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METHODS FOR DETERMINING PERMEABILITY OF WATER-BEARING MATERIALS

WITH SPECIAL REFERENCE TO DISCHARGING-WELL METHODS

BY

L. K. WENZEL

WITH A SECTION ON

DIRECT LABORATORY METHODS

AND

BIBLIOGRAPHY ON PERMEABILITY AND LAMINAR FLOW

BY

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METHODS FOR DETERMINING PERMEABILITY OF WATER-BEARING MATERIALS, WITH SPECIAL REFERENCE TO DISCHARGING-WELL METHODS

By L. K. WENZEL

ABSTRACT

The permeability of a water-bearing material—its capacity to transmit water under pressure—may be determined by laboratory or field tests. In the laboratory the permeability may be determined indirectly by analyses of the size, shape, and arrangement of the grains comprising the material or directly by observations on the rate of percolation of water through samples. In the field permeability may be determined by tests of ground-water velocity or by discharging-well methods, that is, by observing the fluctuations of the water table or piezometric surface in the vicinity of discharging wells.

Many specific variations of these methods have been devised by investigators with the intent to improve their applicability. Thus several formulas are available for computing permeability from the mechanical analyses of samples of the material, and many different types of apparatus are used for measuring percolation through samples. Similarly dye, salt, and other substances may be used to determine the natural rate of movement of ground water, and several formulas have been developed for computing permeability from the draw-down or recovery of the water level near discharging wells.

This report outlines the general methods for determining permeability and includes some of the more widely used variations of each. It includes a bibliography of literature on permeability and laminar flow and a list of organizations in the United States that make permeability tests.

Four pumping tests to determine the permeability of water-bearing materials have been made in Nebraska, in connection with an investigation of the ground-water resources of the State by the Federal Geological Survey in cooperation with the conservation and survey division of the University of Nebraska. Three of the tests were made in the Platte River Valley near Grand Island, Kearney, and Gothenburg, and the fourth was made in the North Platte Valley near Scottsbluff. Observations on the fluctuations of the water level in many observation wells resulted in the collection of a large amount of information on the behavior of the water level in the vicinity of discharging wells. The Federal Geological Survey in cooperation with the Kansas Geological Survey made a similar pumping test in the Arkansas River Valley, near Wichita, Kans., in 1937, in connection with a ground-water investigation. The permeability of the water-bearing materials at the location of each of the five tests was computed by several of the discharging-well formulas outlined in this report. The permeabilities so determined for any one test agree within about 5 percent. Descriptions of the pumping tests and of the permeability computations are included in this report, together with records of the draw-down of the water level in observation wells in the tested areas in Nebraska.

INTRODUCTION

The increase in the use of ground water for municipal, industrial, irrigation, air-conditioning, domestic, and other purposes and the attendant lowering of the water levels in wells have caused much concern regarding the quantity of water that can be withdrawn perennially from subterranean sources. As a result, ground-water hydrologists are persistently confronted with the serious problem of determining the safe yield of underground reservoirs. Such quantitative investigations almost always involve the movement of ground water, and to a large degree the success of these studies depends on a reasonably accurate determination of the quantity of underground percolation.

The quantity of water that will percolate through a given formation is directly proportional to the hydraulic gradient, the cross-sectional area, and the permeability of the material. In most areas the hydraulic gradient can be determined from contour maps of the water table or the piezometric surface, and the cross-sectional area can be approximately ascertained from the logs of wells. The permeability of the water-bearing material, however, is usually more difficult to determine.

The permeability of water-bearing materials may be determined by laboratory or field tests. In the laboratory the permeability may be determined indirectly by analyses of the size, shape, and arrangement of the grains constituting the material, or directly by observations on the rate of percolation of water through samples; in the field the permeability may be determined by tests of ground-water velocity or by observations on the fluctuations of the ground-water level in the vicinity of discharging wells. This report outlines each of the methods and attempts to point out its chief advantages and disadvantages. Special emphasis is placed on the discharging-well methods, and examples of permeability determinations by this method are given for pumping tests made in the Platte River Valley near Grand Island, Kearney, and Gothenburg, Nebr., in the North Platte River Valley near Scottsbluff, Nebr., and in the Arkansas River Valley near Wichita, Kans. Records of draw-down collected in the four Nebraska pumping tests are given at the end of the report. A bibliography on permeability and laminar flow also is included (pp. 20–50). It is hoped that this report will prove helpful to investigators making permeability tests and to all who are interested in quantitative ground-water investigations.

ACKNOWLEDGMENTS

This report was prepared through the encouragement of O. E. Meinzer, geologist in charge of the division of ground water of the Federal Geological Survey, who has long been intensely interested in all phases of the subject. The writer is greatly indebted to him for his advice and suggestions and for his review of this manuscript.

The writer is indebted to G. E. Condra, dean of the conservation and survey division of the University of Nebraska, for his cooperation in making possible the four tests in Nebraska, and to S. W. Lohman, for making available the data collected in the test near Wichita, Kans. He is indebted to A. L. Lugn, H. A. Waite, H. P. Burleigh, Howard Haworth, R. C. Lawrence, R. W. Gable, and Keith Miller, of the conservation and survey division of the University of Nebraska, to E. E. Brackett, chairman, and the late E. B. Lewis, research engineer, of the agricultural engineering department of the University of Nebraska, and to R. C. Cady, of the Federal Geological Survey, for their assistance in making pumping tests in Nebraska. He is also indebted to Fred Meyer, J. Teed, Albert Anderson, and Harry Pieper for cooperation in making their farms and pumping plants available and for assistance in carrying out the tests in Nebraska.

He is indebted to V. C. Fishel for his contribution on laboratory methods for determining permeability and for the summary of organizations that make permeability tests, to Mr. Fishel for contributing and R. G. Kazmann for checking the bibliography on permeability and laminar flow; also to R. C. Cady, A. G. Fiedler, C. E. Jacob, R. M. Leggette, S. W. Lohman, C. V. Theis, and D. G. Thompson—all members of the division of ground water—for their criticism of the conclusions drawn from the tests.

THE DARCY LAW AND ITS RELATION TO PERMEABILITY

STATEMENT OF DARCY'S LAW

Hagen[1] and Poiseuille[2] were the first to study the law of flow of water through capillary tubes. They found that the rate of flow is proportional to the hydraulic gradient. Later Darcy[3] verified this observation and demonstrated its applicability to water percolating through the capillary interstices of filter sands. He expressed this law by means of the formula $v=\frac{Ph}{l}$, in which v is the velocity of the water through a column of permeable material, h is the difference in head at the ends of the column, l is the length of the column, and P is a constant that depends on the character of the material, especially the size and arrangement of the grains.[4] Because it is usually more essential to determine the quantity of water flowing through a certain

[1] Hagen, G., Ueber die Bewegung des Wassers in engen cylindrischen Röhren: Annalen der Physik u. Chemie, vol. 46, pp. 423–442, Leipzig, 1839.

[2] Poiseuille, J. L. M., Recherchés expérimentales sur le mouvement des liquides dans les tubes de très petit diamètre; Royal Acad. Sci. Inst. France Math. Phys. Sci. Mém., vol. 9, p. 433, 1846.

[3] Darcy, Henri, Les fontaines publiques de la ville de Dijon, Paris, 1856.

[4] An attempt has been made in this report to utilize as much as possible a consistent set of symbols in equations and formulas. Thus many of the symbols used by others in their formulas have been transposed accordingly.

cross section of permeable material than to determine the velocity through the material, Darcy's law is sometimes expressed as

$$Q=PIA \quad \text{--------------------} \quad (1)$$

in which Q is the quantity of water discharged in a unit of time, P is the constant, which depends on the character of the material, I is the hydraulic gradient, and A is the cross-sectional area through which the water percolates. This formula serves as a basis for determining the quantities of ground water that percolate from areas of recharge to areas of discharge, and consequently it is used for determining the safe yield of underground reservoirs.

