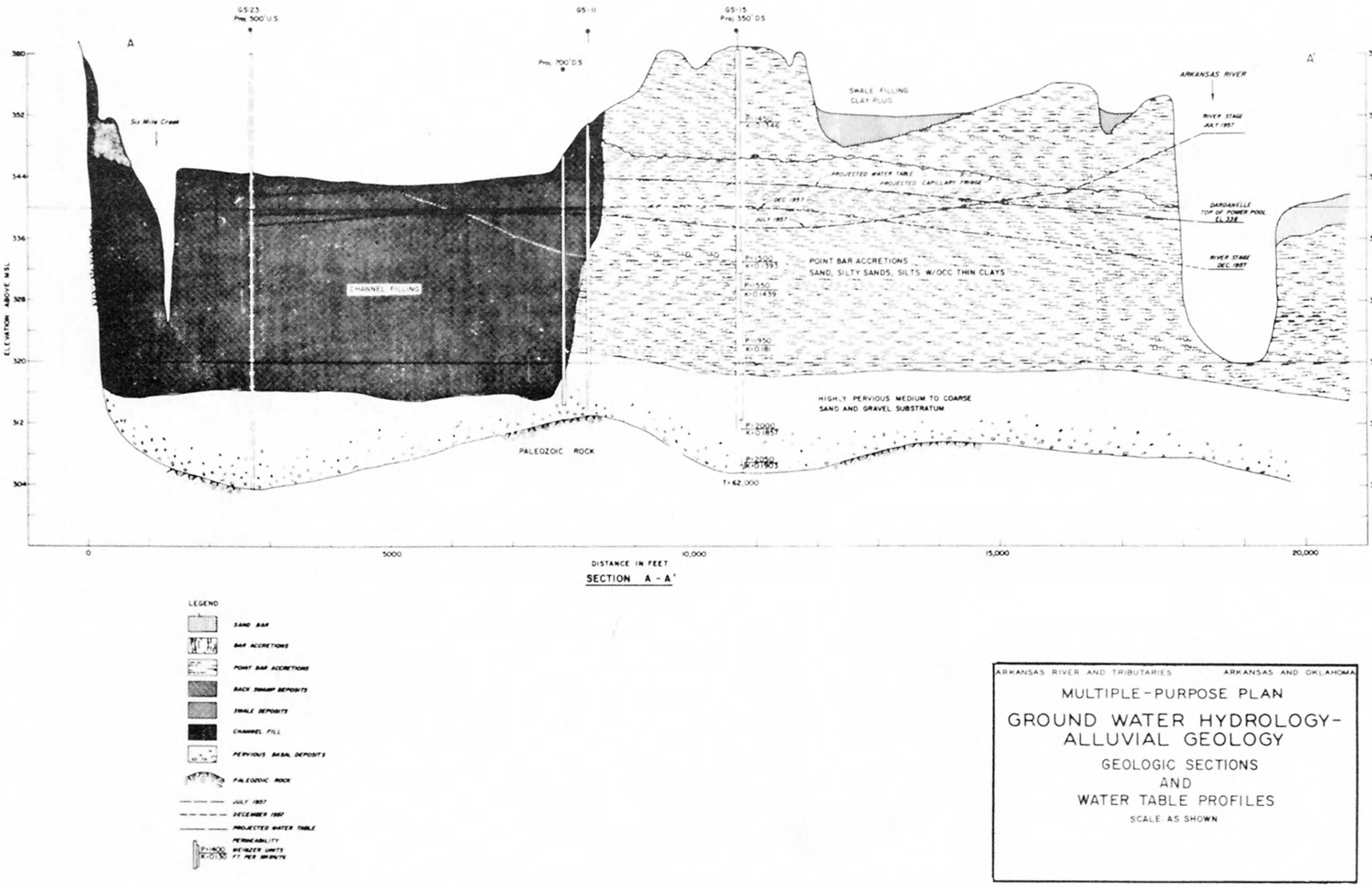

Figure 18.--Geologic sections and water table profiles, Arkansas River Valley, Ark.

