Laboratory Study of Aquifer Properties and Well Design for an Artificial-Recharge Site

By A. I. JOHNSON, R. P. MOSTON, *and* S. F. VERSAW

ARTIFICIAL RECHARGE OF GROUND WATER—GRAND PRAIRIE REGION, ARKANSAS

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ABSTRACT

The first phase of study of artificial recharge through wells in the Grand Prairie region of Arkansas was the collection of detailed geologic and hydrologic data from the proposed test site. Hydrologic and physical properties of the aquifer were determined from analysis of samples taken at the recharge well and from nearby test holes. The samples were analyzed in the Hydrologic Laboratory of the U.S. Geological Survey.

Using laboratory-analysis data, quantitative aquifer characteristics were estimated—a coefficient of transmissibility of 60,000 gallons per day per foot and a specific yield, or coefficient of storage, of about 0.34. Laboratory data also were used to predict a specific capacity of 30 gallons per minute per foot of drawdown for the proposed recharge well.

The aquifer is fairly uniform in particle-size distribution; gravel content is highest in the basal Quaternary sediments deeper than 115 feet, where the median diameter is about 0.5 mm and the uniformity coefficient between 1 and 2. The upper Quaternary sands are less uniform; they consist mostly of very fine particles having a median diameter near 0.1 mm and a uniformity coefficient averaging about 16.

Particle-size analyses were used to develop filter-pack (gravel-pack) and well-screen designs for recharge well 2. An artificially placed filter pack was recommended for the aquifer below 115 feet in depth. A 1.6-mm (0.064 in., or No. 60) slot was recommended for the well screen, combined with a filter pack made up of material having a median diameter of about 2 mm.

Construction of recharge well 2 did not conform to design specifications. The filter pack had a median particle diameter of about 0.7 mm, or approximately one-third the size originally recommended, and the screen had only a 0.016-inch slot. A decrease in permeability was observed during the test of recharge well 2, and laboratory experiments confirmed the belief that this reduction was due to the design of the filter pack and the manner of its placement. The experiments indicated that compaction of the filter pack caused by surging action from well development and from pumping and injection tests, could cause a permeability reduction of approximately 25 percent.

INTRODUCTION

The Grand Prairie region of Arkansas was selected by the U.S. Geological Survey in 1953 as the site for fundamental research on recharging ground-water reservoirs through wells. An apparently continuous aquifer underlying the Grand Prairie provides water for the irrigation of rice. Rice has been grown in this region since 1904, and since 1915 more than 135,000 acres has been devoted to this crop each year. Continual pumping of water from Quaternary deposits to irrigate this large rice acreage has caused a serious overdraft on the ground-water supply. The average water-level decline from 1910 to 1958 was approximately 1 foot per year. Thus, this region is a large natural laboratory for studies of artificial recharge of ground water.

Detailed hydrogeological data were obtained to evaluate and analyze artificial-recharge theory and practice. Initial project activities consisted of test drilling, collection of samples, installation of observation wells, and collection of hydrologic data. A later phase of the study included drilling two recharge wells, constructing water-treatment and water-conveyance facilities, and making a series of pumping and injection tests at the two recharge wells.

This is one of a series of reports on the different phases of the recharge study. (See Engler and others, 1963; Sniegocki, 1959, 1963a, b; Sniegocki and others, 1963; Sniegocki and others, 1965; Sniegocki and Reed, 1963.) In 1958 the senior author compiled unpublished information on the hydrologic and physical properties of the aquifer at the recharge site; at the same time he proposed a design, based on the properties of the aquifer, for the well screen and filter (gravel) pack for recharge well 2. The present report combines the unpublished information of 1958 with results of later laboratory research on how the filter pack used in recharge well 2 affected water movement into that well.

Quantitative analyses of aquifer samples and laboratory studies of the filter pack were made in the Hydrologic Laboratory, U.S. Geological Survey, Denver, Colo., under the direction of A. I. Johnson, chief of the laboratory, by R. P. Moston, S. F. Versaw, Eugene Shuter, I. M. Bloomgren, A. H. Ludwig, and C. R. Jones.

X-ray analyses of samples collected at the artificial-recharge test site were made by L. B. Riley and A. J. Gude at the Geochemistry and Petrology Laboratory, U.S. Geological Survey, Denver, Colo.

This investigation was made under the general direction of R. T. Sniegocki, artificial-recharge project leader and district geologist in charge of ground-water investigations in Arkansas.

AREA OF INVESTIGATION

GEOGRAPHY

The study area is in the Grand Prairie region in east central Arkansas. This large flat prairie is within the Mississippi Alluvial Plain, a subdivision of the Coastal Plain province. It is an irregular, but nearly continuous, tract of prairie between the White River and Bayou Meto extending from near the confluence of the White and Arkansas Rivers northwestward to a short distance beyond Lonoke in Lonoke County. All of Arkansas County and parts of Lonoke, Prairie, and Monroe Counties are in the Grand Prairie region.

The study area covers about 210 square miles in Arkansas County; the Rice Branch Experiment Station of the University of Arkansas is near the center. (See Sniegocki and others, 1963, fig. 14.) The experiment station, covering three-quarters of a square mile in sec. 3, T. 3 S., R. 4 W., was the site of the artificial-recharge tests.

HYDROGEOLOGY

Most detailed study of the hydrology and geology was limited to the area of the Rice Branch Experiment Station and the surrounding 24 square miles (Sniegocki, 1963a). A brief résumé in this report provides background for understanding the laboratory study of aquifer materials.

Sniegocki (1963a) stated that Cretaceous formations of marine origin are about 3,000 feet deep throughout the study area and are unconformable with overlying Tertiary and Quaternary deposits. No water wells are known to tap Cretaceous formations. Tertiary rocks consisting principally of sand, silt, clay, limestone, and lignite underlie Quaternary deposits that blanket the region. Total thickness of Tertiary rocks may be as great as 3,500 feet.

A generalized geologic section of Tertiary and Quaternary formations in Arkansas County is shown in table 1. Quaternary deposits include Pleistocene and Recent Sediments which have not been satisfactorily differentiated in this region.

Quaternary alluvium blankets the Grand Prairie region and ranges in thickness from 75 to 200 feet (fig. 1). The basal Quaternary zone is 25–140 feet thick and consists of very fine to coarse sand and very fine to very coarse gravel complexly interbedded with thin clay and silt lenses. Cobbles and boulders are common in the lower part of the basal zone.

The upper zone, 5–60 feet thick, consists of very dense silt and clay layers that are remarkably continuous over much of the Grand Prairie region. These impermeable sediments make ground-water replenishment by artificial recharge from wells more practicable than replenishment from surface installations. However, some natural recharge is probable in areas where sands of the lower zone are very near the surface.

The aquifer—the basal Quaternary zone—is continuous and relatively homogeneous at the recharge site and in these respects is probably representative of the aquifer throughout the Grand Prairie.

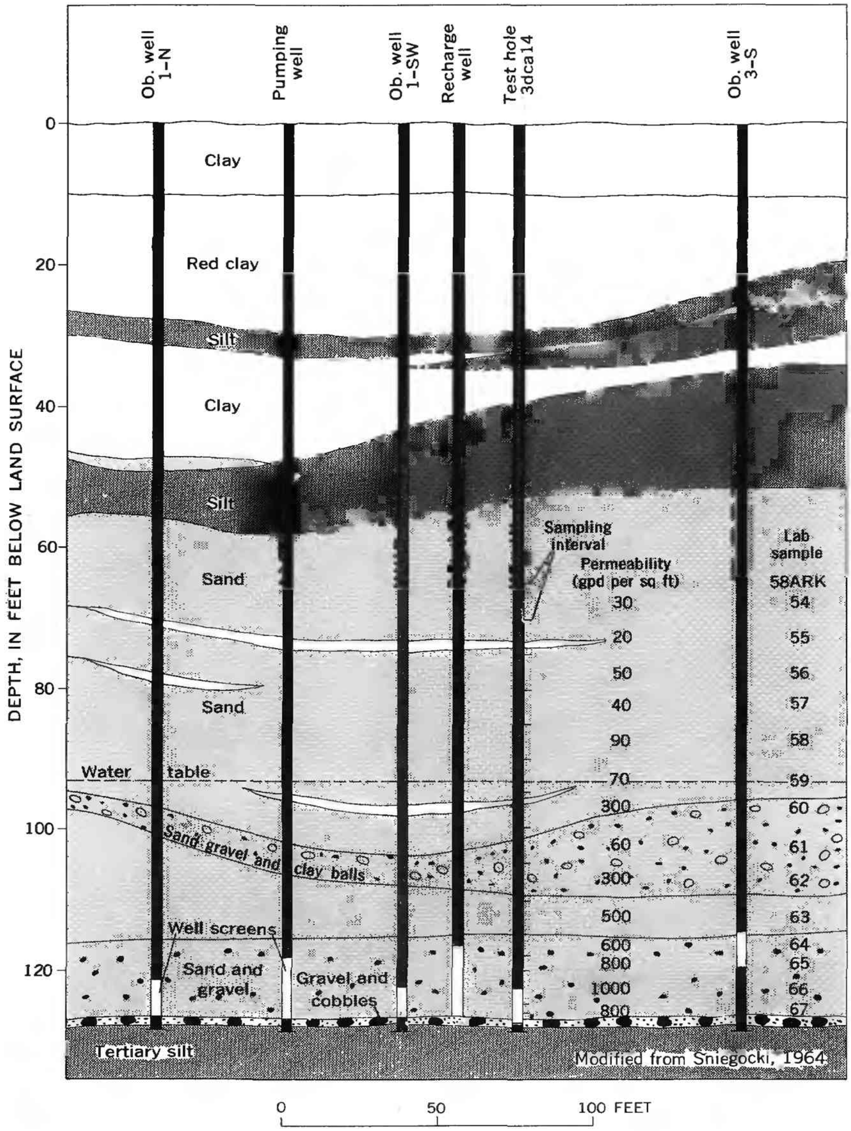


FIGURE 1.—Geologic section in area of recharge well.

TABLE 1.—*Generalized geologic section for Arkansas County*

[After Sniegocki (1964)]

System	Series or epoch	Group	Thickness (feet)	Character	Water-bearing characteristics
Quaternary	Recent and Pleistocene (undifferentiated)		75–200	Relatively impermeable silt and clay; 5–60 feet thick. Very fine to coarse sand and gravel, interbedded with thin silt and clay lenses; 25–140 feet thick.	Sand and gravel beds yield abundant supplies of water and are the principal aquifer in the Grand Prairie region.
Tertiary	Eocene	Jackson	100–350	Clay, sand, and lignite	Not a source of water.
		Claiborne	750–1,400	Sand, thin clay beds, and lignite.	Source of water for deep wells.
		Wilcox	850–1,200	Sand, clay, chalk, and lignite.	The sand is waterbearing, but most of the water is probably salty.
	Paleocene	Midway	450–750	Blue plastic clay, marl, and limestone.	Not a source of water.

Sniegocki (1963a) noted that a few thin lenses of silt, clay, and clay balls occur in the sand and constitute the only interruptions in continuity of the aquifer. The aquifer may be divided into two parts: a coarse-textured zone of gravelly sand, which is generally thicker in depressions of the underlying Tertiary surface; and an overlying medium-textured zone of sand, which generally becomes progressively finer textured upward. Test-hole logs indicate that the sands and gravels of the lower zone are complexly interfingered with the overlying sand.

WELL-NUMBERING SYSTEM

Well numbers in this report indicate locations with respect to the Federal Land Survey used in Arkansas. The first number is the township, north or south; the second number is the range, east or west; and the third number is the section in which the well is located. Lowercase letters (a, b, c, d) designate the quarter section, the quarter-quarter section, and the quarter-quarter-quarter section, or 10-acre tract. Letters are assigned in a counterclockwise direction, beginning with "a" in the northeast quadrant. If two or more wells are within a 10-acre tract, the wells are numbered serially according to the order in which they are described.

223-829 O—66——2

The same numbering system is used for test holes and for wells from which samples were collected. The prefix "L" is used to denote the log of a test hole. Sniegocki (1964) described the well numbering system in more detail.

ACKNOWLEDGMENTS

The assistance of Mr. J. L. Mogg, of E. E. Johnson, Inc., St. Paul, Minn., in review of this manuscript is appreciated. The cooperation, assistance, and advice given by many Federal, State, and city agencies and by companies and individuals are gratefully acknowledged. Detailed acknowledgments were made by Sniegocki (1964).

AQUIFER PROPERTIES

LABORATORY ANALYSIS METHODS

Samples of water-bearing sediments were collected for laboratory analyses from test holes drilled in the vicinity of the artificial-recharge test site. These were disturbed samples obtained by a power auger or by bailing. Each sample was carefully mixed and quartered for shipment to the Hydrologic Laboratory.