LABORATORY INVESTIGATIONS ON FLOW OF FLUIDS

There has been much difference of opinion among hydrologists as to whether Darcy's formula expresses closely the law of flow of water through porous material for all hydraulic gradients, especially for the low hydraulic gradients commonly found in nature. Since the results of Darcy's work were published, many laboratory investigations have been made on the flow of liquids and gases through permeable materials, most of the early experiments having been performed by French and German physicists and engineers.[5] A review of early investigations, including those of Ammon, Fleck, Hagen, Renk, Seelheim, Trautivine, Welitschkowsky, and Wollny was made by King.[6] He also made laboratory investigations of his own on the flow of fluids through wire gauze, disks of perforated brass, sandstone, and sand [7] and the flow of air through sand, sandstone, and capillary tubes.[8] Included in this report is a review of the experiments of F. H. Newell, performed about 1885, on the flow of water and oil through rock.[9] King concluded that although the observations of investigators showed that the flow of fluids was apparently not directly proportional to the head the departures obtained were either systematically plus or systematically minus, as might be expected if the departures were due to errors of observation.[10] Laboratory experiments on the flow of water through tanks of sand and gravel were made later under the direction of Slichter,[11] from 1902 to 1904. He concluded that "the law of direct variation of the flow of ground waters with head under which the flow takes place are verified by the experiments in the tank.[12]

[5] See bibliography in Slichter, C. S., Theoretical investigation of the motion of ground waters: U. S. Geol. Survey 19th Ann. Rept., pt. 2, pp. 380–384, 1899.

[6] King, F. H., Principles and conditions of the movements of ground water: U. S. Geol. Survey 19th Ann. Rept., pt. 2, pp. 178–195, 1899.

[7] Idem, pp. 107–124, 135–157.

[8] Idem, pp. 157–178.

[9] Idem, pp. 124–135.

[10] Idem, p. 204.

[11] Slichter, C. S., Field measurements of the rate of movement of underground waters: U. S. Geol. Survey Water-Supply Paper 140, pp. 29–49, 1905.

[12] Slichter, C. S., op. cit., p. 48.

Experiments have recently been performed in the laboratory of the Geological Survey in Washington, D. C., that confirm the applicability of Darcy's law to very low hydraulic gradients. Using a constant-head discharging apparatus devised by Meinzer [13] (see pp. 56–59), extensive tests were made on beach sand collected at Fort Caswell, N. C. Stearns plotted the hydraulic gradient in feet per mile against discharge in milligrams per second and reports, "The resulting curve down to a gradient of 5 feet to the mile approximates a straight line and supports Darcy's law for this sand for hydraulic gradients ranging from about 5.20 to 0.1 percent, or from about 270 to 5 feet to the mile." [14] The apparatus used did not allow experiments to be carried on accurately with hydraulic gradients much lower than 5 feet to the mile. Later a nondischarging apparatus was designed to accommodate precise experiments with low heads.[15] (See pp. 66–68.) The Fort Caswell sand was again used, and from the experiments performed with the new apparatus it was concluded that "for the type of sand used the flow varies at least approximately with the hydraulic gradient, down to a gradient of 1 foot to the mile and probably to considerably lower gradients." [16] Additional tests with the new apparatus "show rather conclusively that for the material tested [Fort Caswell sand] the rate of flow varies directly as the hydraulic gradient, down to a gradient of 2 or 3 inches to the mile and that there are indications that Darcy's law holds for indefinitely low gradients." [17]

It has been recognized for some time that the flow of water in open channels and pipes may be either laminar or turbulent. With laminar flow the water particles move in more or less parallell lines, whereas with turbulent flow eddies occur and the water particles move in circuitous paths. In general, laminar flow occurs at relatively low velocities and turbulent flow at higher velocities.

The nature of the two modes of fluid motion was first demonstrated by Reynolds [18] in a series of experiments on parallel glass tubes of various diameters up to 2 inches. The velocity at which eddy formation is first noted in a long tube is termed the higher critical velocity. There is also a lower critical velocity at which the eddies in originally turbulent flow die out. Over the range between the two critical velocities the fluid, if moving with streamline flow, is in an unstable state, and a slight disturbance may cause it to break down into turbu-

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[13] Stearns, N. D., Laboratory test on physical properties of water-bearing materials: U. S. Geol. Survey Water-Supply Paper 596, pp. 144–147, 1928.

[14] Idem, p. 155.

[15] Meinzer, O. E., and Fishel, V. C., Tests of permeability with low hydraulic gradients: Am. Geophys. Union Trans., 1934, pp. 405–406.

[16] Idem, p. 409.

[17] Fishel, V. C., Further tests of permeability with low hydraulic gradients: Am. Geophys. Union, Trans., 1935, p. 503.

[18] Reynolds, Osborne, An experimental investigation of the circumstances which determine whether the motion of water shall be direct or sinuous and of the law of resistance in parallel channels: Roy. Soc. London Trans., vol. 174, pp. 935–982, 1883.

lent motion. Reynolds showed that the conditions of flow for any tube and liquid could be characterized by the nondimensional quantity

$$R=\frac{vD\rho}{\mu} \qquad (2)$$

in which v is the mean velocity, D is the diameter of the tube, ρ is the density of the liquid, and μ is the viscosity of the liquid. R is called the Reynolds number. R has a value of approximately 2,000 for the lower critical velocity. Thus

$$v_L=\frac{2{,}000\mu}{D\rho} \qquad (3)$$

in which v_L is the lower critical velocity.

From the above expression it is evident that laminar flow depends on the velocity of the fluid and is not limited to tubes of capillary size. Tolman [19] has made a valuable contribution by pointing out the popular fallacy that laminar flow is associated only with capillary tubes.

So long as the flow through granular materials is laminar the velocity varies directly as the loss in head—that is, the flow conforms to Darcy's law. When the flow is turbulent, however, the velocity increases less rapidly than does the loss in head. It follows, therefore, that Darcy's law and all hydrologic work based on Darcy's law pertain only to laminar flow.

The rate of percolation of most ground waters is very slow, and it is likely that laminar flow occurs under the natural hydraulic gradients that exist in most water-bearing formations. This is confirmed by many recent experiments, including those performed in the hydrologic laboratory of the Federal Geological Survey, in which the flow of water through samples of sand was observed to vary directly as the head under gradients between 270 feet and 2 or 3 inches to the mile. Tolman,[20] from an analysis of the work of Poland,[21] Givan,[22] Hickox,[23] McCurdy [24] and others, concludes that "at normal ground-water gradients, which seldom exceed 1 percent, or 53 feet to the mile, turbulent flow in sands and gravels is virtually nonexistent." Muskat,[25] in discussing the higher gradients that occur near discharging wells, states "* * * it is clear that it is safe to conclude that in the great majority of flow systems of physical interest the flow will be strictly governed by Darcy's law, except possibly in very localized parts of the porous medium of very limited dimensions."

19 Tolman, C. F., Ground water, p. 196, New York, McGraw-Hill Book Co., Inc., 1937.

20 Tolman, C. F., op. cit., p. 200.

21 Poland, J. F., Unpublished experimental work mentioned by Tolman, C. F., op. cit., p. 197.

22 Givan, C. V., Flow of water through granular material: Unpublished thesis, Stanford University, 1933.

23 Hickox, G. H., Flow through granular materials: Am. Geophys. Union Trans 1934, pp. 567–572.

24 McCurdy, R. C., A study of the petroleum drainage problem: Unpublished thesis, Standord University, 1933.

25 Muskat, Morris, The flow of homogeneous fluids through porous media, p. 68, New York, McGraw-Hill Book Co., Inc., 1937.

It is evident that the several methods for determining permeability which are outlined in this paper and which are based on Darcy's law can be used only when the ground-water flow is of the laminar type. There appears to be ample evidence, however, to indicate that most ground-water movement is of the laminar type and that the movement closely follows Darcy's law.