(Illustration from Bedinger, M. S., Tanaka, H. H., and others, 1960)

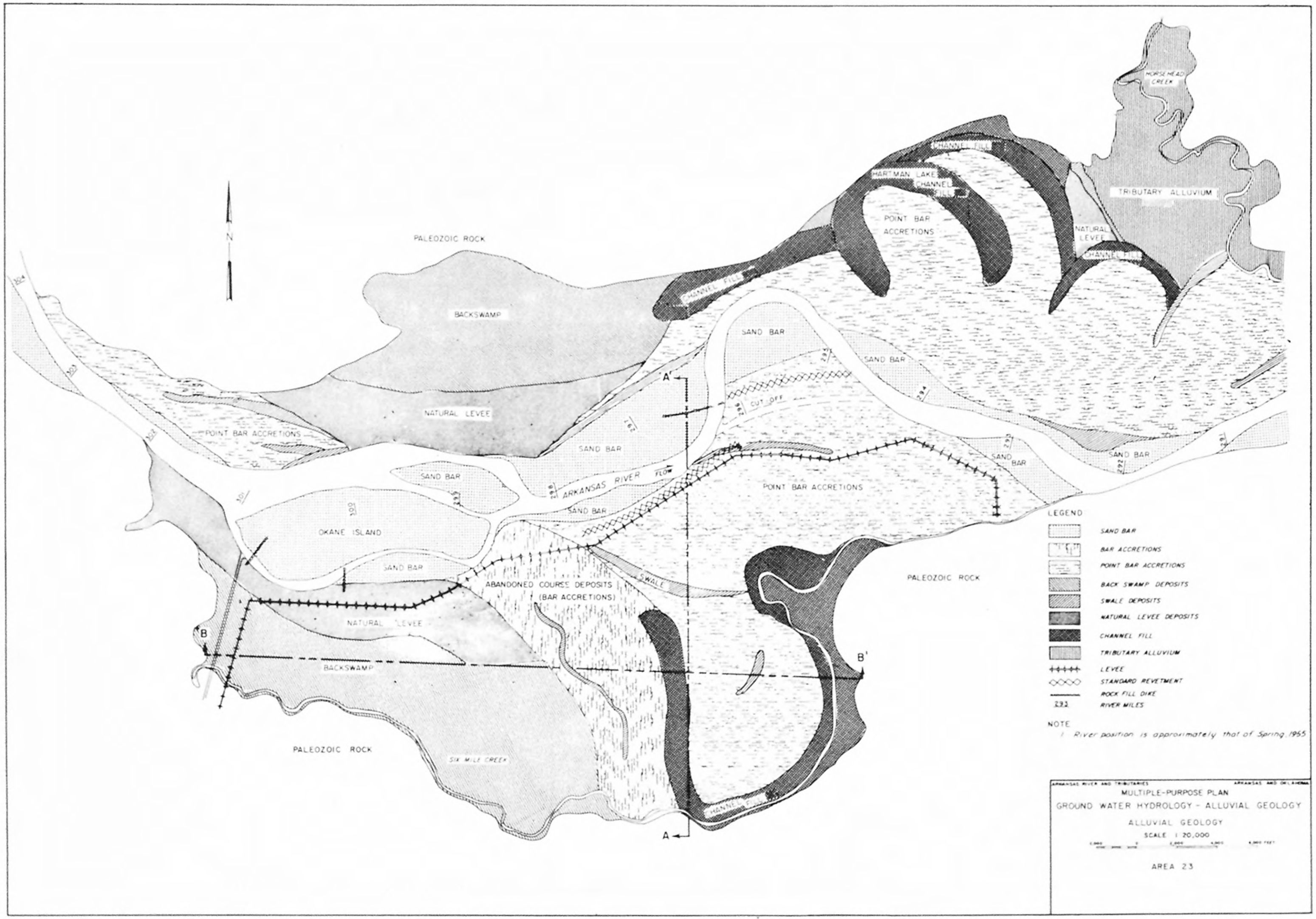

Figure 19.--Alluvial geology showing location of cross-sections, Arkansas River Valley, Ark.