Preparation for laboratory analysis began with the air-drying of these disturbed samples. The chunks of air-dried material were then gently but thoroughly separated into individual particles with a mortar and rubber-covered pestle. Care was taken not to crush the particles.

Samples were analyzed by means of standard methods described briefly in the following paragraphs. Additional information on theory and methods of analysis can be obtained from publications by the American Society for Testing Materials (1958) and by Johnson, A. I., and Morris (1962).

PARTICLE-SIZE DISTRIBUTION

Particle-size analysis, also termed "mechanical analysis," is determination of the distribution of particle sizes in a sample. Particles smaller than 0.0625 mm were separated by hydrometer; particles larger than 0.0625 mm, by wet-sieve analysis.

From hydrometer and sieve analyses, the percentage of particles smaller than a given size was calculated and plotted as a cumulative distribution curve. The particle sizes, in millimeters, were plotted as abscissas on a logarithmic scale; and the cumulative percentages of particles smaller than the size shown, by weight, as ordinates on an arithmetic scale. The percentage of size range was then determined from this curve. The size categories are as follows:

Description	*Diameter (mm)*
Gravel	>2.0
Very coarse sand	1.0–2.0
Coarse sand	0.5–1.0
Medium sand	0.25–0.5
Fine sand	0.125–0.25
Very fine sand	0.0625–0.125
Silt	0.004–0.0625
Clay	<0.004

This classification is used by the Water Resources Division, U.S. Geological Survey, and is identical with classifications proposed by Wentworth (1922) and the National Research Council (1947), except for their further subdivisions of gravel, silt, and clay. References to sand, silt, and clay in this report relate to sizes specified in the foregoing table.

PERMEABILITY

Permeability is the capacity of rock or unconsolidated material to transmit water under pressure. It can be determined in the laboratory by measuring the rate of water percolation through a sample of known length and cross-sectional area, under a known head loss.

The coefficient of permeability (k) used in ground-water studies by the U.S. Geological Survey is 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 (Wenzel, 1942). Because virtually pure water is specified, fluid density is neglected. Permeability in feet per year can be obtained by multiplying the coefficient of permeability by 48.8.

Coefficients of permeability were determined in constant-head and variable-head permeameters. Figure 2 illustrates the permeability apparatus used in the Hydrologic Laboratory of the U.S. Geological Survey.

Air entrapped in a sample may cause plugging of pore space, reducing the apparent coefficient of permeability. Thus, a specially designed vacuum system used in the Hydrologic Laboratory provides deaired tapwater as the percolation fluid. (See Johnson, A. I., and others, 1963, for chemical analysis of the water.)

The samples were repacked in the percolation cylinders of the permeameters using a specially designed packing machine (Morris and Johnson, 1966). The percolation cylinders then were installed directly in the permeability apparatus for the tests. The reported coefficient of permeability was the maximum value obtained after several test runs and represents saturation permeability.

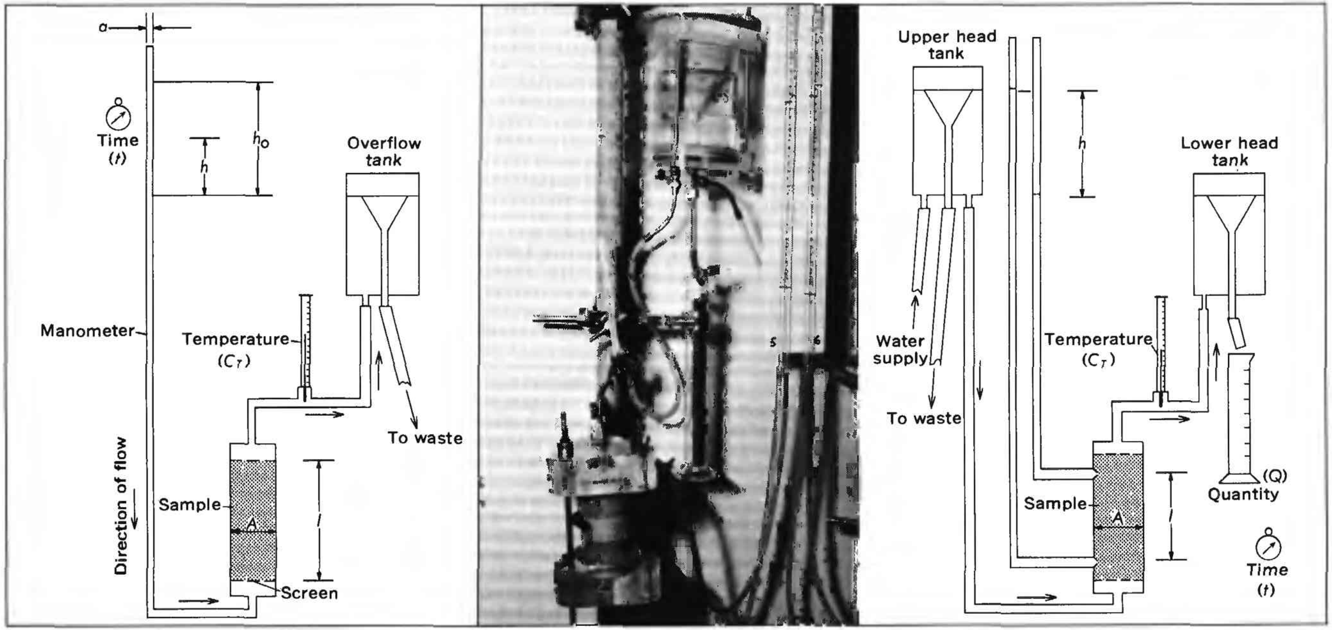


FIGURE 2.—Permeability apparatus. Left, Variable-head type, where $k=2.3\,\frac{al}{At}\log\frac{h_o}{h}\,C_T$. Right, Constant-head type, where $k=\frac{Ql}{At(\Delta h)}\,C_T$.

POROSITY

Porosity is the ratio of the volume of void spaces to the total volume of the rock or soil sample, expressed as a percentage.

Therefore $$n=\frac{V_v\,(100)}{V}=\frac{\gamma_s-\gamma_d}{\gamma_s}(100)$$

where

n = porosity, in percent,
V_v = volume of voids, in cubic centimeters,
V = total mass volume, in cubic centimeters,
γ_s = unit weight of particles, in grams per cubic centimeter (in metric system, equal numerically to specific gravity of solids),
γ_d = dry unit weight of repacked sample, in grams per cubic centimeter.

After dry unit weight (repacked) and specific gravity of the sample solids were determined, porosity was calculated using the foregoing equation.

SPECIFIC YIELD

Specific retention of a rock is the percentage of total rock volume occupied by water which will not be yielded to the pull of gravity after the rock is saturated with water.

Specific yield of a rock is the pore space that will yield water to wells and is equal to porosity of the rock minus its specific retention. It is water that the rock yields by gravity after it is saturated with water.

Centrifuge moisture equivalent of a rock is the amount of water, expressed as a percentage of the dry weight, retained by the material which has been saturated with water and then subjected to a force equal to 1,000 times the force of gravity for 1 hour. The centrifuge moisture equivalent is multiplied by the dry-unit weight to obtain the moisture equivalent by volume. Johnson, A. I., Prill, and Morris (1963) discussed the centrifuge test in detail.

The centrifuge moisture equivalent, converted to percent of volume, was determined and then adjusted by a correction factor proposed by Piper (1933). This adjusted value was considered to be equivalent to the specific retention. The specific retention was then subtracted from the porosity to obtain the specific yield.

RESULTS AND INTERPRETATION OF LABORATORY ANALYSES

Fourteen samples (58ARK54–67) from the basal Quaternary zone were collected from test hole L3S–4W–dca14, which was drilled by the U.S. Army Corps of Engineers 20 feet west of recharge well

2(L3S–4W–dca16). These disturbed samples were obtained by bailing inside a 5-inch casing. Care was used to make sure that the bailer was picking up material only at the end of the 5-inch casing. New lengths of casing were added as bailing progressed and the hole was deepened. The sediments were kept from heaving upward inside the casing by a head of clear water maintained over the bailer as it was operated. Each sample removed from the bailer was carefully mixed and quartered for collection prior to shipment to the Hydrologic Laboratory. The log of the test hole is given in table 2. The static water level at this location is approximately 95 feet. A water level of approximately 85 feet resulted during a recharge test (300 gpm) at recharge well 2.

By use of a power auger, three disturbed samples (59ARK44–46) of the upper Quaternary sands were collected from three test holes in the vicinity of the artificial-recharge test site. Care was taken to insure that the auger was bringing to the surface only material from the end of the auger flights. The sample material was carefully mixed and quartered and shipped to the laboratory for analysis.

There is no reason to believe that particle-size characteristics of the samples are not representative of the particle sizes of the aquifer at the artificial-recharge site. However, the samples had to be repacked for other analyses, and the data from these analyses are not entirely representative of data which might be obtained from the undisturbed sediments. The coarsest materials undoubtedly were not brought to the surface and, because of this, measured permeabilities are probably lower than they would be under undisturbed and representative conditions.

The results of the laboratory analyses are summarized in table 3 and presented in figures 3–7.

PARTICLE-SIZE DISTRIBUTION

Although some variation in particle-size distribution is evident, the materials are remarkedly uniform, with the deeper samples being the coarsest and the most uniform. Particle-size distribution curves for the basal sediments from test hole L3S–4W–3dca14 (figs. 3–6) show that gravel content (2–12 percent) is highest, and silt and clay content (<1 percent) lowest, in sediments deeper than 115 feet.

Particle-size distribution curves for samples from test holes 5S–3W–17ddd1, 5S–2W–36abb1, and 5S–5W–13aaa1 are shown in figure 7. The graph shows that the upper Quaternary deposits are predominately very find sand (46–50 percent) and have a much greater silt and clay content (21–44 percent) than the basal sediments.

Although the lower sediments are very uniform, lithologic breaks do occur as thin discontinuous clay lenses and clay-ball zones.

TABLE 2.—*Log of test hole L3S–4W–3dca14*

[Location: About 1,260 ft north of section-line road, about 50 ft west of access road and 20 ft west of recharge well 2 (L3S–4W–3dca16). Surface alt, 203 ft. After Sniegocki (1964)]

	Thickness (feet)	Depth (feet)	Lab. sample No.
Road fill, soil, silt, light-gray; contains organic material	1	1	No sample.
Clay, very silty; variegated from light gray to medium reddish brown to light yellowish brown; small iron nodules	9	10	No sample.
Clay, dark-reddish-brown; light-gray streaks	1	11	No sample.
Clay, dark-reddish-brown; very calcareous; contains calcareous modules; sandy to silty lenses at 30 ft and shell fragments at 35 ft	29	40	No sample.
Clay, medium- to dark-brown; very calcareous; some bluish-gray clay and shell fragments	3	43	No sample.
Silt, clayey to sandy, light-bluish-gray; micaceous; very calcareous; iron-stained zones and thin clay lenses	7	50	No sample.
Sand, very fine to fine; slightly to very silty; micaceous; light-bluish-gray; very calcareous; may contain some clay	15	65	No sample.
Sand, fine to medium, light-bluish-gray; calcareous in part; some very fine and very coarse sand; well-rounded slightly frosted crystal quartz grains are the predominant mineral	5	70	58ARK54
Sand, fine to medium, dark-bluish-gray; calcareous in part; some very fine and coarse sand; dark-bluish-gray clay lens at 74 ft	5	75	58ARK55
Sand, fine to medium, dark-bluish-gray; calcareous in part; some very fine and coarse sand; thin medium-yellowish-brown and bluish-gray clay lenses at 78 ft	5	80	58ARK56
Sand, fine to medium, dark-bluish-gray; calcareous in part; wood fragments at 83.5 ft	5	85	58ARK57
Sand, fine to medium, light-bluish-gray; calcareous in part; silt and very fine to very coarse sand; dark-reddish-brown clay lens at 87 ft	5	90	58ARK58
Sand, fine to medium, light-bluish-gray; calcareous in part; some fine and some coarse sand; well-rounded slightly frosted crystal quartz grains are the predominant mineral	5	95	58ARK59
Sand, fine to medium, light-bluish-gray; calcareous in part; some very fine and coarse sand	5	100	58ARK60
Sand, fine to coarse, light-bluish-gray; calcareous in part; some very fine and very coarse sand; lenses of very clayey sand, clay, and clay balls at 102–104 ft	5	105	58ARK61

TABLE 2.—*Log of test hole L3S–4W–3dca14*—Continued

	Thickness (feet)	Depth (feet)	Lab. sample No.
Sand, fine to medium, light-bluish-gray; calcareous in part; some very fine and coarse sand; scattered clay balls and clay	5	110	58ARK62
Sand, fine to medium, light-bluish-gray; calcareous in part; scattered very fine, coarse, and very coarse sand	5	115	58ARK63
Sand, medium to very coarse, light-bluish-gray; calcareous in part; some fine sand and about 10 percent very fine to medium gravel	3	118	58ARK64
Same as unit immediately above	2	120	58ARK65
Sand, medium to coarse, light-bluish-gray; calcareous in part; some fine sand and larger amounts of very coarse sand to medium gravel; scattered pebbles	5	125	58ARK66
Sand, medium, light-bluish-gray; calcareous in part; coarse to very coarse sand and scattered very fine to fine gravel	2. 5	127. 5	58ARK67
Boulders, cobbles, and pebbles at top of deposits of Tertiary age; very clayey very sandy medium-olive-gray silt; many badly weathered fossil shells	. 5	128	No sample.