COEFFICIENT OF PERMEABILITY

The constant P in the equation $Q=PIA$ has been designated by different names and has been expressed in various units. Although there still are no generally accepted dimensions for the constant it is now rather widely called the coefficient of permeability and is usually expressed as

$$P=\frac{\text{volume of flow}}{\text{(time) (cross-sectional area) (hydraulic gradient)}}$$

Two coefficients of permeability are used by the division of ground water of the Geological Survey. One coefficient is defined by Meinzer [26] as the rate of flow of water, in gallons a day, through a cross-sectional area of 1 square foot under a hydraulic gradient of 100 percent at a temperature of 60° F. (See fig. 1.) That is,

$$P_m=\frac{\text{1 gal. at 60° F.}}{\text{(day)(ft.}^2\text{)(1 ft. }H_2O\text{/ft.)}} \qquad (4)$$

This coefficient may be expressed in field terms as the number of gallons of water that would be conducted, were the temperature of the water 60° F., through each mile of water-bearing bed under investigation (measured at right angles to the direction of flow) for each foot of thickness of the bed and for each foot per mile of hydraulic gradient.

The other coefficient of permeability used by the division of ground water may be called the field coefficient of permeability and is defined as the number of gallons of water a day that percolates under prevailing conditions through each mile of water-bearing bed under investigation (measured at right angles to the direction of flow) for each foot of thickness of the bed and for each foot per mile of hydraulic gradient.

In this report the symbol P is used to denote the coefficient of permeability expressed in any units, the symbol P_m is used to denote the coefficient of permeability as defined by Meinzer, and the symbol P_f is used to denote the field coefficient of permeability just defined. Thus

$$P_m=C_tP_f \qquad (5)$$

where C_t is a temperature correction (see p. 62).

[26] Stearns, N. D., Laboratory tests on physical properties of water-bearing materials: U. S. Geol. Survey Water-Supply Paper 596, p. 148, 1928.

It is recognized that the coefficient of permeability, in order to relate only to the structure of the water-bearing material, should be defined also in terms of the acceleration due to gravity, g, and the

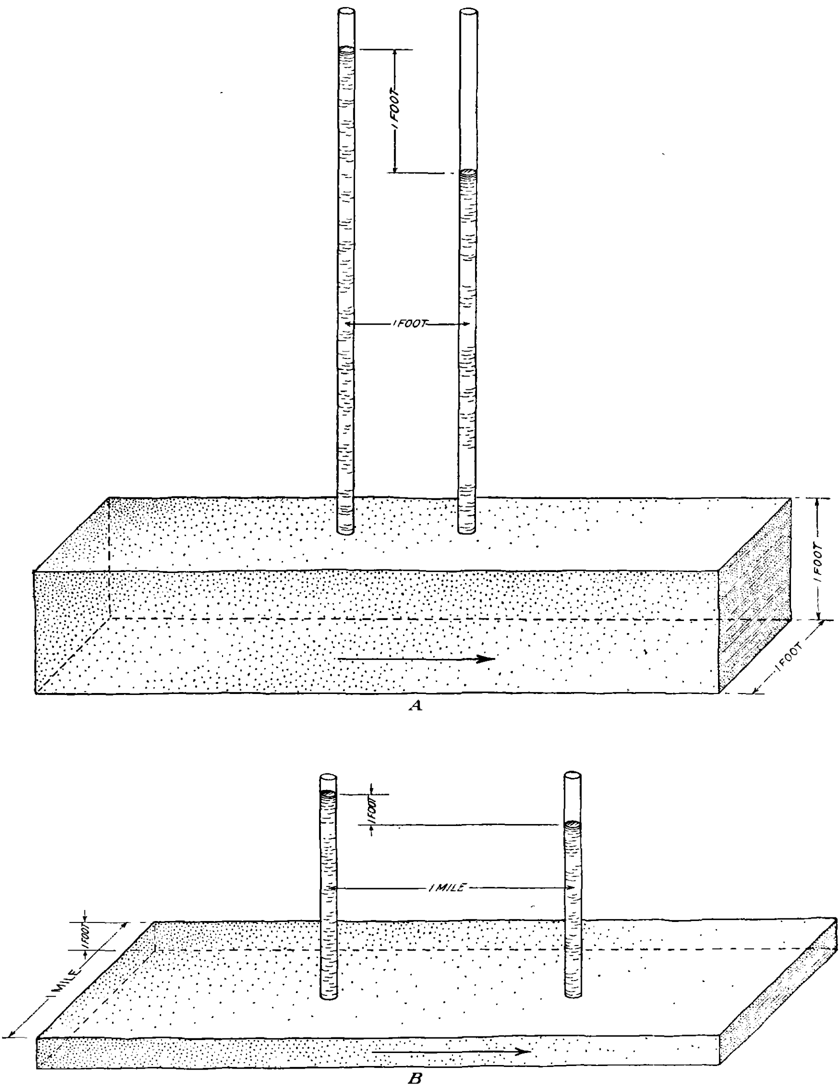

FIGURE 1.—Diagram illustrating laboratory and field application of the coefficient of permeability, P_m, expressed in Meinzer's units. A, Rate of flow, in gallons a day, through a cross section of 1 square foot, under a hydraulic gradient of 100 percent at 60° F. B, Rate of flow, in gallons a day, through a 1-foot thickness of water-bearing material 1 mile in width, under a hydraulic gradient of 1 foot a mile, at 60° F.

density, ρ, of water. However, changes in the coefficient of permeability caused by changes in g and ρ are extremely small, and it is not generally considered necessary to correct for them.

The units of gallon, day, and square foot, selected by Meinzer as those most generally applicable to ground-water work, in this report are called Meinzer's units.

Other permeability units in use in the United States are given below, and conversion factors for changing these units into Meinzer's units or Meinzer's units to these units, computed by V. C. Fishel, of the Geological Survey, are given in the table on page 10 and are followed by the data used for computing the conversion factors.

The coefficients of permeability expressed in various units for water at temperatures of 60° and 68° F. can be changed into Meinzer's units, $\frac{\text{1 gal. at 60° F.}}{(\text{day})(\text{ft.}^2)(\text{ft. } H_2O/\text{ft.})}$, by multiplying by the proper factor in the third or fourth column of the conversion table. The fifth and sixth columns give conversion factors for changing the coefficient of permeability expressed in Meinzer's units at a temperature of 60° F. into the other units at temperatures of 60° and 68° F.

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.

Conversion table

[Prepared by V. C. Fishel]

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	$\frac{1\ cm.^3}{sec.\ cm.^2\ (1\ cm.\ H_2O/cm.)}$	1.897×10^{4}	2.120×10^{4}	5.270×10^{-5}	4.716×10^{-5}.
2	$\frac{1 cm.^3}{sec.\ cm.^2\ (gm./cm.^2)\ cm.}$	1.894×10^{4}	2.118×10^{4}	5.280×10^{-5}	4.721×10^{-5}.
3	$\frac{1\ cm.^3}{sec.\ cm.^2\ (dyne/cm.^2)\ cm.}$	1.848[b] $\times 10^{7}$	2.077×10^{7}	5.410×10^{-8}	4.814×10^{-8}.
4	$\frac{1\ cm.^3}{sec.\ cm.^2\ (atmosphere/cm.)}$	18.24[b]	20.50	5.482×10^{-2}	4.877×10^{-2}.
5	$\frac{1\ ft.^3}{min.\ ft.^2\ (1\ ft.\ H_2O)/ft.)}$	9.640×10^{3}	1.077×10^{4}	1.037×10^{-4}	9.283×10^{-5}.
6	$\frac{1\ ft.^3}{sec.\ ft.^2\ (1/g\ ft.\ H_2O/ft.)}$	1.861×10^{7}	2.079×10^{7}	5.374×10^{-8}	4.809×10^{-8}.
7	$\frac{1\ in.}{hr.\ (1\ ft.\ H_2O/ft.)}$	13.39	14.96	7.470×10^{-2}	6.684×10^{-2}.
8	$\frac{1\ in.^3}{min.\ in.^2\ (lb./in.^2)\ in.}$	28.97	32.40	3.452×10^{-2}	3.086×10^{-2}.
9	$\frac{1\ in.^3}{hr.\ ft.^2\ (lb./in.^2)\ 0.5\ in.}$	0.966	1.080	1.036	0.926.
10	$\frac{1\ ft.^3}{sec.\ ft.^2\ (lb./ft.^2)\ ft.}$	3.604×10^{7}	4.031×10^{7}	2.774×10^{-6}	2.481×10^{-6}.