Permeability of Rock and Soil Materials

Although the best permeability data are those obtained from analysis of samples actually obtained from the study area, projects may not always have time or funds to collect the samples or have them analyzed. Figures 20 through 24 and table 4 are presented to provide the project hydrologist with a working list of permeability coefficients representative of the rock or soil materials found in his area. In most cases, the data or relationships result from research in the Hydrologic Laboratory.

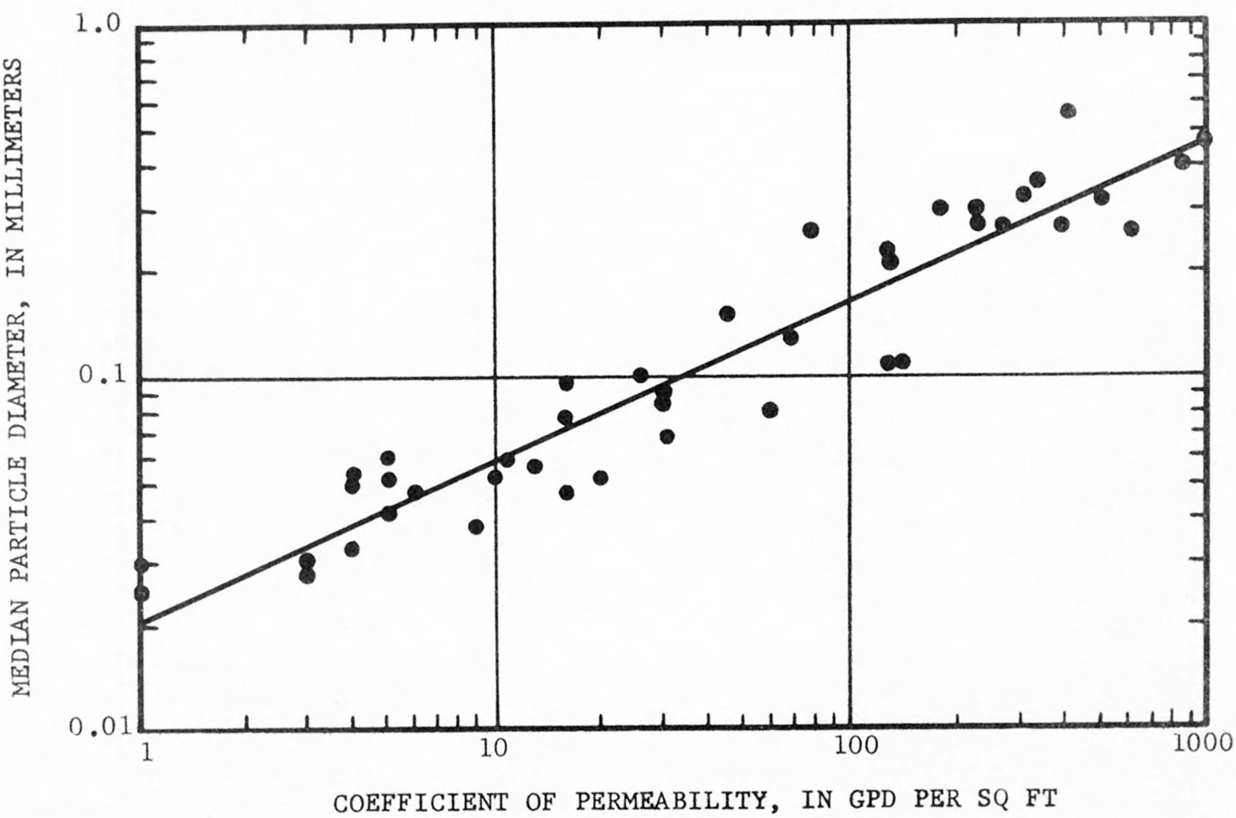

Figure 20.--Relation of permeability to particle size for alluvial sediments near Chapman, Nebr.