STATISTICAL MEASURES

It is convenient for purposes of comparison and statistical analysis, to express characteristics of particle-size distribution (mechanical-analysis) curves as numbers.

The measure of central tendency is the value (size of particle) about which all other values (sizes) cluster. One measure of central tendency is the median diameter, defined as that particle diameter which is larger than 50 percent of the diameters and smaller than the other 50 percent. It is determined by reading the particle diameter at the point where the cumulative curve intersects the 50-percent line.

Quartile deviation is a measure of particle-size spread. Quartiles are the particle diameter values at the intersections of the distribution curve with the 25 (Q_1), 50 (Q_2), and 75 (Q_3) percent lines. By convention, Q_3 (third quartile) is always taken as the larger value, regardless of the manner of plotting. The geometrical quartile deviation, or the "sorting coefficient" (*So*) of Trask (1932, p. 70–72), is represented by the equation

$$So=\sqrt{Q_3/Q_1}.$$

TABLE 3.—*Hydrologic and physical properties of samples*

[Samples 58ARK54–67 are from test hole L3S-4W-3dca14. Samples 59ARK44, 45 and 46 are from test holes 5S-3W-17ddd1, 5S-2W-36abb1, and 5S-5W-3aaa1, respectively]

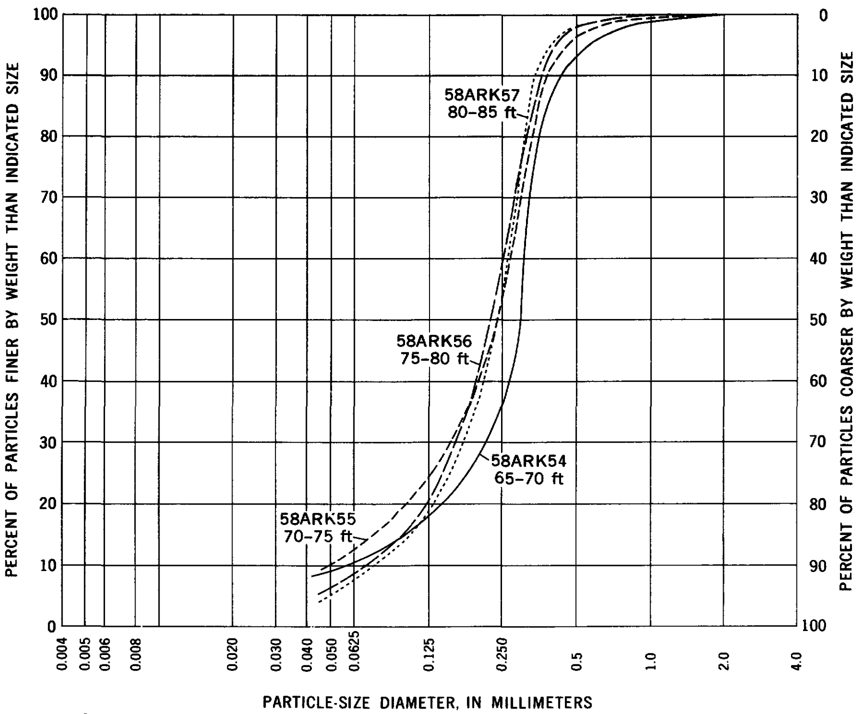
Lab. sample No.	Sample depth (ft)	Specific gravity of solids	Dry unit weight (g per cc)	Particle size (percent by weight)			Centrifuge moisture equivalent (percent)	Specific retention (percent)	Total porosity (percent)	Specific yield (percent)	Coefficient of permeability (gpd per sq ft)
				Silt and clay size (<0.0625 mm)	Sand (0.0625—2.0 mm)	Gravel (2-64 mm)					
58ARK54	65–70	2.65	1.78	10.8	88.9	0.3	0.2	1.1	32.8	31.7	30
55	70–75	2.68	1.75	13.4	86.6		.4	2.0	34.7	32.7	20
56	75–80	2.67	1.68	9.0	91.0		.4	1.9	37.1	35.2	50
57	80–85	2.68	1.70	7.8	92.2		.4	2.0	36.6	34.6	40
58	85–90	2.65	1.64	5.8	93.7	.5	.2	1.0	38.1	37.1	90
59	90–95	2.66	1.78	5.3	94.7		.2	1.1	33.1	32.0	70
60	95–100	2.65	1.71	2.6	97.4		.6	2.8	35.5	32.7	300
61	100–105	2.63	1.59	7.4	91.5	1.1	1.4	4.8	39.5	34.7	60
62	105–110	2.67	1.68	1.5	98.5		.1	.6	37.1	36.5	300
63	110–115	2.65	1.64	.7	98.8	.5	.1	.6	38.1	37.5	500
64	115–118	2.67	1.82		88.3	11.7	.1	.6	31.8	31.2	600
65	118–120	2.68	1.82	.2	88.4	11.4	.1	.6	32.1	31.5	800
66	120–125	2.66	1.72		96.4	3.6	.1	.6	35.3	34.7	1,000
67	125–127.5	2.65	1.66	.4	97.6	2	.1	.6	37.4	36.8	800
59ARK44	10–32	2.65	1.60	21.0	79.0		5.7	12.3	39.6	27.3	8
45	27–47	2.68	1.62	44.6	55.4				39.6		3
46	7–37	2.66		23.6	76.4						20

The log quartile deviation is the log of the geometrical quartile deviation or sorting coefficient, *So*, and is represented by the equation

$$\mathrm{Log}_{10}\, So = (\log Q_3 - \log Q_1)/2.$$

The log *So* can be expressed to the base 10 (Krumbein and Pettijohn, 1938, p. 232) and is so tabulated in this report.

As noted by Krumbein and Pettijohn (1938, p. 232), the geometric quartile measures are ratios between quartiles and thus have the advantage over the arithmetic quartile measures in that they eliminate both the size factor and the unit of measurement. They do not, however, give a directly comparable value for the spread of the curve. The logarithmic measures, though, do give a direct comparison because the $\log_{10} So$ (the log quartile deviation) increases arithmetically.



PERCENT OF PARTICLES OF INDICATED SIZE

SILT 0.004-0.0625	SAND Very fine 0.0625-0.125	SAND Fine 0.125-0.25	SAND Medium 0.25-0.5	SAND Coarse 0.5-0.1	SAND Very Coarse 1-2	GRAVEL Very fine 2-4
——— 10.8	7.3	18.1	58.0	5.2	0.3	0.3
– – – 13.4	11.3	28.6	43.4	3.2	.1	
—— 9.0	11.6	38.5	39.7	1.2		
········ 7.8	11.1	34.9	44.7	1.4	.1	

FIGURE 3.—Particle sizes for sampled interval 65–85 feet.

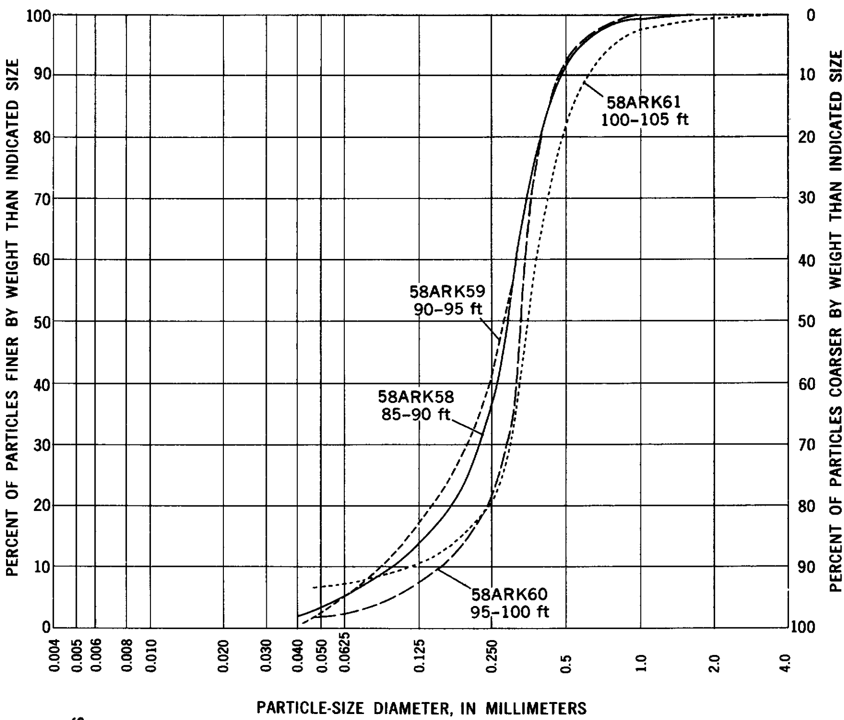
Thus, a sediment with $\log_{10} So = 0.402$ has twice as much spread between Q_1 and Q_3 as one with $\log_{10} So = 0.201$.

The effective size concept was proposed by Hazen (1892) and is the maximum particle diameter in the finest 10 percent of a sample.

"Uniformity coefficient" is also a term proposed by Hazen (1892); it is the ratio of the maximum particle size of the finest 60 percent of the sample to the maximum particle size of the finest 10 percent.

Statistical measures for all samples are given in table 4 and are summarized as follows:

1. Median diameters for the basal sediments (58ARK54–67) range from 0.22 to 0.55 mm, and for the upper sands, from 0.067 to 0.1 mm.
2. Sorting coefficients (So) for the basal sediments range from 1.17 to 1.56, the average being 1.35; and for the upper sands, from 1.41 to 1.54, averaging



PERCENT OF PARTICLES OF INDICATED SIZE

	SILT 0.004–0.0625	SAND Very fine 0.0625–0.125	SAND Fine 0.125–0.25	SAND Medium 0.25–0.5	SAND Coarse 0.5–1	SAND Very Coarse 1–2	GRAVEL Very fine 2–4
———	5.8	8.2	22.1	55.6	7.7	0.1	0.5
- - - -	5.3	11.8	23.9	50.1	8.8	.1	
— —	2.6	4.5	13.7	72.3	6.8	.1	
....	7.4	3.0	9.5	61.8	15.7	1.5	1.1

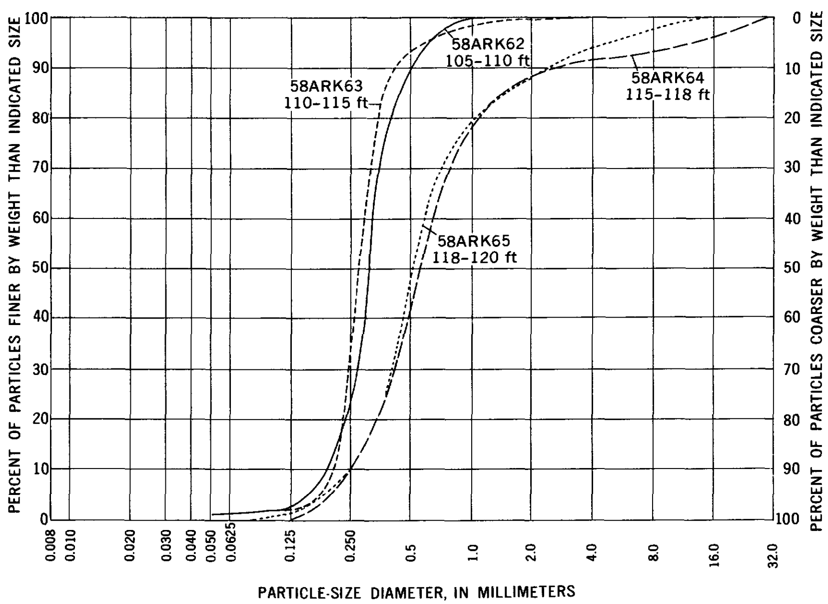
FIGURE 4.—Particle sizes for sampled interval 85–105 feet.

1.49. According to Krumbein and Pettijohn (1938, p. 232), a value less than 2.5 indicates a well-sorted sediment, 3 a normally sorted sediment, and 4.5 a poorly sorted sediment.