[a] The numbers refer to those used in the preceding list of permeability units.
[b] Determined for a viscosity of 1 centipoise, that is, for a temperature of approximately 68.4° F.

Data for computing conversion factors

Density of water at 60° F. = 0.9990 gms./cm.^{3}
Density of water at 68° F. or 20° C. = 0.9982 gms./cm.^{3}
Viscosity of water at 60° F. = 1.124 centipoises.
Viscosity of water at 68° F. = 1.005 centipoises.
1 gm. = 980.665 dynes (assumed value).
1 lb. = 453.5924 gms.
1 lb./in.^{2} = 2.309 ft. water at 60° F.
1 lb./in.^{2} = 2.311 ft. water at 68° F.
1 lb./in.^{2} = 70.31 gms./cm.^{2}
1 gm./cm.^{2} = 1.001 cm. water at 60° F.
1 gm./cm.^{2} = 1.002 cm. water at 68° F.
1 atm. = 76.0 cm. mercury at 32° F.
1 atm. = 76.0 x 13.5951 gms./cm.^{2} = 1,033.228 gms./cm.^{2}
1 atm. = 1.01325×10^{6} dynes/cm.^{2}
1 atm. = 1,034.2 cm. water at 60° F.
1 atm. = 1,035.1 cm. water at 68° F.
1 inch = 2.5400 cm.
1 ft. = 30.480 cm.
1 ft.^{2} = 929.03 cm.^{2}
1 cm.^{3} = 0.26417×10^{-3} gal.
1 ft.^{3} = 7.4806 gal.
1 gal. = 0.13368 ft.^{3}
1 gal. = 231.00 in.^{3}

Recently Theis [27] introduced the very convenient term "coefficient

[27] Theis, C. V., The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage: Am. Geophys. Union Trans., 1935, p. 520.

of transmissibility," which is the product of the field coefficient of permeability and the thickness of the saturated portion of the aquifer. It is equal to the quantity P_fA in the equation $Q=P_fIA$ divided by the width of the section considered. The field coefficient of permeability for a homogeneous formation is a constant factor, whereas the coefficient of transmissibility varies according to the thickness of the saturated part of the formation.

PERMEABILITIES OF NATURAL EARTH MATERIALS

The permeabilities of natural earth materials vary widely. Fine sand is in general less permeable than coarse sand and therefore transmits less water through equal cross-sectional areas under the same hydraulic gradient. Clay may contain more water per unit volume than sand or gravel, but the permeability of a clayey material is generally low, and therefore the quantity of water transmitted through it is usually much less than is transmitted through sand and gravel. Coefficients of permeability, expressed in Meinzer's units, ranging from about 0.0002 for a clayey silt to 90,000 for a gravel have been determined in the hydrologic laboratory of the Geological Survey. Thus the gravel carries water at a rate about 450,000,000 times that of the clayey silt. There doubtless are materials with permeabilities higher and lower than those determined in the laboratory.

The material with the coefficient of permeability of 0.0002 consisted of 21 percent of clay, 44 percent of silt, and 35 percent of coarser grained material, but it had a porosity of 58.2 percent (see table, p. 13). Under a gradient of 10 feet to the mile the rate of movement of water through this clayey silt would be about 0.0004 inch a year or 1 foot in about 30,000 years. In the material with a coefficient of permeability of 90,000 about 90 percent of the grains were larger than 2 millimeters. The porosity was 38 percent. The rate of movement of water through this coarse material under a hydraulic gradient of 10 feet to the mile would be about 60 feet a day, or 1 mile in about 3 months. Under higher gradients the velocities through both the fine and coarse materials would be proportionally greater.

Although there are many water-bearing materials of low permeability, most formations that are sufficiently water-bearing to be utilized by wells have coefficients that are whole numbers of two or more figures when expressed in Meinzer's units—that is, above 10.[28] The yields of wells depend, of course, not only on the permeability of the formations they tap but also on the thickness of the formations, the drawn-down of the water level, and the diameter and construction of the wells. For many places in the United States the physical and economic conditions are such that wells with moderate to high yields—

[28] Meinzer, O. E., Movements of ground water: Am. Assoc. Petroleum Geologists Bull., vol 20, No. 6, p. 710, 1936.

100 gallons a minute or more—generally penetrate materials with coefficients of permeability of 100 or more.

Meinzer [29] cites the Carrizo sand in the Winter Garden region of Texas as an example of a more or less average performance of a moderately productive water-bearing formation. This formation, which is believed to have an average coefficient of permeability of about 200 and a porosity of about 40 percent transmits water under a hydraulic gradient of 10 feet to the mile at an average rate of about 50 feet a year, or about 1 mile in 100 years. This slow motion gives a computed flow of water through a 60-mile section of the formation, about 200 feet thick, of about 24,000,000 gallons a day, or about 27,000 acre-feet a year.

The hydrologic laboratory for determining the physical properties of natural earth materials was established under Meinzer's direction, in the Geological Survey, Washington, D. C., in 1923. Since that time tests have been made in the laboratory on more than 2,000 samples of material for composition, apparent specific gravity, porosity, moisture equivalent, or coefficient of permeability, and small specimens of the materials have been preserved in the laboratory for reference. Most of the samples tested have been collected in connection with intensive quantitative ground-water investigations carried on by the Geological Survey in comparatively small areas, and as a result the physical properties of only a few of the more effective water-bearing formations have as yet been determined.

Coefficients of permeability have been determined in the hydrologic laboratory for 1,327 samples of material from 23 States. Of these determinations less than 500 are published, but the others are available for inspection in the files of the Geological Survey, Washington, D. C. Many other permeability tests have been made by the Geological Survey with the variable-head type of discharging apparatus described on pages 59–64, but these tests have been performed in the field and the results are not readily available.

The physical properties of 35 earth materials from the United States are listed in the accompanying table according to the coefficients of permeability. The list includes the highest and lowest coefficients determined in the hydrologic laboratory, together with a representative group of samples with coefficients that fall within these extreme limits. The table shows that the coarser-grained materials in general have larger coefficients of permeability, but it also shows that there is no strict relation between the size of grains and the coefficient of permeability. The table also indicates that it is difficult to specify a range of coefficients within which a material predominately clay, silt, fine sand, medium sand, coarse sand, or gravel will fall. For example, samples with laboratory numbers 2,254 and 2,159 include

[29] Meinzer, O. E., op. cit., p. 710.

respectively 32.8 percent and 31.8 percent of medium sand, which is the predominant material in both samples. Sample 2,254, however, includes considerable fine sand, very fine sand, silt, and clay, whereas sample 2,159 includes comparatively little of these fine-grained materials. As a result the coefficient of permeability of sample 2,254 is 45 and that of sample 2,159 is 8,350.