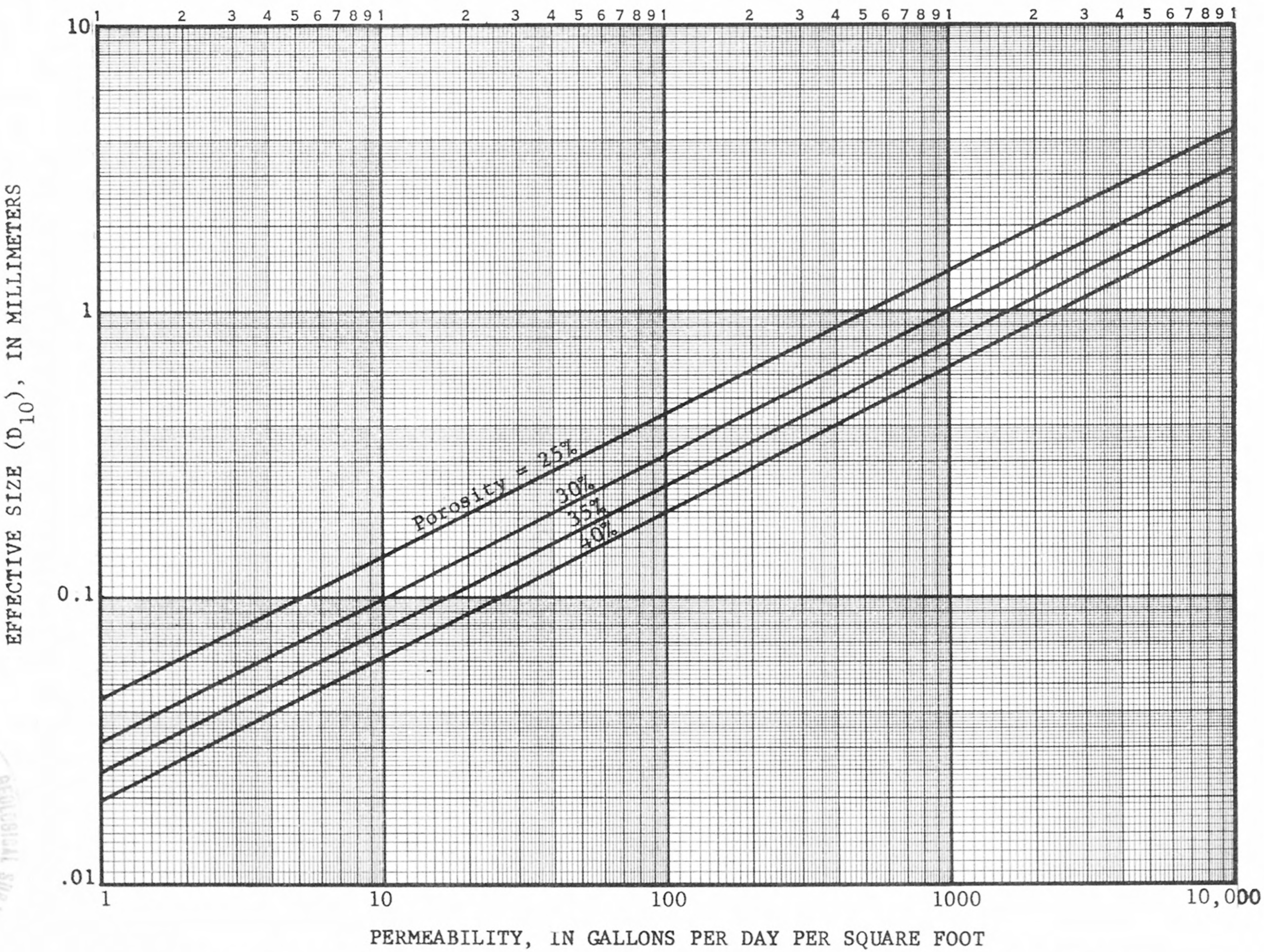

Figure 21.--Relationship between effective size, porosity, and permeability. (After Turneaure, F. E., and Russell, H. L., 1947)