3. The log quartile deviations ($\log_{10} So$) for the basal sediments range from 0.070 to 0.194, the maximum spread being about three times as great as the minimum. The range for the upper sands is from 0.150 to 0.188.
4. Effective sizes for the basal sediments range from 0.05 to 0.25 mm, averaging 0.15 mm. The material gradually becomes coarser with depth; yet the increase in effective size is only 0.20 mm. Effective sizes for the upper sands are smaller, ranging from 0.0027 to 0.017 mm.
5. Uniformity coefficients for the basal sediments range from 1.4 to 5.4; the smaller values are representative of samples below 105 feet. The average uniformity coefficient is 3.0. The upper sands are less uniform; uniformity coefficients range from 6.8 to 28.6 and average 16.3

MINERALOGY

The mineralogy of samples collected from the Grand Prairie region was determined by X-ray. The minerals in three samples collected from test hole L3S–4W–3dca14 (table 3) were identified by the Geochemistry and Petrology Laboratory, U.S. Geological Survey, Denver,



PERCENT OF PARTICLES OF INDICATED SIZE

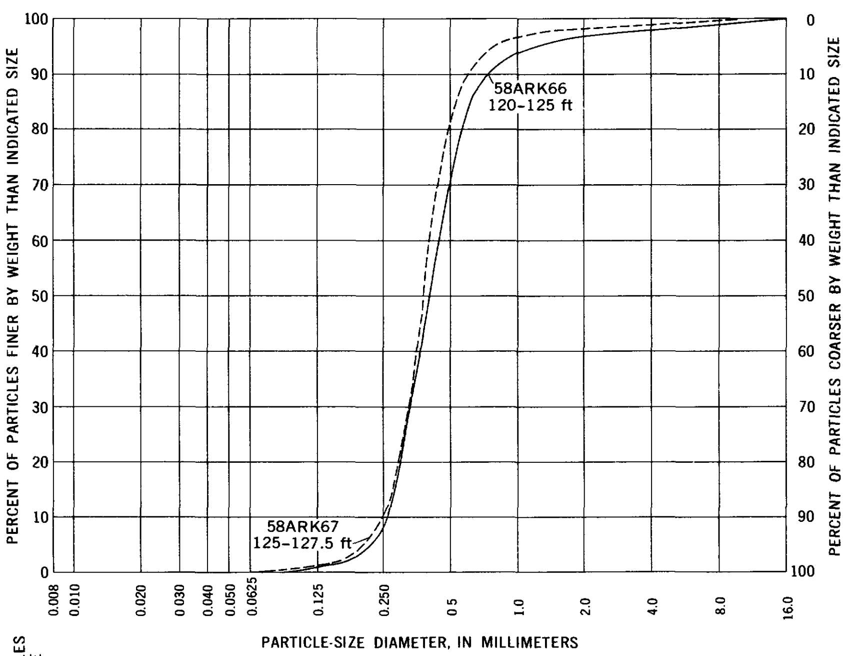
	SILT	SAND					GRAVEL			
	0.004-0.0625	Very fine 0.0625-0.125	Fine 0.125-0.25	Medium 0.25-0.5	Coarse 0.5-0.1	Very Coarse 1-2	Very fine 2-4	Fine 4-8	Medium 8-16	Coarse 16-32
———	1.5	0.9	20.1	67.6	9.5	0.4				
- - - -	.7	.7	33.2	59.0	4.9	1.0	0.5			
— —		.1	10.5	32.2	35.9	9.6	2.7	1.7	3.3	4.0
·······	.2	.7	9.9	37.5	31.7	8.6	5.2	3.6	2.6	

FIGURE 5.—Particle sizes for sampled interval 105–120 feet.

TABLE 4.—*Statistical measures for samples from test holes*

[Samples 58ARK54–67 are from test hole L3S-4W-3dca14. Samples 59ARK44, 45, and 46 are from test holes 5S-3W-17ddd1, 5S-2W-36abb1, and 5S-5W-13aaa1, respectively]

Lab. sample No.	Sample depth (ft)	Median diameter D_{50} (mm)	Geometrical quartile deviation (sorting coefficient) *So*	Log quartile deviation (log sorting coefficient) $\log_{10}$ *So*	Effective size (mm)	Uniformity coefficient
58ARK54	65–70	0.29	1.32	0.122	0.06	5.4
55	70–75	.23	1.58	.197	.05	5.3
56	75–80	.22	1.45	.161	.07	3.7
57	80–85	.23	1.35	.131	.07	3.5
58	85–90	.30	1.36	.134	.10	3.2
59	90–95	.28	1.48	.171	.09	3.7
60	95–100	.33	1.17	.068	.15	2.2
61	100–105	.34	1.27	.104	.11	3.2
62	105–110	.31	1.24	.094	.19	1.8
63	110–115	.28	1.20	.080	.20	1.4
64	115–118	.55	1.56	.194	.25	2.6
65	118–120	.51	1.51	.180	.25	2.4
66	120–125	.40	1.30	.115	.25	1.8
67	125–127.5	.37	1.27	.103	.25	1.7
59ARK44	10–32	.10	1.41	.150	.017	6.8
45	27–47	.067	1.54	.188	.0027	28.6
46	7–37	.10	1.43	.157	.0085	13.5



PERCENT OF PARTICLES OF INDICATED SIZE

	SILT	SAND					GRAVEL		
	0.004-0.0625	Very fine 0.0625-0.125	Fine 0.125-0.25	Medium 0.25-0.5	Coarse 0.5-1	Very Coarse 1-2	Very fine 2-4	Fine 4-8	Medium 8-16
———		0.1	7.9	64.2	21.4	2.8	1.3	1.2	1.1
– – –	0.4	.4	9.5	67.7	18.2	1.8	.6	1.1	.3

FIGURE 6.—Particle sizes for sampled interval 120–127.5 feet.

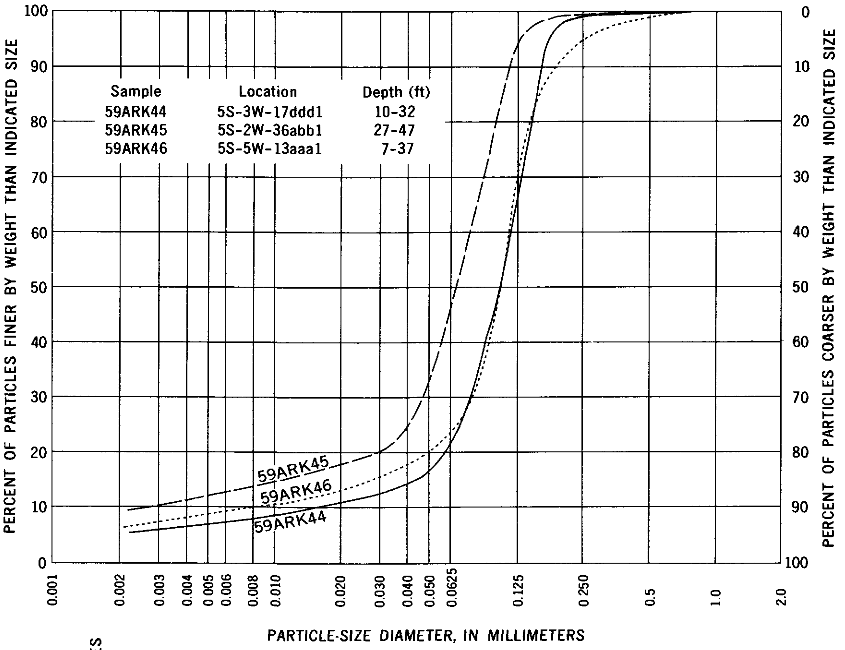
and are listed in the approximate order of relative abundance as follows: MAJOR, Minor, (Trace), and (Questionable?).

At 74 feet: QUARTZ, Feldspar, (Mica?), and (Montmorillonite?)

At 78 feet: QUARTZ, Feldspar, (Montmorillonite), (Mica), and (Kaolinite)

At 102–104 feet: QUARTZ, (Feldspar), (Mica), (Kaolinite), and (Montmorillonite?)

Six samples representative of the upper Quaternary clay and silt deposits were collected from a roadcut near Clarendon (sec. 36, T. 1 N., R. 4 W.) and were analyzed by J. E. Hackett and H. D. Glass of the Illinois Geological Survey, Urbana, Ill. The following is a general description of the samples and their depths (after Sniegocki, 1964):



PERCENT OF PARTICLES OF INDICATED SIZE

CLAY	SILT	SAND				
<0.004	0.004-0.0625	Very fine 0.0625-0.125	Fine 0.125-0.25	Medium 0.25-0.5	Coarse 0.5-1	Very Coarse 1-2
—— 6.5	14.5	46.0	32.6	0.2		0.2
— — 11.3	33.3	49.8	5.1	.1	0.2	.2
······· 8.2	15.4	47.2	24.0	4.6	.2	.4

FIGURE 7.—Particle sizes for upper sands.

	Depth (feet)
1. Silt, gray; contains some very fine sand and oxidized particles; has a loesslike appearance	0.2–0.4
2. Silt, yellowish-brown; contains oxidized material; has a loesslike appearance	1.5
3. Silt, yellowish-brown; contains some very fine sand; has a loesslike appearance	2.5
4. Silt, light-yellowish-brown; contains fresh organic fragments; has a loesslike appearance	2.5–3
5. Silt, clayey, dark-reddish-brown; forms pinnacles, in part, upon weathering; slightly bedded	5
6. Clay, silty, dark-reddish-brown; forms pinnacles upon weathering; slightly bedded	8

According to Dr. H. D. Glass of the Illinois State Geological Survey, Clay Mineralogy Section, X-ray traces indicate that montmorillonite is the predominant clay mineral in the samples. Abundant feldspar is indicated, with orthoclase more prevalent than plagioclase. A small amount of illite and poorly crystallized kaolinite is also present. Moderate amounts of quartz occur in all samples. The mineralogy of all samples is very similar, with some minor differences. Dr. Glass indicated that samples 1–4 have a strong resemblance to loess, both visually and by X-ray-trace comparisons, while samples 5 and 6 show the similarity only in the X-ray trace. The larger illite content of samples 5 and 6 is probably the greatest difference between samples 1–4 and samples 5 and 6.

A clay sample collected from the test hole at the recharge site also was analyzed by the Illinois State Geological Survey. The clay, which came from a depth of about 18 feet, is dark reddish brown, very silty, and calcareous, and contains many white specks. Very low quartz content, the presence of calcite, and greater amounts of illite and kaolinite are the principal mineralogic differences of this sample compared with samples 1–6. Also, there is less feldspar in this sample.

PERMEABILITY AND TRANSMISSIBILITY

The coefficient of permeability depends in general on the degree of sorting and on the arrangement and sizes of the particles. It is usually low for clay and other fine-grained or tightly cemented materials, and high for coarse clean gravel; values from 0.00001 to 90,000 gpd per sq ft (gallons per day per square foot) have been obtained in the laboratory. In general, permeability parallel to bedding planes is greater than permeability perpendicular to bedding planes. Major water-bearing materials have coefficients of permeability above 100.

The coefficient of transmissibility is the rate of water flow in gallons per day (at the prevailing water temperature), through a vertical strip of the aquifer 1 foot wide extending the full saturated height of

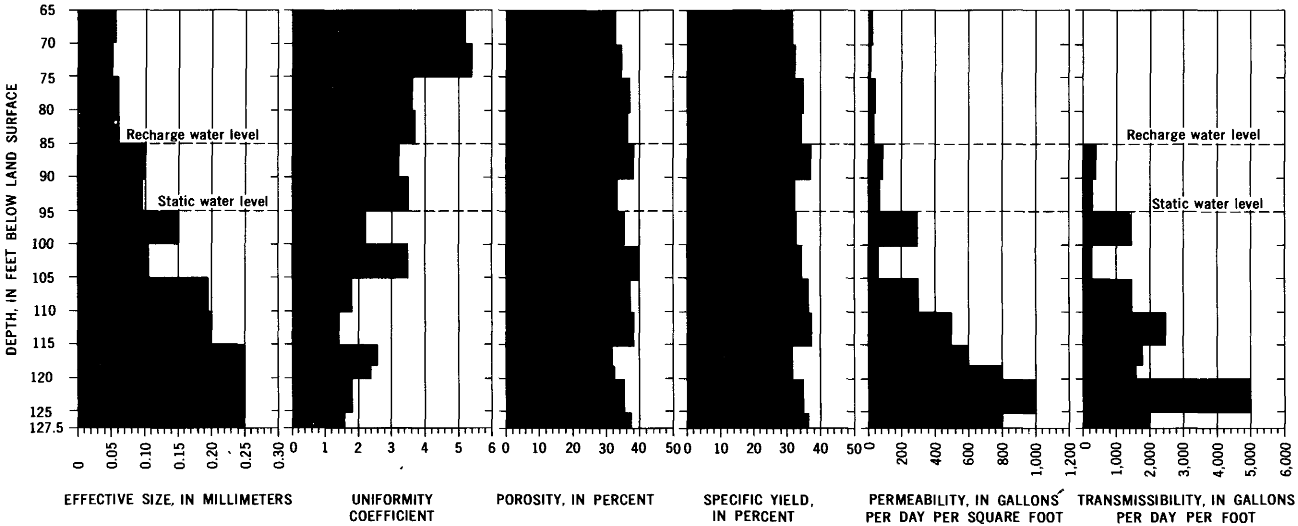


FIGURE 8.—Aquifer properties for test hole L3S–4W–3dca14.

the aquifer under a hydraulic gradient of 1 foot per foot. Thus, the coefficient of transmissibility is the product of the field coefficient of permeability and the saturated thickness of the aquifer. It is usually expressed in gallons per day per foot.