Physical properties of representative materials from the United States

[Samples are listed according to the coefficient of permeability]

Laboratory No.	Size of grain (percent by weight)								Apparent specific gravity	Porosity (percent)	Moisture equivalent (percent by volume)	Coefficient of permeability
	Larger than 2.0 mm. (gravel)	2.0–1.0 mm. (fine gravel)	1.0–0.5 mm. (coarse sand)	0.50–0.25 mm. (medium sand)	0.25–0.125 mm. (fine sand)	0.125–0.062 mm. (very fine sand)	0.062–0.005 mm. (silt)	Smaller than 0.005 mm. (clay)				
1,001	--------	[1] 0.6	[2] 1.0	[3] 3.0	[4] 5.7	[5] 24.7	[6] 44.0	21.0	1.62	58.2	49.5	0.0002
2,278	--------	--------	--------	[7] 2.5	.9	1.0	45.3	49.3	1.20	55.5	37.4	.2
2,275	--------	--------	--------	[7] 3.2	8.4	23.2	53.7	11.8	1.44	45.1	18.1	6
2,282	--------	--------	--------	[7] 8.4	26.1	15.9	20.4	28.6	1.19	54.2	21.8	20
2,286	19.6	24.2	17.4	25.9	8.8	1.3	[8] 1.5	--------	1.54	37.0	9.7	30
2,254	--------	[1] 3.2	17.2	32.8	21.2	19.6	[8] 6.8	--------	1.58	39.3	9.6	45
2,261	--------	[1] 6.1	26.2	49.4	15.2	1.9	[8] 1.3	--------	1.40	46.6	9.7	60
2,259	--------	[1] 34.5	16.3	25.0	14.2	6.8	[8] 3.3	--------	1.74	34.3	9.4	85
2,277	--------	--------	--------	[7] .3	17.0	49.1	23.9	10.0	1.27	52.2	9.4	100
1,382	15.4	15.2	20.2	19.5	16.4	7.0	4.5	1.5	1.92	26.3	3.0	150
1,389	14.3	11.9	18.2	25.1	18.7	6.5	3.0	1.7	1.88	41.8	3.1	220
1,383	17.3	10.7	13.1	29.4	24.4	3.2	1.0	.4	1.84	30.2	3.0	350
1,374	29.7	16.9	18.9	17.1	15.4	1.3	.4	.2	1.90	27.1	2.6	480
1,234	17.7	13.3	21.2	24.3	12.5	5.2	[8] 4.3	--------	1.75	33.2	3.0	590
1,385	27.4	14.9	16.3	22.4	11.8	3.7	2.1	1.0	1.92	25.6	3.0	730
1,381	15.9	11.0	20.1	33.4	15.4	2.6	.4	.2	1.83	31.2	2.7	925
2,292	21.1	17.7	25.8	23.5	9.7	.7	[8] .2	------	1.85	28.9	1.4	1 000
1,562	17.9	31.4	32.2	14.0	2.0	.8	[8] .4	--------	1.63	31.4	--------	1,200
1,396	31.3	21.0	19.6	19.6	6.5	1.2	.5	.1	1.95	26.1	2.3	1,370
1,376	16.8	15.2	25.8	29.4	10.5	1.6	.5	.1	1.80	32.3	2.0	1,460
1,398	8.5	16.5	28.2	36.6	8.9	.7	.3	.1	1.84	29.7	1.7	1,820
1,386	20.6	19.6	19.7	19.1	9.7	4.3	4.4	.9	1.92	25.0	2.8	2,095
2,287	25.9	33.3	27.1	11.0	1.0	.1	[8] .4	--------	1.77	30.0	2.3	2,400
1,397	[9] 46.9	14.5	17.1	16.6	4.1	.4	.2	.1	1.91	27.5	--------	2,515
1,393	40.4	15.5	22.8	16.5	3.9	.4	.3	.1	1.87	27.2	2.6	2,600
2,156	31.3	14.8	32.8	15.2	2.0	3.3	[8] .5	--------	1.77	33.3	--------	3,450
2,327	63.3	9.9	15.4	9.3	1.4	.4	[8] .2	--------	1.99	25.4	--------	3,970
2,325	75.2	8.6	9.4	5.2	.7	.2	[8] .2	--------	2.06	23.4	--------	4,200
2,316	48.1	21.2	13.4	7.1	4.4	2.8	[8] 2.3	--------	1.86	28.1	3.7	4,400
108	[10] 71.7	13.7	10.2	3.1	[11] .9	[12] .1	[8] .4	--------	1.67	31.9	7.1	6,200
2,159	23.4	7.5	26.9	31.8	5.9	3.6	[8] .4	--------	1.79	33.3	--------	8,350
1,564	68.2	14.8	11.8	4.2	.4	.1	[8] .2	--------	1.86	25.6	--------	12,800
99	79.8	1.1	2.2	4.9	[11] 4.5	[12] 2.7	[13] 3.6	1.2	1.89	25.1	--------	20,663
2,250	70.0	19.4	6.9	3.6	.3	.2	[8] .2	--------	--------	36.8	--------	25,000
2,241	90.0	7.9	1.0	1.0	.1	.1	[8] .1	--------	--------	38.0	--------	90,000

[1] Larger than 1.0 mm.
[2] 1.0 to 0.59 mm.
[3] 0.59 to 0.26 mm.
[4] 0.26 to 0.09 mm.
[5] 0.09 to 0.05 mm.
[6] 0.05 to 0.005 mm.
[7] Larger than 0.25 mm.
[8] Includes clay.
[9] 34.1 percent larger than 5 mm.
[10] Large pebbles discarded in field.
[11] 0.25 to 0.10 mm.
[12] 0.10 to 0.05 mm.
[13] 0.05 to 0.005 mm.

The following is a brief summary of the permeability determinations made in the hydrologic laboratory of the Geological Survey. References are given to the published permeability figures. Where no references are given the results have not been published but are on file and may be consulted in the office of the Geological Survey, Washington, D. C.

1,001. Escalante Valley, Utah, SE¼NW¼ sec. 36, T. 28 S., R. 11 W. Sample from 8.4-inch auger hole; depth 3.3–3.4 feet. Unpublished.

2,278. Flathead Valley, Mont. Subsoil at well 30; depth 0.5–2 feet. Published (see footnote 34).

2,275. Flathead Valley, Mont. Silty sand in steep bank on south side of Flathead River at Jackson gage. Published (see footnote 34).

2,282. Flathead Valley, Mont. Subsoil 100 yards west of well 5; depth 0–0.5 foot. Published (see footnote 34).

2,286. Arkansas Valley, Kans., NE¼NW¼ sec. 29, T. 26 S., R. 1 E. From well 3 miles north of Wichita; depth 18–19 feet. Published in this report (p. 143).

2,254. San Luis Valley, Colo., sec. 23, T. 39 N., R. 11 E. From well 12N23N1; depth 5.2–6.3 feet. Late Pliocene or early Pleistocene, Alamosa formation. Published (see footnote 30).

2,261. San Luis Valley, Colo., sec. 14, T. 38 N., R. 10 E. From well 13M14D1; depth 3.0–4.5 feet. Late Pliocene or early Pleistocene, Alamosa formation. Published (see footnote 30).

2,259. San Luis Valley, Colo., sec. 36, T. 40 N., R. 10 E. From well 11M 36R1; depth 5.0–5.7 feet. Late Pliocene or Early Pleistocene, Alamosa formation. Published (see footnote 30).

2,277. Flathead Valley, Mont. Sand from south bank of Flathead River 150 feet north of well 23. Published (see footnote 34).

1,382. Platte Valley, Nebr., NW¼ sec. 17, T. 11 N., R. 8 W. From drilled well; depth 42–46 feet. Pleistocene. Published (see footnote 35).

1,389. Platte Valley, Nebr., NW¼ sec. 17, T. 11 N., R. 8 W. From drilled well; depth 78–86 feet. Pleistocene. Published (see footnote 35).

1,383. Platte Valley, Nebr., NW¼ sec. 17, T. 11 N., R. 8 W. From drilled well; depth 46–51 feet. Pleistocene. Published (see footnote 35).

1,374. Platte Valley, Nebr., NW¼ sec. 17, T. 11 N., R. 8 W. From drilled well; depth 6–10 feet. Pleistocene. Published (see footnote 35).

1,234. Platte Valley, Nebr., NE¼ sec. 21, T. 8 N., R. 16 W. From auger hole; depth 2–5 feet. Pleistocene sand and gravel. Published (see footnote 35).

1,385. Platte Valley, Nebr., NW¼ sec. 17, T. 11 N., R. 8 W. From drilled well; depth 55–61 feet. Pleistocene. Published (see footnote 35).

1,381. Platte Valley, Nebr., NW¼ sec. 17, T. 11 N., R. 8 W. From drilled well; depth 40–42 feet. Pleistocene. Published (see footnote 35).