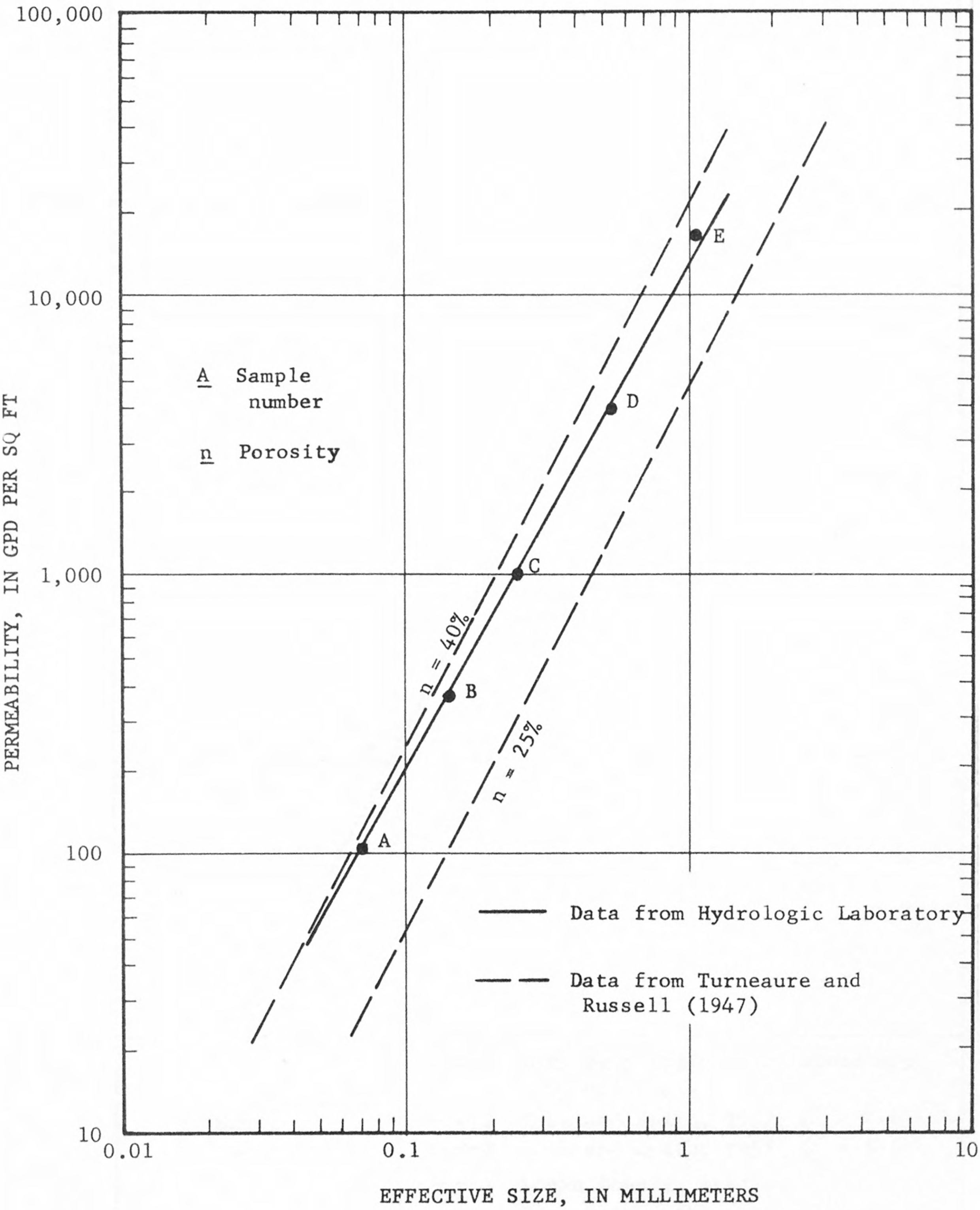

Figure 22.--Relationship of permeability to effective size.