The coefficients of permeability for samples from the basal Quarternary zone range from 20 to 1,000 gpd per sq ft, and for samples from the upper sands, from 3 to 20 gpd per sq ft (table 3).

For test hole L3S–4W–3dca14 (fig. 8), the coefficients of permeability are less than 100 for all samples to a depth of 95 feet, as well as for samples from depths of 100–105 feet. All other samples have coefficients of permeability of 300 or greater. Although a sample was not collected from the cobble bed at 127.5–128 feet, a permeability of 80,000 gpd per sq ft is reasonable and will be assumed for future calculations. Sediments at 118–128 feet have the greatest permeability (weighted average equals about 4,900 gpd per sq ft) and should provide the best section of water-bearing material for installation of the well screen.

As figure 9 shows, the permeability of samples from test hole L3S–4W–3dca14 increases as particle size or uniformity of particle size increases. Coefficients of permeability range from approximately 20 gpd per sq ft at an effective size (D_{10}) of 0.05 mm to approximately 1,000 gpd per sq ft at 0.3 mm. Permeability of approximately 20 gpd per sq ft is obtained when the uniformity coefficient is 5, but permeability increases to approximately 1,000 gpd per sq ft as the coefficient becomes slightly less than 2.

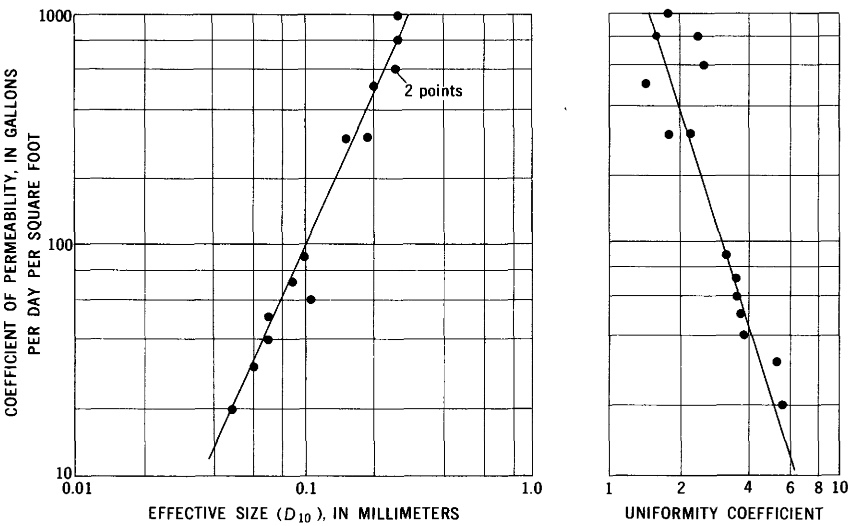


FIGURE 9.—Relation of permeability to effective size and uniformity coefficient for samples from test hole L3S–4W–3dca14.

Coefficients of transmissibility (fig. 8) for each sample interval in test hole L3S–4W–3dca14 range from 200 to 5,000 gpd per ft at 60°F. Using the estimated permeability of 80,000 gpd per sq ft, the coefficient of transmissibility for the cobble bed at a depth of 127.5–128 feet would be 40,000 gpd per ft. The coefficient of transmissibility for the total saturated thickness would be 57,000 gpd per ft at 60°F, or 60,000 gpd pėr ft at the temperature of the ground water (64°F). These values were predicted in a 1958 unpublished report, but in later tests (Sniegocki and others, 1965) the coefficient of transmissibility for nearby recharge well 1 was determined to be about 67,000 gpd per ft after 1,800 minutes (1.25 days) of pumping and about 63,000 pgd per ft after 5,760 minutes (4 days).

SPECIFIC GRAVITY OF SOLIDS, DRY UNIT WEIGHT, AND POROSITY

The specific gravity of solids for a sediment is the average of the specific gravities of the constituent mineral particles. The specific gravity of solids for most clean sands is near 2.65. The specific gravity of solids for samples described in this report ranged from 2.63 to 2.68 (fig. 8 and table 3).

The dry unit weight of sediments varies according to differences in shape, arrangement, and mineral composition of the constituent particles; the degree of sorting; the amount of compaction; and the amount of cementation. Dry unit weights of unconsolidated sediments commonly range from 1.2 to 1.8 g per cc (grams per cubic centimeter) (75–112 lb per cu ft). The dry unit weight of samples from the recharge site ranged from 1.59 to 1.82 g per cc, or 99 to 113 lb per cu ft (fig. 8 and table 3).

Porosity is calculated from the dry unit weight and specific gravity of the sediment and is dependent upon the same factors. Most natural sands have porosities ranging from 25 to 50 percent, and soft clays have porosities which range from 30 to 60 percent. Compaction and cementation tend to reduce these values. Porosities for samples described in this report range from 31.8 to 38.1 percent (fig. 8 and table 3).

The samples were disturbed at the time of collection and were repacked in the laboratory to obtain dry unit weight and porosity data. However, the ranges of these data are believed to be fairly representative of the dry unit weight and porosity ranges of the sediments in place.

SPECIFIC YIELD

For samples from the recharge area, specific retention is about 1–5 percent for the lower Quaternary sediments and about 12 percent for the upper sediments. In test hole L3S–4W–3dca14, specific retention of samples from depths down to 105 feet is slightly greater than for samples from greater depths. However, slightly greater porosity for the deeper samples results in specific yields of approximately the same magnitude for all depths.

Specific yields for samples analyzed in the laboratory range from approximately 31 to 38 percent for the lower sediments and are about 27 percent for the upper sediments. The average specific yield determined for the lower sediments by laboratory analysis is about 34 percent, but that determined from a short-term pumping test would be considerably less. Half of the laboratory value would not be unusual for a 24-hour test, and even lower values would be obtained for shorter periods of pumping. Saturated sediments, when allowed to drain, may yield water for a long period of time—although most of the water may drain out in a day or two. The specific yields summarized in this report represent values expected after sufficient time, possibly as long as a few weeks or even months, has elapsed for drainage to reach equilibrium. The values predicted by this previously unpublished data have been supported by later data (Sniegocki and others, 1965) obtained by aquifer tests which determined that the coefficient of storage (specific yield) for recharge well 1 was about 0.14 after 1,800 minutes of pumping, and 0.28 after 5,760 minutes.

SPECIFIC CAPACITY ESTIMATE

Specific capacity is the ratio of the yield of a well to its drawdown. If yield is expressed in gallons per minute, and drawdown, in feet, the specific capacity is expressed as gallons per minute per foot. The specific capacity depends not only on the transmissibility of the aquifer but on such factors as the screen type, well diameter, degree of aquifer penetration, and completeness of well development. In general, a large specific capacity indicates a high-quality well.

If a well has been designed and constructed perfectly (100 percent efficient), its specific capacity can be predicted by a simple derivation of the Thiem equation, which relates yield and drawdown of a well to the transmissibility of its aquifer. Wenzel (1942, p. 81) presented Thiem's equation as follows:

$$P=\frac{527.7\,Q\log(r_2/r_1)}{m(s_1-s_2)} \tag{1}$$

where

P = field coefficient of permeability, in gallons per day per square foot,

Q = rate of discharge of the pumped well, in gallons per minute,

r_1 = radius to near observation point, in feet,

r_2 = radius to far observation point, in feet,
s_1 = drawdown in well at distance r_1, in feet,
s_2 = drawdown in well at distance r_2, in feet,
m = saturated thickness of the aquifer, in feet.

If it is assumed that r_2 is the radius at which there is no drawdown ($s_2=0$), and that s_1 is the drawdown at the pumped well (r_1 is the effective radius of the pumped well), then the specific capacity of the well is approximated by the following equation:

$$\frac{Q}{s}=\frac{Pm}{527.7\ (\log r_2/r_1)}=\frac{T}{527.7\ (\log r_2/r_1)} \tag{2}$$

where

$\frac{Q}{s}$ = specific capacity of pumped well, in gallons per minute per foot of drawdown,
T = coefficient of transmissibility, in gallons per day per foot.

Although an estimate of specific capacity is the information desired for this report, the preceding and following equations can also be used to estimate the transmissibility of the aquifer when the specific capacity of a well is known.

The value of r_2 may vary from 100 to over 10,000 feet, depending on the pumping period and the storage coefficient (S), which is the volume of water the aquifer releases from or takes into storage per unit of surface area of the aquifer per unit change in the component of head normal to that surface. The radius r_2 will be small for water-table conditions ($S\approx0.03$–0.30) and will be large for artesian conditions ($S\approx0.00003$–0.003). Ordinarily, however, a value of 1,000 feet may be used for r_2 in equation 2 for water-table conditions such as existed at the artificial-recharge site. Because the specific capacity (or transmissibility) in equation 2 varies with the logarithm of r_2/r_1, large variations in estimated radii (r_2) result in only small differences in the computed value of the specific capacity (or transmissibility).

If it is assumed that the pumped well has an effective radius (r_1) of 1 foot and the radius of influence (r_2) of the well is 1,000 feet, equation 2 becomes approximately

$$\frac{Q}{s}=\frac{Pm}{1,590}=\frac{T}{1,590} \tag{3}$$

or

$$T=1,590(Q/s). \tag{4}$$

If r_2 is assumed to be 10,000 feet instead of 1,000 feet, equation 4 is changed to $T=2,120\ (Q/s)$. If r_1 is assumed to be 0.5 feet instead of 1 foot, equation 4 is changed to $T=2,280\ (Q/s)$.

If equation 3 is applied to test hole L3S–4W–3dca14 (estimated coefficient of transmissibility equals 57,000 gpd per ft), then the specific capacity (assuming full efficiency) would be

$$\frac{Q}{s}=\frac{57,000}{1,590}=36.$$

This specific capacity is based on a water temperature of 60°F. For the recharge site water temperature of 64°F, the specific capacity would be estimated at 38 for a 100-percent efficient well. Most wells, however, are only about 80 percent efficient at best. Thus, the specific capacity predicted for recharge well 2 would be 30.

If a more accurate estimate of specific capacity is desired, then the actual distance (r_2) to the point of zero drawdown must be determined from the following equation (modified from Jacob and Lohman, 1952, p. 566):

$$r_2=\sqrt{\frac{0.3Tt}{S}} \tag{5}$$

where t is the time, in days, since pumping started, and S, T, and r_2 are as previously defined.

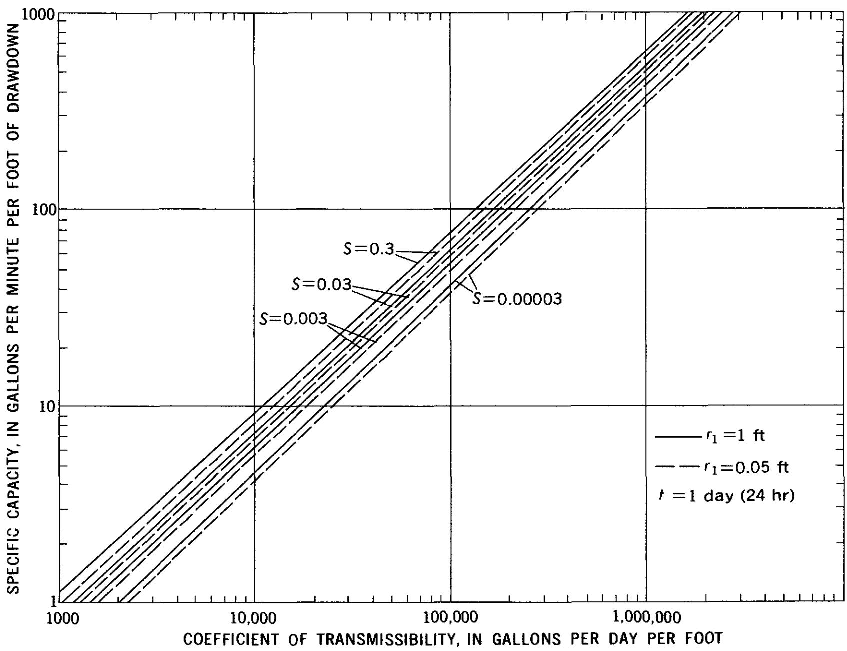


FIGURE 10.—Relation of specific capacity to transmissibility for a 24-hour pumping period. S is storage coefficient; r_1 is radius of pumped well in feet; t is time of pumping in days.