2,292. Arkansas Valley, Kans., NE¼NW¼ sec. 29, T. 26 S., R. 1 E. From well 3 miles north of Wichita; depth 36–38 feet. Published in this report (p. 143).

1,562. Long Island, N. Y., Creedmoor State Hospital, Queens Village. From well; depth 360 feet. Cretaceous. Unpublished.

1,396. Platte Valley, Nebr., SE¼ sec. 12, T. 8 N., R. 17 W. From drilled well. Sand and gravel. Pleistocene. Published (see footnote 35).

1,376. Platte Valley, Nebr., NW¼ sec. 17, T. 11 N., R. 8 W. From drilled well; depth 16–20 feet. Pleistocene. Published (see footnote 35).

1,398. Platte Valley, Nebr., SE¼ sec. 12, T. 8 N., R. 17 W. From drilled well. Sand and gravel. Pleistocene. Published (see footnote 35).

1,386. Platte Valley, Nebr., NW¼ sec. 17, T. 11 N., R. 8 W. From drilled well; depth 61–66 feet. Pleistocene. Published (see footnote 35).

2,287. Arkansas Valley, Kans., NE¼NW¼ sec. 29, T 26 S., R. 1 E. From well 3 miles north of Wichita; depth 19–20 feet. Published in this report (p. 143).

1,397. Platte Valley, Nebr., SE¼ sec. 12, T. 8 N., R. 17 W. From drilled well. Pleistocene sand and gravel. Published (see footnote 35).

1,393. Platte Valley, Nebr., SE¼ sec. 12, T. 8 N., R. 17 W. From drilled well. Pleistocene sand and gravel. Published (see footnote 35).

2,156. South-central Nebraska, sec. 4, T. 2 N., R. 10 W. From gravel pit 12 feet above water table. Pleistocene sand and gravel. Published (see footnote 35).

2,327. Croton Valley, N. Y., about 1 mile downstream from Croton Dam. From well D20D. Pleistocene glacial valley fill. Unpublished.

2,325. Croton Valley N, Y., about 1 mile downstream from Croton Dam. From well D9C. Pleistocene glacial valley fill. Unpublished.

2316. Croton Valley, N. Y., about 1 mile downstream from Croton Dam. From well 14E. Pleistocene glacial valley fill. Unpublished.

108. Delair, N. J., Puchack Run field of Camden Water Department. From test well 2; depth 185 feet. Upper Cretaceous, Raritan formation. Published (see footnote 36).

2,159. South-central Nebraska, sec. 4, T 2 N., R. 10 W. From gravel pit 30 feet above water table. Pleistocene sand and gravel. Published (see footnote 35).

1,564. Long Island, N. Y., Creedmoor State Hospital, Queens Village. From well; depth 670 feet. Cretaceous. Unpublished.

99. Fergus County, Mont., SE¼ sec. 30, T. 16 N., R. 18 E. Quaternary, Pleistocene (?) gravel of Judith Basin. Published (see footnote 33).

2,250. Long Island, N. Y., Locust Valley Water District, Locust Valley. Depth 525–527 feet. Cretaceous. Unpublished.

2,241. Long Island, N. Y., Village of Hempstead. From well; depth 195½–234 feet. Pleistocene glacial gravel. Unpublished.

Arkansas.—Permeability determinations have been made on 45 samples of material taken from wells in the Grand Prairie region. The materials tested are alluvium of Pleistocene age—probably early Pleistocene—which represent the water-bearing formations that extend from about 50 to 150 feet below the surface. From these materials 1,000 or more irrigation wells withdraw water at individual rates ranging from about 500 to 3,000 gallons a minute. The coefficients of permeability of the samples range from 0.78 to 1,790; 12 of the samples have coefficients above 1,000 and 38 have coefficients above 200. The records are unpublished.

California.—Tests for permeability have been made on 179 samples of material collected in the Mokelumne area near Lodi, Calif. The materials represent the Victor formation, of Pleistocene age, and Recent alluvium. The results are not published.

Colorado.—Permeability determinations have been made on [illegible] samples of valley fill from the Closed Basin area in San Luis Valley. The samples were taken from 12 wells on the valley floor and represent the Alamosa formation, of Late Pliocene or early Pleistocene age. The coefficients of permeability of the samples range from about 1 to 650.[30]

Delaware.—Permeability tests have been made on 8 samples of material from a well at Laurel representing material from depths of 21 to 90 feet. The coefficients of permeability range from 734 to 4,011. The results are unpublished.

Idaho.—Tests for permeability have been made on 30 samples of material from Idaho. Seven of the samples are from Jerome, Fremont, Caribou, Jefferson, and Clark Counties and represent loess, black gumbo, and gravelly loam soils and clay. The coefficients of permeability range from 0.26 to 20.[31] Three samples of loess have coefficients of 7.3, 8.4, and 11. The results of tests on 23 samples, including 1 from Malad Valley and 22 from Kootenai Valley, are unpublished.

Iowa.—One sample of a water-bearing gravel from Sheldon has been tested for permeability. The coefficient is 457. The analysis is unpublished.

Kansas.—Permeability tests have been run on 42 samples of material from Kansas, 10 of which are alluvium from a well in the Arkansas Valley near Wichita. The coefficients of permeability range from 30 to 4,500 and average 2,470. The analyses of the well samples are given in this paper (p. 143), but those for the other 32 samples are unpublished.

Maryland.—Permeability determinations have been made on 8 samples of material from a well at Salisbury, The coefficients range from 252 to 1,190, The results are unpublished.

Michigan.—Tests for permeability have been made on 10 samples of material from Roscommon County. The coefficients range from 350 to 1,500. The results are unpublished.

Montana.—Thirty-one samples of material from Montana have been tested for permeability in the hydrologic laboratory. Seventeen

[30] Robinson, T. W., and Waite, H. A., Ground water in the San Luis Valley, Colorado: U. S. Geol. Survey mimeographed report, p. 26, 1937.

[31] Stearns, N. D., Laboratory tests on physical properties of water-bearing materials: U. S. Geol Survey Water-Supply Paper 596, p. 164, 1928.

of the samples, representing formations ranging in age from Quaternary to Upper Cretaceous, are from Rosebud County. The coefficients range from about 1 to 1,233.[32] One sample of Pleistocene (?) gravel is from Judith Basin in Fergus County and has a coefficient of 20,663.[33] The coefficients of 10 samples of glacial delta material from Flathead Valley range from 0.2 to 850.[34] Of these samples 8 have coefficients of 20 or less. The results obtained by tests on 3 additional samples are unpublished.

Nebraska.—Tests for permeability have been made on 47 samples of material from Nebraska, the results of which are published.[35] Nineteen of the samples represent Pleistocene clay, sand, and gravel taken from a well in the Platte River Valley near Grand Island. The coefficients of permeability range from 2 for a sample of clay to 4,350 for a sample of sand and gravel (see p. 118). The average permeability of the section represented by the 19 samples is about 1,200. Four samples of loess were collected from the Platte Valley. The coefficients ranged from 1 to 4. Seven samples of Pleistocene sand and gravel and one sample from the Ogallala formation of Tertiary age, were taken from a well in the Platte Valley near Kearney. The coefficients for the sand and gravel range from 770 to 2,600 and the coefficient for the Ogallala formation is 15. Five samples of soil and six samples of sand from the Platte Valley were also tested. The coefficients for the soil range from less than 1 to 3 and for the sand from 270 to 2,600. Five samples of Pleistocene sand and gravel were collected from above the water table in a gravel pit near Cowles, Webster County. The coefficients range from 250 to 8,350 and average 2,650.

New Jersey.—Permeability tests have been made on 181 samples of material from New Jersey. Coefficients for 33 of the samples from various parts of the State, listed in order of geologic age, are published.[36] The samples range in geologic age from Recent to Upper Cretaceous and in coefficients from 1.6 to 10,464. Coefficients for 24 samples representing the so-called 800-foot sand, of Tertiary age, at Atlantic City range from 616 to 10,464.[37] Four of these determinations are duplicates of those published by Stearns. According to Thompson the average coefficient of the 24 determinations is 2,662. Thompson lists the coefficients of permeability for two samples of the Mount Laurel-Wenonah sand, of Upper Cretaceous

[32] Stearns, N. D., op. cit., p. 168. Renick, B. C., Geology and ground-water resources of central and southern Rosebud County, Mont.: U. S. Geol. Survey Water-Supply Paper 600, p. 36, 1929.