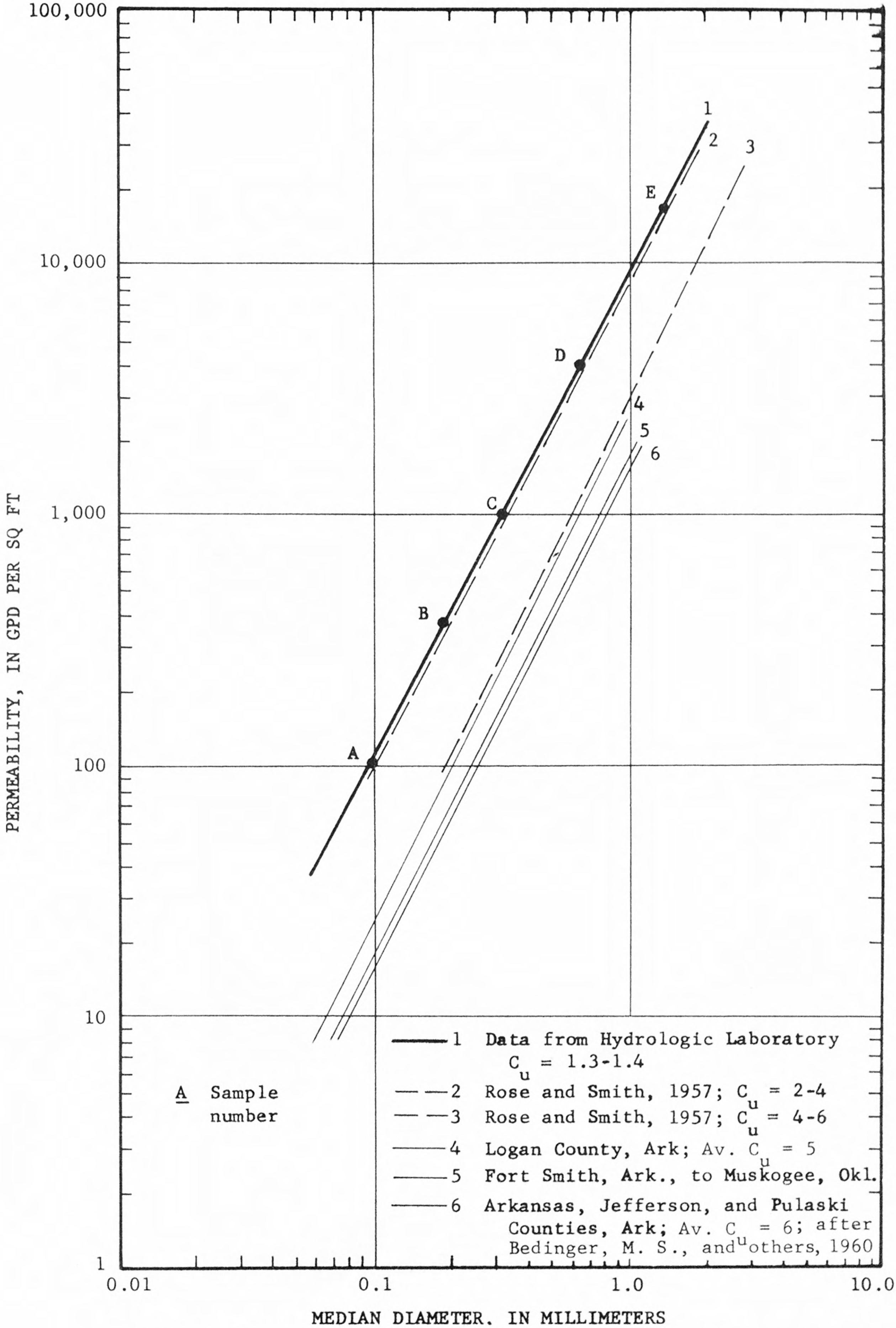

Figure 23.--Relationship of permeability to median diameter.