Substituting different values of r_1, t, S, and T in equations 2 and 5, a graph such as figure 10 can be derived to obtain more accurate estimates of specific capacity or transmissibility. The graph and equations illustrate the importance of stating the discharge and the duration of pumping at which a particular value of specific capacity is obtained.

The specific capacity for each interval or unit can be estimated using equation 3, if permeability (P) and thickness of sampled interval or lithologic unit (m) are known. When added together, these "unit specific capacities" provide an estimate of the specific capacity of the

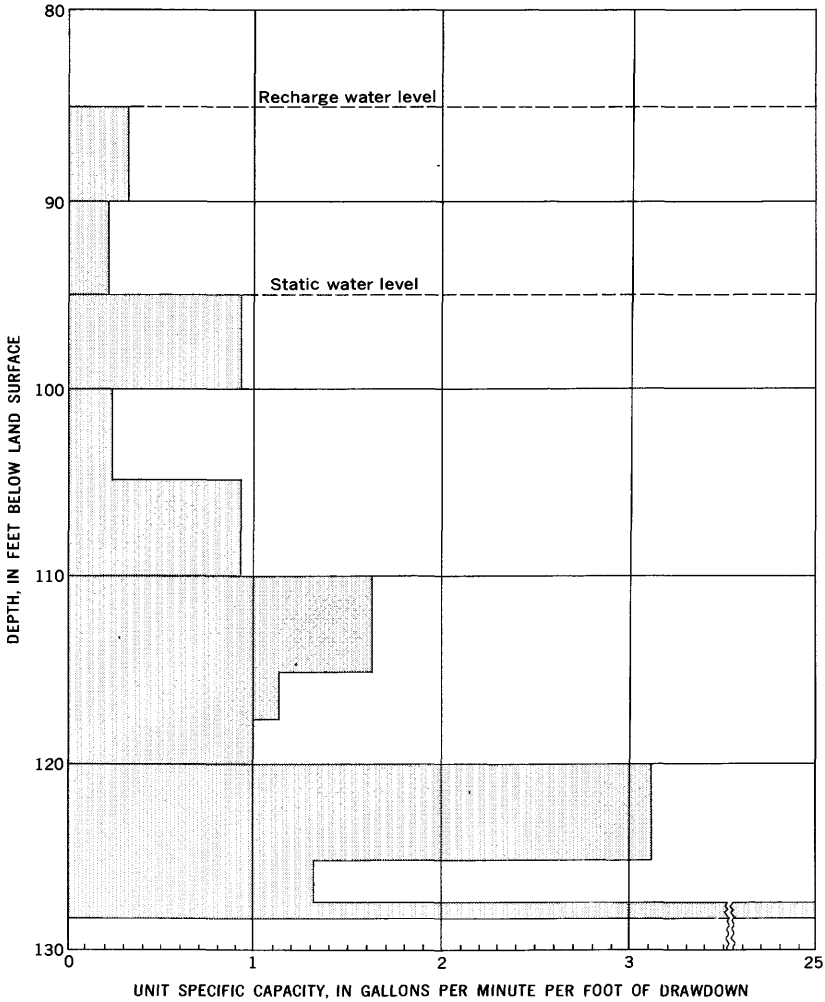


FIGURE 11.—Estimated unit specific capacities for sampling intervals in test hole L3S–4W–3dca14.

well. By use of laboratory permeability data, a graph of unit specific capacities may be prepared to indicate the most efficient producing zones in an aquifer. Figure 11 shows estimated unit specific capacities for each interval sampled in test hole L3S–4W–3dca14 and indicates that the section below 105 feet, and especially that below 127.5 feet, is the most efficient section of the aquifer to develop.

FILTER-PACK AND WELL-SCREEN DESIGN

THEORY OF DESIGN

Successful completion of a well in sand and gravel formations requires proper selection of the screen, or slot openings, and proper development of a natural or artificially produced sand or gravel filtering zone around the casing. Ahrens (1957) stated that this zone commonly is called a "gravel pack," but he noted that the terminology is misleading because packs may be of different particle sizes—from fine sand to coarse gravel—depending upon the size gradation of aquifer constitutents. Therefore, the term "filter pack," a more precise term, is used in this report.

A filter pack of uniform coarse sand or gravel surrounding the well screen can be provided in two ways (Johnson, E. E., 1955). A natural filter pack is produced by removing the fine sand and silt from the adjacent aquifer material and bringing this fine material through the well-screen openings by surging and bailing. An artificial filter pack is made by drilling the hole larger than the well screen, centering the screen in the hole, and then filling the annular space around the screen with carefully sized sand or gravel. The properly designed filter pack not only increases the effective diameter of the well but also insures a sand-free well.

By correct choice of screen-opening sizes, a natural filter pack may be produced that extends some distance from the well screen (E. E. Johnson, 1955, 1963). For the artificially placed filter pack, a properly graded sand or gravel to retain part of the aquifer material and a screen (or perforations) to retain most of the filter pack will insure that the well will not continue to pump sand or become plugged with fine material.

Early well designs were formulated largely by trial and error, resulting in a variety of rules of thumb. However, in recent years, field and laboratory study has provided scientific criteria for designs of well screens and filter packs. Now it is generally known that optimum well design starts with analysis and interpretation of aquifer properties, including determination of particle-size distribution of the aquifer materials (Johnson, A. I., 1963).

The U.S. Army Corps of Engineers (1941, 1942) did considerable laboratory and field research on the proper design of filter packs and screens for pressure relief wells. The conclusions were that particle-size-distribution curves for filter pack and aquifer should be approximately parallel to minimize washing of the fine aquifer material into the filter pack. Filter-pack design was found to depend on the following criteria for filtering stability:

$$\frac{\text{15-percent finer size of filter pack}}{\text{85-percent finer size of finest aquifer material}} \leqq 4;$$

and for maximum permeability:

$$\frac{\text{15-percent finer size of filter pack}}{\text{85-percent finer size of coarsest aquifer material}} \geqq 4.$$

The Corps of Engineers studies also brought forth conclusions regarding well-screen design. For screens installed without filter packs, they found that screen diameter had relatively little effect on efficiency of the well system but that the perforated section should have at least 100 perforations—totaling an open area of 3 square inches per foot of section—for most efficient operations. For screens installed with filter packs, the perforated section should have at least 25 perforations—totaling an open area of 1 square inch per foot of section. Sand influx after initial pumping was prevented if the screen, or perforated openings, was designed according to the following criteria:

$$\frac{\text{85-percent finer size of filter pack or aquifer material}}{\text{Screen opening or perforated opening}} \geqq 1.$$

Recent laboratory studies by the Corps of Engineers (1948) resulted in establishment of the following additional criteria for greater filter-pack stability:

$$\frac{\text{15-percent finer size of filter pack}}{\text{15-percent finer size of coarsest aquifer materials}} < 20$$

and

$$\frac{\text{50-percent finer size of filter pack}}{\text{50-percent finer size of aquifer materials}} < 25$$

E. E. Johnson (1955, 1963) found that a filter pack only a fraction of an inch thick would successfully retain aquifer particles regardless of water velocity. The thicker the filter pack, the more difficult it becomes to remove completely drilling-mud cake from the aquifer during completion of the well. Thus, E. E. Johnson (1963) pointed out that a larger effective well diameter may be somewhat beneficial, but only if the sealing effect of drilling mud can be undone and the original permeability of the aquifer restored. Because a filter pack only a fraction of an inch thick cannot be expected to surround a screen completely, a thickness of 3 inches is the practical minimum for field installation. A filter-pack thickness of 8–9 inches is considered to be the maximum that will insure a clean drill hole and restoration of original aquifer permeability.

E. E. Johnson (1962, 1963) pointed out that for wells with natural filter packs, screen openings are chosen so that about 40 percent of the aquifer material is retained and 60 percent passes through. A higher percentage may be retained if the water is extremely corrosive.[1] The artificially placed filter pack is chosen so that it will retain much of the aquifer material, and the screen opening then is selected to retain the filter pack. E. E. Johnson (1963) recommended an opening that will retain 90 percent of the pack.

The artificially placed filter pack designed by E. E. Johnson (1963) has a uniformity coefficient of 2.5 or less, with a 70-percent retained (30-percent passing) size about four to six times as large as the 70-percent retained size of the aquifer material. The factor 4 is used if the aquifer is fine grained and uniform in particle size, and 6 is used if it is coarser and nonuniform. If the pack material is almost uniform in size, there is less hydraulic segregation of the various sizes while the filter-pack material is settling in the annular space around the well casing.

PROPOSED DESIGN FOR RECHARGE WELL

Much time and effort are required to complete a screened well correctly, whether it has a nautral or an artificial filter pack; however, proper development will improve almost any type of well. If design relationships are disregarded in construction of the well, fine sand may pass into the filter pack and decrease the yield of the well. Also, if these relationships are not observed, fine sand may continue to pass through the filter pack and the screen into the well, possibly leading to considerable damage to the pumping equipment, or even to collapse of the well itself. Thus. well design for the recharge research project must be in accord with the best possible criteria known.

Filter packs and screens designed from laboratory and field studies by the U.S. Army Corps of Engineers (1941, 1942, 1948) were suited for pressure relief wells in which continuous operation and maximum influx of sand were not primary concerns. A more conservative design must be used for the usual water well because water wells should not continue to pump sand and at the same time should have the

[1] Fiedler, A. G., Screens for water wells: Unpub. paper presented at 1964 Conf. of the Pennsylvania Water Works Operators' Assoc., Pennsylvania State Univ., Aug. 3, 1964.

highest possible specific capacity. Therefore, criteria established by E. E. Johnson (1963), as well as those established by the Corps of Engineers, have been used in designing a filter pack and a well screen for the artificial-recharge wells. Corps of Engineers criteria for filter-pack and well-screen design are as follows:

$$D_{15} \text{ filter pack} \geqq 4(D_{15} \text{ aquifer})$$
$$< 20(D_{15} \text{ aquifer})$$

$$D_{50} \text{ filter pack} < 25(D_{50} \text{ aquifer})$$

$$\text{Screen opening} \leqq D_{85} \text{ aquifer}$$

wnere

D_{15}=particle diameter corresponding to 15 percent finer on the particle-size distribution curve,

D_{50}=particle diameter corresponding to 50 percent finer,

D_{85}=particle diameter corresponding to 85 percent finer.

Criteria established by E. E. Johnson (1963) and used for the present filter-pack and well-screen design are as follows:

$$D_{30} \text{ filter pack} \geqq 4(D_{30} \text{ aquifer})$$
$$< 6(D_{30} \text{ aquifer})$$

$$\text{Screen opening} \leqq D_{50\text{-}70} \text{ aquifer}$$
$$\leqq D_{10} \text{ filter pack}$$

where

D_{70}=particle diameter corresponding to 70 percent finer,

D_{50}=particle diameter corresponding to 50 percent finer,

D_{30}=particle diameter corresponding to 30 percent finer,

D_{10}=particle diameter corresponding to 10 percent finer.

Data determined by using these design criteria are summarized in table 5 for all aquifer samples obtained from test hole L3S–4W–3dca14, an exploratory hole for recharge well 2. These design data were then used to derive the particle-size distribution graphs (fig. 12) for an artificial filter pack for recharge well 2. The design curves based on Corps of Engineers criteria were derived by drawing curves for low uniformity coefficients through the filter-pack design data points, with primary use of the median diameter (D_{50}). The design curves based on E. E. Johnson (1963) criteria were derived by drawing curves of low uniformity coefficients through the filter-pack design data point at the 30-percent finer size (D_{30}).

TABLE 5.—*Data for proposed design of well screen and filter pack, recharge well 2*

Lab. sample No.	Aquifer				U. S. Army Corps of Engineers (1948) design data				E. E. Johnson (1963) design data				
					Filter pack		Screen design		Filter pack	Screen design			
							Screen opening without filter pack			Screen opening with filter pack		Screen opening without filter pack	
	D_{15} size (mm)	D_{30} size (mm)	D_{50} size (mm)	D_{85} size (mm)	D_{15} size limits	Maximum D_{50} size (mm)	Inches	Slot No.	Average D_{10} size (mm)	Inches	Slot No.	Inches	Slot No.
58ARK54	0.10	0.22	0.29	0.37	0.4–2.0	7.2	0.014	14	0.075	0.030	30	0.012	12
55	.08	.15	.23	.36	.3–1.5	5.7	.014	14	.075	.030	30	.009	8
56	.10	.16	.22	.34	.4–2.0	5.5	.013	14	.075	.030	30	.009	8
57	.10	.17	.23	.32	.4–2.0	5.7	.012	12	.075	.030	30	.009	8
58	.13	.22	.30	.43	.5–2.5	7.5	.017	16	.075	.030	30	.012	12
59	.12	.20	.28	.44	.5–2.5	7.0	.017	16	.075	.030	30	.011	10
60	.20	.28	.33	.42	.8–4.0	8.2	.016	16	.075	.030	30	.013	12
61	.19	.30	.34	.54	.8–4.0	8.5	.021	20	.075	.030	30	.014	14
62	.21	.27	.31	.44	.8–4.0	6.5	.017	16	.075	.030	30	.012	12
63	.21	.24	.28	.36	.8–4.0	7.0	.014	14	.075	.030	30	.011	10
64	.27	.42	.55	1.50	1.1–5.5	14.5	.059	60	1.60	.064	60	.022	22
65	.29	.40	.51	1.50	1.2–60	12.7	.059	60	1.60	.064	60	.020	20
66	.28	.33	.40	.62	1.1–5.5	10.0	.024	20	1.60	.064	60	.016	16
67	.27	.33	.37	.54	1.1–5.5	9.2	.021	20	1.60	.064	60	.015	14

Figure 12 shows that the aquifer materials are of two general size groups, one from depths of 65–115 feet (represented by samples 58ARK54–63) and the other from depths of 115–127.5 feet (represented by samples 58ARK64–67). Thus, the filter-pack-design curves are also in two general groups and are represented by the two patterned bands in figure 12. Any pack having a particle-size distribution within its appropriate band in figure 12 will be satisfactory.