[33] Stearns, N. D., op. cit., p. 165.

[34] Cady, R. C., Effect upon ground-water levels of proposed surface-water storage in Flathead Lake, Montana: U. S. Geol. Survey Water-Supply Paper 849, p. 80, 1941.

[35] Lugn, A. L., and Wenzel, L. K., Geology and ground-water resources of south-central Nebraska: U. S. Geol. Survey Water-Supply Paper 779, pp. 90–93, 98, 1938.

[36] Stearns, N. D., op. cit., pp. 166–167.

[37] Thompson, D. G., Ground-water supplies of the Atlantic City region: New Jersey Dept. Cons. and Devel. Bull. 30, pp. 89–91, 1928.

age, from a well at Avon by the Sea as 566 and 877.[38] Coefficients have been determined for seven samples representing the No. 1 sand in the Raritan formation, of Upper Cretaceous age, near Parlin.[39] The coefficients of permeability range from 210 to 3,500. Results of 119 tests on New Jersey materials are unpublished.

New Mexico.—Permeability determinations have been run on 66 samples of material, of which 24 from Lea County have been published.[40] The materials from Lea County are Tertiary sands that were collected from outcrops. The coefficients range from 15 to 125 and average about 60.

New York.—Twenty-three samples of material from wells on Long Island have been tested for permeability in the hydrologic laboratory. The coefficients, all of which are unpublished, range from 500 to 90,000. The samples represent materials ranging in age from Pleistocene to Cretaceous.

North Carolina.—One hundred thirty-two permeability tests have been made on samples of material from North Carolina. Ninety-nine of the tests were run on samples of beach sand from Fort Caswell, in which the flow of water through each sample was observed under several heads.[41] The coefficients of 17 samples from the Elizabeth City area have also been determined.[42] Of these, four samples with coefficients of 350 to 750 are from a deep test well, eight samples with coefficients of 475 to 700 are from shallow test holes, and five samples with coefficients of 75 to 1,450 are from road cuts, a sand pit, and a dug well. Determinations on 16 samples from North Carolina are not published.

Oregon.—Permeability tests have been made on nine samples of material from Harney Valley and on two samples from Willamette Valley. Eight of the samples from Harney Valley represent valley fill and one sample represents the Harney formation (?). Coefficients of permeability of these materials range from 2 to 73,000. The two samples from Willamette Valley represent valley fill and have coefficients of 695 and 1,050. The determinations are unpublished.

Pennsylvania.—Two samples representing water-bearing material tapped by the Meadville City wells have been tested for permeability. The coefficients are 670 and 2,130. The determinations are unpublished.

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38 Thompson, D. G., Ground-water supplies in the vicinity of Asbury Park: New Jersey Dept. Cons. and Devel. Bull. 35, p. 37, 1930.

39 Barksdale, H. C., Water supplies from the No. 1 sand in the vicinity of Parlin, N. J.: New Jersey Water Policy Comm. Special Rept. 7, p. 10, 1937.

40 Theis, C. V., Progress report on the ground-water supply of Lea County, New Mexico: 11th Bienn. Rept. of State Engineer of New Mexico, p. 133, 1934.

41 Stearns, N. D., op. cit., pp. 153–159.

42 Lohman, S. W., Geology and ground-water resources of the Elizabeth City area, N. C.: U. S. Geol. Survey Water-Supply Paper 773, pp. 26, 38–39, 1936.

South Dakota.—Permeability determinations have been made on three samples of sandstone from the Dakota group, of Cretaceous age, from Canton.[43] The coefficients are 57, 81, and 69.

Tennessee.—Permeability tests have been run on 172 samples of material, mostly sands, collected from wells and outcrops in western Tennessee. Of these samples 112 have been published.[44] The following table gives a summary of the determinations.

Permeability of material from western Tennessee

Number of samples	Geologic formation or group	Source	Coefficient		
			Maximum	Minimum	Average
12	Wilcox group (Tertiary)	Well 51 of the Memphis Artesian Water Department.	1,181	503	840
22	do	Wells in Memphis and nearby areas.	3,936	348	1,295
48	do	Outcrop area	1,488	9	514
7	Ackerman formation (Tertiary).	Wells	919	132	802
23	Ripley formation (Cretaceous).	Outcrop area	2,347	29.5	670

Texas.—Tests for permeability have been made on 286 samples of material from several areas in Texas. Nine samples of the Trinity sand from the Big Spring area were found to have coefficients ranging from 9 to 90. The average of the coefficients is 34. Coefficients of permeability were determined on two samples of "basal sands" of the Trinity group in Hood County.[45] The average of the coefficients is 176. Thirty-five samples were obtained from a well near Lufkin. The coefficients of the samples range from less than 1 to 435 and average 171.

Utah.—Permeability tests have been made on two samples of material from the Escalante Valley. The coefficients are 0.0002, the lowest yet determined in the hydrologic laboratory, and 80. Tests have also been made on two samples of material from the vicinity of Salt Lake City. The coefficients are 0.2 and 5,250. The analysis of the sample with the very low permeability from Escalante Valley is given in this report (p. 13). The other three analyses are unpublished.

Virginia.—Permeability tests have been made on 16 samples of material from Virginia. Eight of the samples were obtained during the construction of the Bell well and Swart well 162 near Washington, D. C.[46] The coefficients of five samples from the Bell well range from

[43] Meinzer, O. E., Problems of the soft-water supply of the Dakota sandstone: U. S. Geol. Survey Water-Supply Paper 597, p. 163, 1929.

[44] Wells, F. G., Ground-water resources of western Tennessee: U. S. Geol. Survey Water-Supply Paper 656, pp. 82–83, 96–104, 1933.

[45] Fiedler, A. G., Artesian water in Somervell County, Tex.: U. S. Geol. Survey Water-Supply Paper 660, p. 46, 1934.

[46] For location of the wells see Water levels and artesian pressures in the United States in 1935: U. S. Geol. Survey Water-Supply Paper 777, p. 250, 1936.

1 to 7 and those of three samples from the Swart well range from 1 to 18.[47] Coefficients for eight samples from southeastern Virginia are unpublished.

Wyoming.—Eight samples of material from the vicinity of Jackson Lake have been tested in the laboratory for permeability. Six samples collected along the shore of the lake have coefficients ranging from 11 to 164 and two samples obtained from wells have coefficients of 178 and 187. The analyses are unpublished.

ORGANIZATIONS MAKING PERMEABILITY TESTS IN THE UNITED STATES

The Geological Survey in 1935 made an inventory of the organizations in the United States that are making or have made laboratory or field tests of the permeability of rock materials or other porous media. A questionnaire soliciting information regarding methods used to determine permeability and the manner of expressing results was sent to 59 organizations that were believed to be interested in permeability. Replies to the questionnarie were received from 35 organizations. Replies were not received from a few organizations known to have made permeability studies, and there were probably others that failed to receive the questionnaire. Replies were received from 17 organizations engaged in studies relating to oil production with the view to increasing the yield of oil, such as by flooding or repressuring the formations; 5 organizations engaged solely in general research relating to the flow of liquids through porous media; 4 organizations concerned with the permeability of soils used for agricultural purposes—in this connection with studies of the reclaiming of alkali soils, of the effect of entrapped air on the rate of movement of soil water, and of the rate at which water can be applied to soils for irrigating; 3 organizations that employed permeability tests in connection with quantitative studies of ground-water supplies, including the determination of the transmissibility of water-bearing formations and the leakage from reservoirs; 3 organizations interested in the permeability of soils in connection with engineering projects; 2 organizations engaged in earth and foundation engineering and the construction of dams; and 1 organization engaged in highway engineering. One reply stated that permeability tests were made to study the movement of gas in coal strata with the view to determining the laws governing the movement, control, and recovery of gas. Tests of permeability were made in one laboratory in connection with investigations of the drying behavior of porcelain bodies, the burning behavior of different kinds of brick, and the problems involved in the utilization of refractories in water-gas sets and boiler settings. One reply stated that permeability tests were being made on stone used in masonry structures. Tests of permea-

[47] Cady, R. C., Ground-water resources of northern Virginia: Virginia Geol. Survey Bull. 50, p. 36, 1938.

bility of soils and subsoils are being made in one laboratory in connection with the improvement of the public highways.