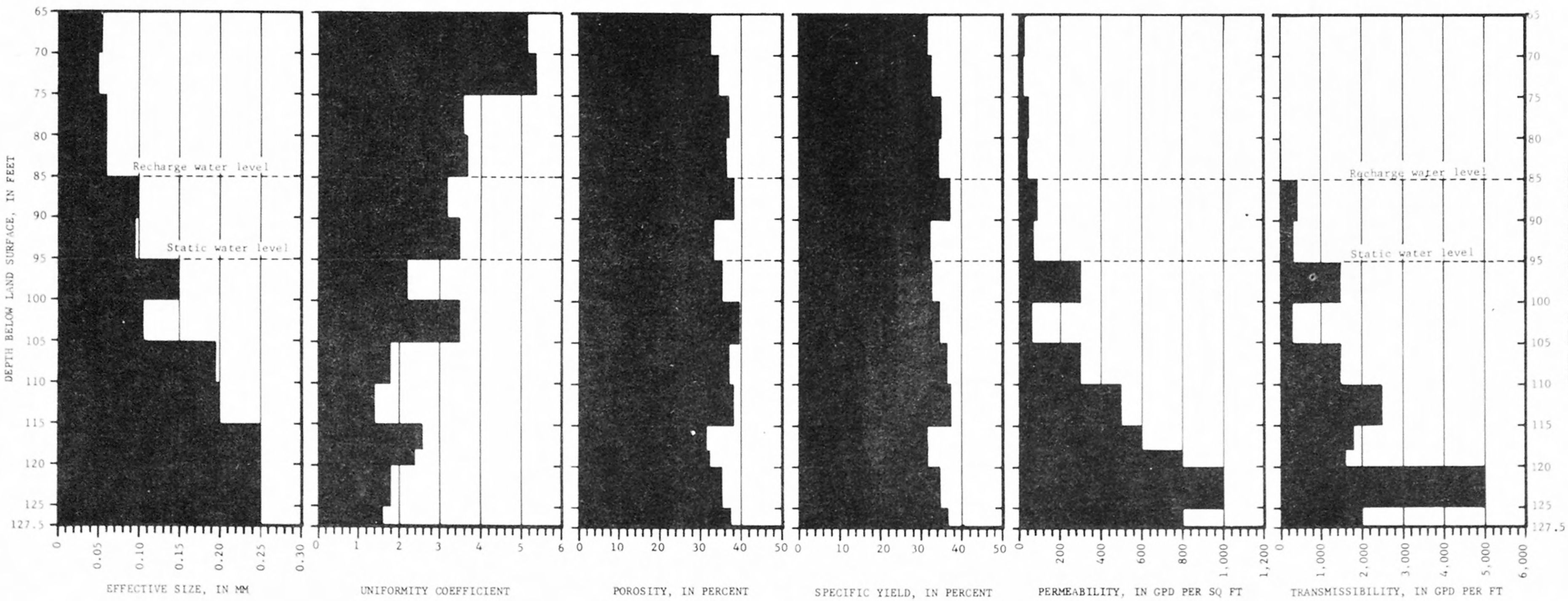

Figure 24.--Composite graph of aquifer properties for test hole L3S-4W-3dca14, Artificial Recharge Project, Ark.

Table 4.--Typical coefficients of permeability.

Material	Permeability (gpd per sq ft @ 60°F)
Granite	0.0000009 - 0.000005
Slate	0.000001 - 0.000003
Dolomite	0.00009 - 0.0002
Hematite	0.000002 - 0.009
Limestone	0.00001 - 0.002
Gneiss	0.0005 - 0.05
Basalt	0.00004 - 1
Tuff	0.0003 - 10
Sandstone	0.003 - 30
Till	0.003 - 0.5
Loess	1 - 30
Beach sand	100 - 400
Dune sand	200 - 600
Alluvium	(see individual materials below)
Clay	0.001 - 1
Silt	1 - 10
Very fine sand	10 - 100
Fine sand	100 - 1,000
Medium sand	1,000 - 4,500
Coarse sand	4,500 - 6,500
Very coarse sand	6,500 - 8,000
Very fine gravel	8,000 - 11,000
Fine gravel	11,000 - 16,000
Medium gravel	16,000 - 22,000
Coarse gravel	22,000 - 30,000
Very coarse gravel	30,000 - 40,000
Cobbles	Over 40,000

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