RECOMMENDATIONS

Optimum design of the recharge well requires placement of a pack having a distribution similar to the right-hand pattern (fig. 12) at depths below 115 feet and similar to the left-hand pattern at depths above 115 feet. It is not practical to place two different packs for most wells, so a pack designed for the aquifer with the finest material should be used if both fine and coarse aquifers are screened. Thus, a pack

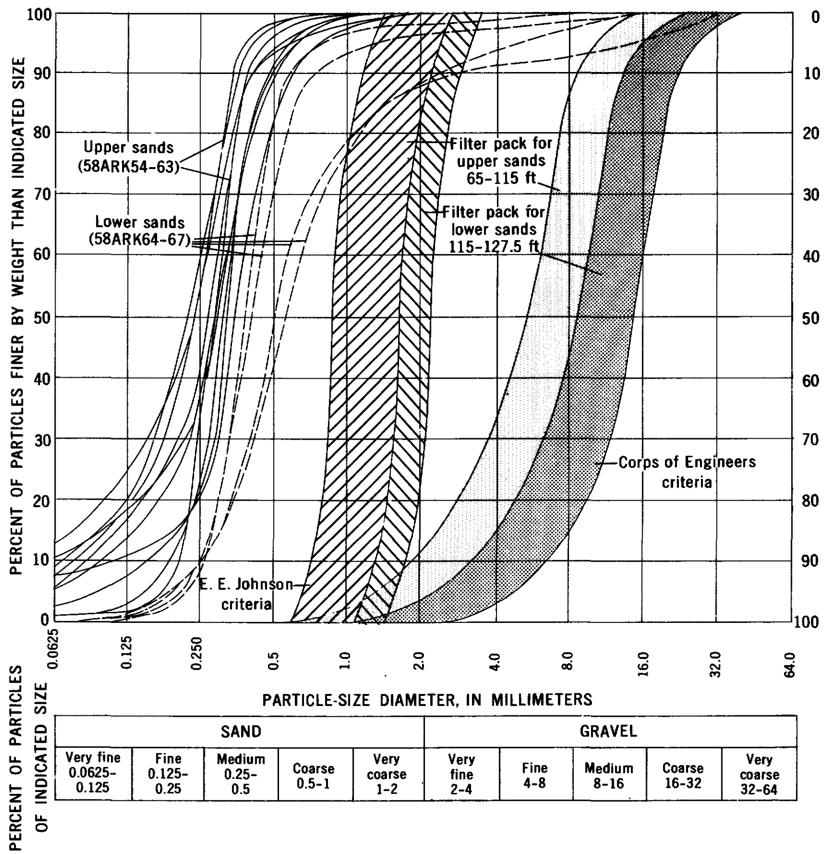


FIGURE 12.—Filter-pack design curves proposed for recharge well 2.

similar to the distribution of the left-hand part of the design filter pack (fig. 12), using either Army Corps of Engineers (1948) or E. E. Johnson (1963) criteria, should be used under such conditions. However, if only the coarse or most permeable aquifer is to be screened, then the filter-pack design should be based on design curves for that particular material; for example, the right-hand part of the design curves in figure 12.

Because E. E. Johnson (1963) criteria were established more specifically for water-supply wells rather than for pressure-relief wells, the design filter pack based on those criteria (left-hand curves, fig. 12) is recommended for the recharge well. Only the coarse aquifer (depth below 115 ft) should be screened, so the filter pack should have a distribution similar to the right-hand part of the set of curves.

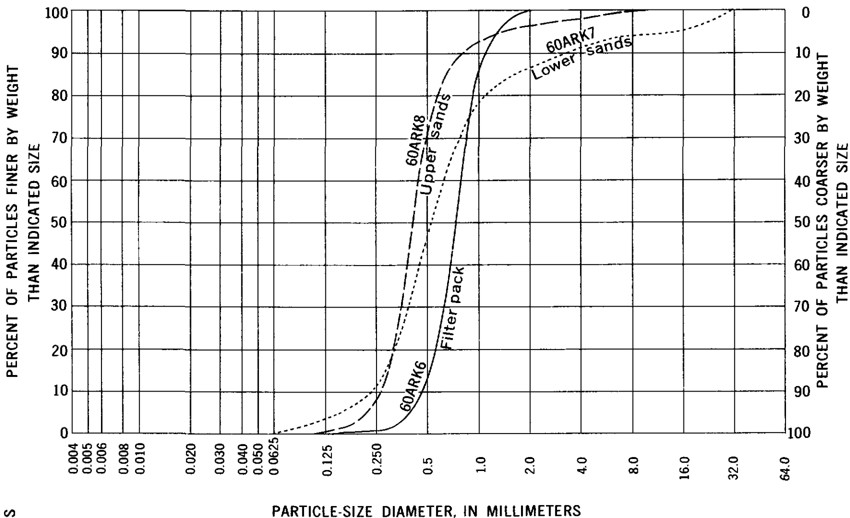
An artificially placed filter pack is recommended because small screen openings would be required for natural development. The screen is also designed according to criteria established by E. E. Johnson (1963); a screen with openings of 1.6 mm (0.064 in., or slot No. 60) is recommended.

LABORATORY STUDY OF FILTER-PACK OPERATION

REASON FOR LABORATORY STUDY

It was difficult to redevelop recharge well 2 after long-term recharge tests. Thus, a laboratory-model study was made to determine the reason for the permeability decrease in recharge well 2 and the amount of decrease that could have been reasonably expected. For a well that is alternately recharging and pumping, an improperly designed filter pack can reduce permeability by permitting the migration of fine material from aquifer into filter pack, or by filter-pack movement into the aquifer or into the well screen. Compaction of the filter pack by alternate pumping and surging after pack installation can also reduce permeability.

Owing to unforeseen circumstances, the filter pack actually used by the driller in the construction of recharge well 2 (fig. 13) had a median diameter about a third finer than that originally recommended by the writers (fig. 12). The filter pack used had about 73 percent coarse sand (slightly coarser than the coarsest aquifer zone) rather than having a predominance of very coarse sand to very fine gravel, as was recommended. Table 6 lists the particle-size data for samples of the filter pack used in recharge well 2, as well as the design criteria and particle-size data for the aquifer samples used in the laboratory-model tests. The design criteria obviously exceed the critical points of the filter pack used.



PERCENT OF PARTICLES OF INDICATED SIZE

SILT	SAND					GRAVEL				
0 004-0.0625	Very fine 0.0625-0.125	Fine 0.125-0.25	Medium 0.25-0.5	Coarse 0.5-1	Very coarse 1-2	Very fine 2-4	Fine 4-8	Medium 8-16	Coarse 16-32	Very coarse 32-64
60ARK6 0.2	0.0	0.3	12.5	72.9	14.1					
60ARK7 .3	3.6	6.9	36.0	31.5	7.8	5.1	2.9	1.1	4.8	
60ARK8 .2	.1	6.8	63.5	21.9	4.1	1.5	1.0	.9		

FIGURE 13.—Particle-size distribution for aquifer and filter materials used at recharge well 2.

TABLE 6.—*Design properties of aquifer and filter materials for recharge well 2, as constructed*

Lab. sample No.	Particle-size data			Filter-pack design criteria	
	15 percent size (mm)	50 percent size (mm)	85 percent size (mm)	15 percent size limits (mm)	Maximum 50 percent size (mm)
60ARK6 (filter pack)	0.52	0.74	0.99		
60ARK7 (lower aquifer)	.28	.53	1.7	1-5	13
60ARK8 (upper aquifer)	.30	.41	.66	1-6	10

The screen used in recharge well 2 had openings of 0.42 mm (0.016 in., or slot No. 16), a considerably smaller size than that originally recommended. It was a proper choice, however, for the filter pack actually used in the well. The screen was installed between the approximate depths of 121 and 126 feet.

LABORATORY PROCEDURE

To study the interrelationship of the filter pack and the aquifer, and thereby determine the location and cause of decreased permeability, a large permeameter (fig. 14) was constructed to hold the filter-pack and aquifer materials in contact. In this permeameter, permeability could be measured within the aquifer material, within the filter-pack material, and across the interface between the two materials.

The permeameter was basically the same as that shown in figure 2, except that additional pressure taps were installed in the permeameter cylinder so that permeability values could be calculated from the head losses occurring between these taps. To prevent channeling along the cylinder walls, the pressure taps were placed in the permeameter cylinder so that each tap was 90° around the cylinder from the tap below. Each tap was connected to a calibrated piezometer to measure the heads.

Because of a shortage of samples remaining from previous tests, one aquifer sample was a composite of samples 58ARK64, 58ARK65, 60ARK2, and 60ARK3, from depths of 115–120 feet; it was designated as sample 60ARK7. A second composite made up of samples 58ARK66, 58ARK67, 60ARK4, and 60ARK5, from depths of 120–127.5 feet, was designated as sample 60ARK8. The filter-pack mate-

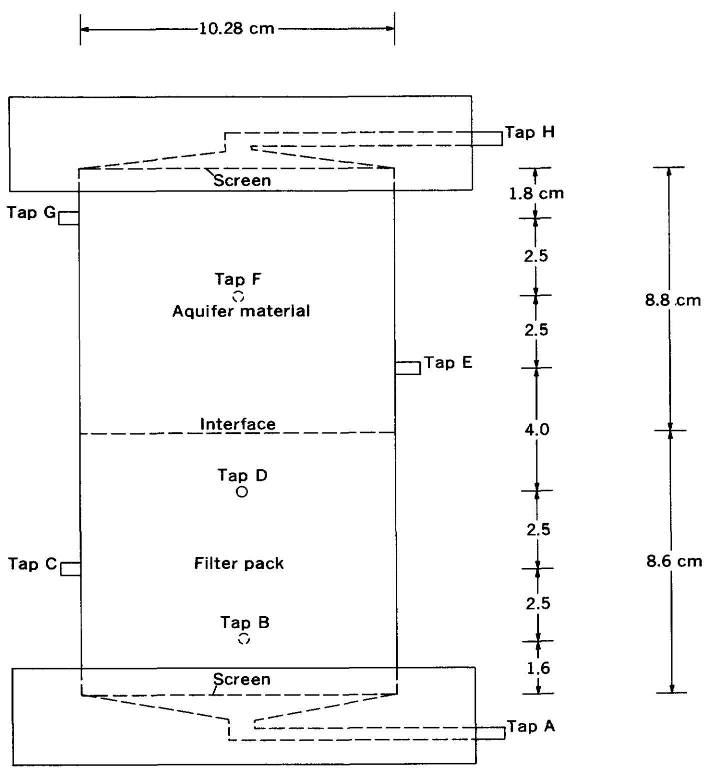


FIGURE 14.—Permeameter cylinder used to determine interrelationship of aquifer materials and filter pack at recharge well 2.

rial was designated as sample 60ARK6. Figure 13 shows the particle-size distribution curves for these samples.

Permeability tests were made with the two samples of aquifer material in contact with filter-pack material. For each test, aquifer material was packed (by a mechanical jolting machine) into half of the permeameter cylinder, and the filter-pack material was placed in the remainder of the cylinder without any packing. The full cylinder was then inverted so that the filter-pack material was on the bottom; the permeability test was then started (figs. 15, 16).

During the first hours of testing, water flowed through the permeameter cylinder from bottom to top (filter pack to aquifer) under a small hydraulic gradient. Readings were taken approximately every hour until the permeability reached a maximum value. The hydraulic gradient was increased twice, and after each increase readings were taken until a maximum value was reached.

After testing at three different hydraulic gradients, the permeameter cylinder was turned over and opened. A small amount (about 2 percent of the original volume) of additional filter-pack material was added to fill the space caused by compaction of the filter-pack material. The permeameter then was assembled as before and the test resumed, with flow through filter pack to aquifer. The flow then was reversed so that water flowed from top to bottom (aquifer to filter pack) for all the remaining tests.

To determine the effect of porosity reduction due to compaction of the filter-pack material, the permeameter cylinder was tapped with a rubber mallet at approximately 60 taps per minute while water flowed through the sample. Test reading were taken after 5 and 10 minutes of tapping.

For the last part of the tests, the samples were surged by raising and lowering the upper head tank. Lowering the tank 4 feet and then raising it 4 feet was considered to be one surge. Readings were taken after 60, 120, and 180 surges.

EXPERIMENTAL RESULTS

Figures 15 and 16 illustrate how permeability was affected by different factors, such as varied compaction and surging. In these figures, permeability is plotted as a function of time since start of percolation through the sample. The interval for which permeability was measured is indicated by the letters designating taps (fig. 14) from which head readings were taken.

The permeameter interval B–G includes almost the total sample, excluding the retaining screens at the ends of the sample. The readings thus represent an average for the filter-pack-aquifer interface. Per-

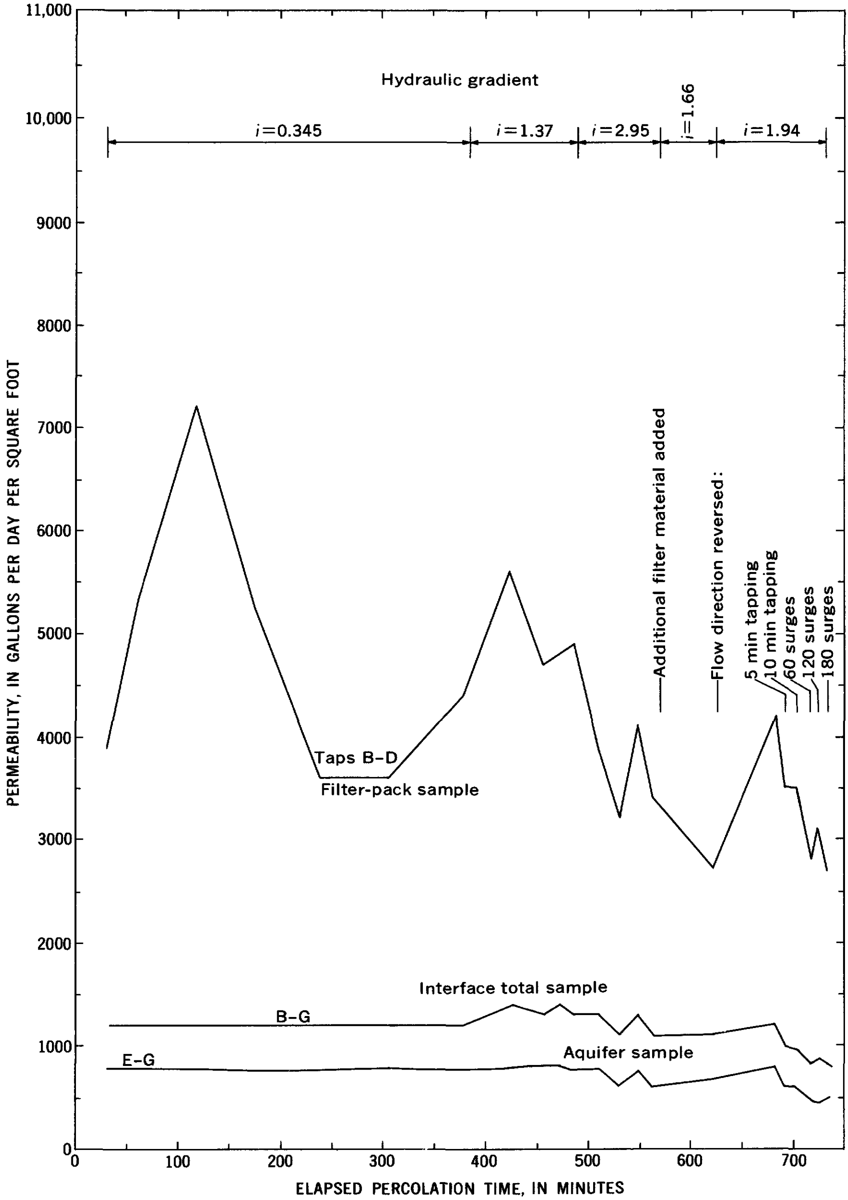


FIGURE 15.—Changes in permeability with time and special treatment of the lower sands of recharge well 2.

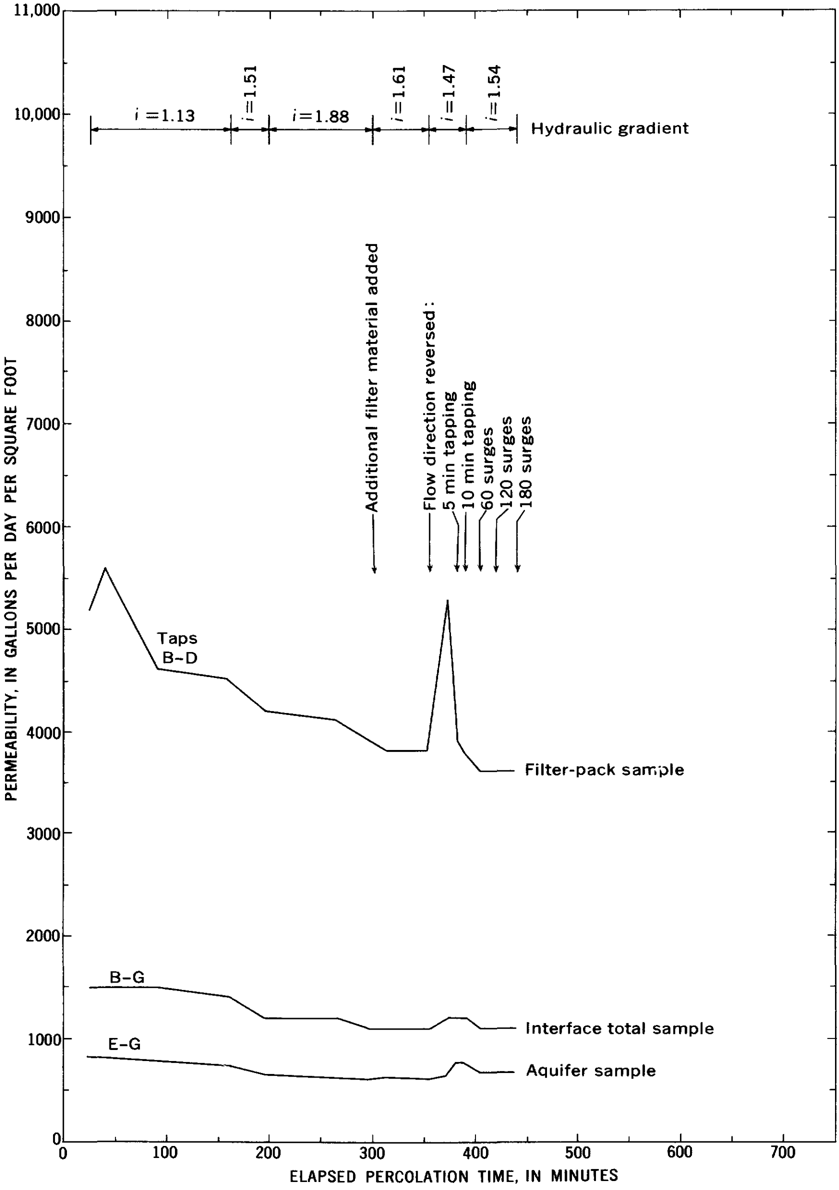


FIGURE 16.—Changes in permeability with time and special treatment of the upper sands of recharge well 2.

meability across the interface (B–G) system for the lower sands (60ARK7) ranged from a high of about 1,400 to a low of about 800 gpd per sq ft (fig. 15), or a reduction of 42 percent. Permeability across the interface (B–G) system for the upper sands (60ARK8) ranged from a high of about 1,500 to a low of about 1,100 gpd per sq ft (fig. 16), or a reduction of 27 percent.

Permeameter interval B–D is the filter-pack material. Permeability of the filter pack ranged from a high of about 7,200 to a low of about 2,700 gpd per sq ft, or a reduction of 61 percent, when used in combination with sample 60ARK7 of the lower sands (fig. 15). When used in combination with sample 60ARK8 of the upper sands, permeability of the filter pack ranged (fig. 16) from a high of about 5,600 to a low of about 3,600 gpd per sq ft, or a reduction of 36 percent.

Permeability of the aquifer materials is represented by the permeameter interval E–G. The permeability of the lower sands (60ARK7) ranged from a high of about 800 to a low of about 400 gpd per sq ft (fig. 15), or a reduction of 50 percent. Permeability of the upper sands (60ARK8) ranged from a high of about 800 to a low of about 600 gpd per sq ft (fig. 13), or a reduction of 25 percent.

The tapping and surging was done to simulate pumping, surging, and other well-development techniques which caused packing of the filter pack and reduced its porosity. Compaction caused by tapping, and possibly by surging, tended to decrease permeability by about 35 percent in the filter pack and 45 percent in the aquifer material for the test of the lower sands (60ARK7). Tapping and surging tended to decrease the permeability by about 30 percent in the filter pack and 6 percent in the aquifer materials for the test of the upper sands (60ARK8).

INTERPRETATION

The permeability reduction accompanying the tapping and surging was probably caused by compaction of the filter-pack material. Some permeability decrease also may have resulted from migration of fine particles from the aquifer into interstices of the filter-pack material, and by plugging due to entrained air (Sniegocki, 1959). The reduction caused by these factors is much greater for the lower sands (60ARK7) than for the upper sands (60ARK8). Figure 13 shows that the filter-pack material used has a particle size very much like that of the lower sands and thus is less suitable for the filter pack designed for the lower sands than for the filter pack designed for the upper sands. Reduction in permeability can be expected when the filter pack is not properly designed in relation to the aquifer material.

The foregoing tests indicate that at least part of the reduction in permeability and well efficiency evident from successive tests of recharge well 2 could have been caused by filter-pack plugging due to inappropriate sizes of pack materials; an even greater permeability decrease seems possible because of compaction of the loosely placed pack around the recharge well. Other reasons for reduction in well efficiency were discussed in some detail by Sniegocki (1963b).

SUMMARY

The upper zone of the aquifer consists predominately of fine to medium sands, with a uniformity coefficient close to 3, to a depth of about 115 feet. The lower zone consists predominately of gravelly medium to coarse sand, with a uniformity coefficient close to 2, to a depth of 127.5 feet. A highly permeable ½-foot-thick layer of gravel cobbles, and boulders is below these lower sands.

The coefficient of permeability for all except one sample was less than 100 gpd per sq ft to a depth of 105 feet. All other samples had coefficients of permeability of 300–1,000 gpd per sq ft. Although a sample of the cobble bed was not collected, a permeability of 80,000 gpd per sq ft is considered to be reasonable. Sediments between depths of 118 and 128 feet had the greatest permeability (weighted average 4,900 gpd per sq ft), and they should provide the best section for installation of the screened section of the recharge well. On the basis of these permeability data, the coefficient of transmissibility was estimated at 60,000 gpd per ft.

Specific yield determined by laboratory analysis of aquifer samples ranged from approximately 31 to 38 percent and averaged about 34 percent. Later aquifer tests on recharge well 1 resulted in determination of a coefficient of transmissibility of about 63,000 gpd per ft and a storage coefficient (specific yield) of about 28 percent after 4 days of pumping (Sniegocki and others, 1965).

Specific capacity of the recharge well was predicted from laboratory permeability data to be 30 gpm per foot of drawdown. Specific capacity tests were made (Sniegocki and others, 1963) on recharge well 2 and the specific capacity was found to be 27 gpm per ft after development.

An artificially placed gravel pack designed for the aquifer below 115 feet deep is recommended for recharge well 2. The design filter (gravel) pack should be predominately very coarse sand to very fine gravel (median diameter about 2 mm), the uniformity coefficient less than 2, and the pack thickness between 3 and 8 inches.

The screen should be set in the aquifer below a depth of 115 feet. The optimum screen size recommended for recharge well 2 is 1.6 mm (0.064 in., or slot No. 60).

Redeveloping recharge well 2 after long-term recharge tests was difficult. The specific capacity was considerably reduced below the 27 gpm per ft obtained in the earliest test. The filter pack used in this well was loosely placed and did not have the particle-size distribution recommended by the authors. A laboratory-model study was made to determine the reason for the decrease in permeability and well efficiency. A large permeameter was used to hold samples of the aquifer and the filter pack in contact similar to that existing in the well.

The laboratory tests indicated that the improperly designed filter pack used in the well may have resulted in plugging of the pore space as fine particles moved from the aquifer into the filter pack. However, it appears that the greatest part of the decrease in permeability and well efficiency may have been caused by compaction of the filter pack resulting from surging action from well-development procedures and alternate recharge and pumping tests.

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