Names and addresses of organizations replying to permeability questionnaire

Carter Oil Co., Tulsa, Okla.
Clinger Oil & Gas Co., Tidioute, Pa.
Crew Levick Co., Titusville, Pa.
Forest Oil Corporation, Bradford, Pa.
Ginter Chemical Laboratory, Tulsa, Okla.
Gulf Research & Development Corporation, Pittsburgh, Pa.
Harvard University, Cambridge Mass.
Humble Oil & Refining Co., Houston, Tex.
Iowa Institute of Hydraulic Research, Iowa City, Iowa.
Iowa State College, Ames, Iowa.
Los Angeles Department of Water and Power, Los Angeles, Calif.
National Bureau of Standards, Washington, D. C.
Olean Petroleum Co., Olean, N. Y.
Oregon State Agricultural College, Corvallis, Oreg.
Pacific Hydrologic Laboratory, San Francisco, Calif.
Pennsylvania State College, State College, Pa.
Petroleum Reclamation Co., Bradford, Pa.
Phillips Petroleum Co., Bartlesville, Okla.
Shell Petroleum Corporation, Tulsa, Okla.
Sinclair Prairie Oil Co., Independence, Kans.
The Sloan & Zook Cos., Bradford, Pa.
Stanford University, Department of Mining Engineering, Stanford, Calif.
Stanford University, Department of Geology, Stanford, Calif.
Stanolind Oil & Gas Co., Tulsa, Okla.
Torrey, Fralich & Simmons, Bradford, Pa.
United States Bureau of Mines, Bartlesville, Okla.
United States Department of Agriculture, Washington, D. C.
United States Geological Survey, Washington, D. C.
University of California, College of Agriculture, Davis, Calif.
University of California, Hydraulics Laboratory, Berkeley, Calif.
University of Idaho, Moscow, Idaho.
University of Illinois, Urbana, Ill.
University of Minnesota, Minneapolis, Minn.
West Virginia University, Morgantown, W. Va.
Yale University, New Haven, Conn.

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By V. C. Fishel

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METHODS FOR DETERMINING PERMEABILITY

The interrelation and classification of the various methods for determining permeability of water-bearing materials is indicated by the chart following. No attempt has been made to describe each method completely but only to present the most important features. For many formulas the symbols used by the originator have been changed for consistency.

LABORATORY METHODS

The laboratory methods for determining permeability consist of indirect and direct methods. Permeability is determined by the indirect methods from analyses of samples of material for such physical properties as grain size and porosity and by the direct methods from observations on the percolation of water through samples of the material. The coefficient of permeability is computed by the indirect methods through the evaluation of semiempirical formulas that include factors for the size and arrangement of the soil particles, or conversely, the voids formed by the particles; the formulas for the direct methods include factors for the observed rate of percolation, cross-sectional area of the sample of material, and hydraulic gradient under which the percolation takes place. In general, the factors for the indirect formulas are more difficult to determine and are usually less accurate than those for the direct formulas.

INDIRECT METHODS

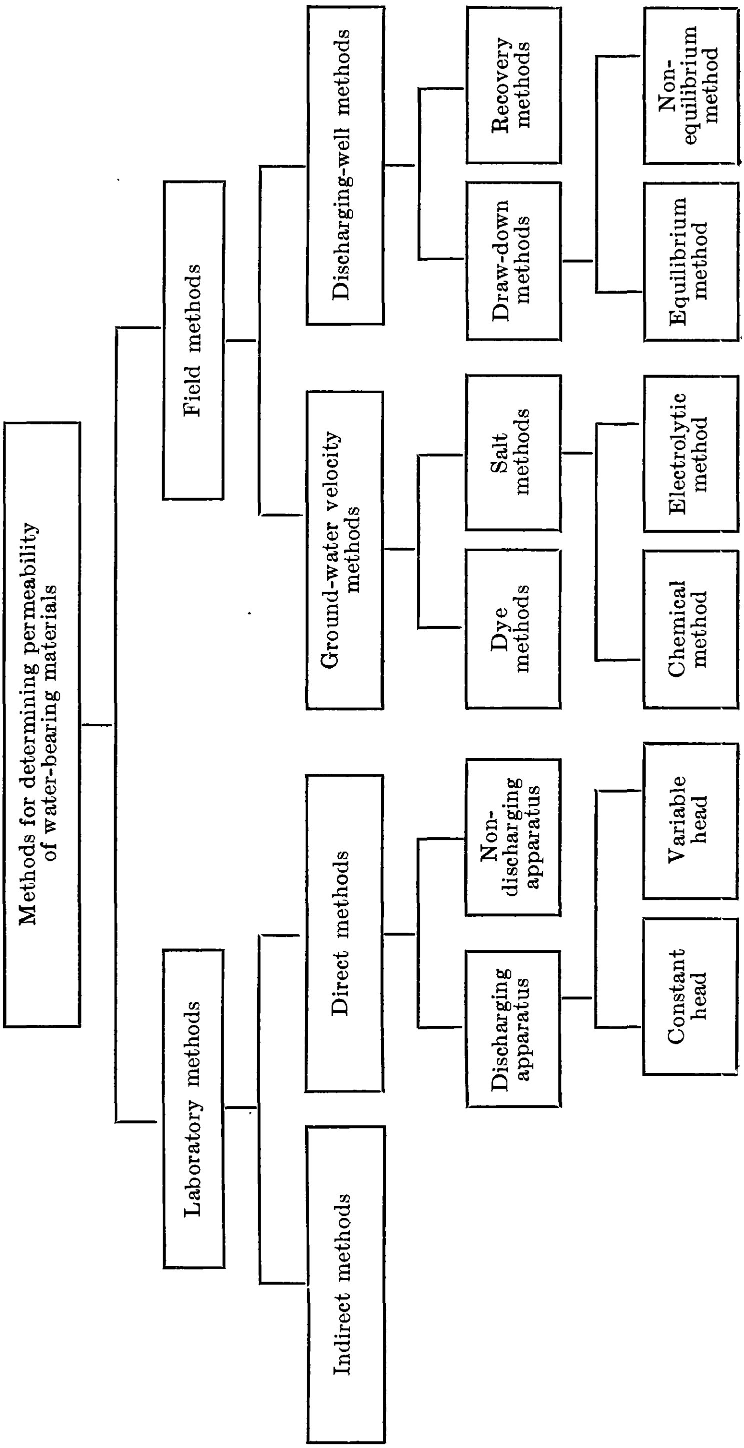
Presented here are the indirect permeability formulas of Hazen, Slichter, Terzaghi, Hulbert and Feben, and Fair and Hatch. A general discussion of the value of the indirect methods is given under the heading "Comparison of methods" (pp. 68–71).

Hazen formula.—Hazen's formula [48] for computing the flow of water through sand includes the determination of permeability by means of a mechnical analysis of the sand. His formula is

$$v=\frac{Cd_e^2h}{l}(0.70+0.03\theta) \qquad (6)$$

in which v is the velocity of the water, in meters a day, in a solid column of the same area as that of the sand, C is a constant, d_e is the "effective

[48] Hazen, Allen, Some physical properties of sands and gravels with special reference to their use in filtration: Massachusetts State Board of Health 24th Ann. Rept., p. 553, 1893.


Methods for determining permeability of water-bearing materials
Field methods
Laboratory methods
Discharging-well methods
Ground-water velocity methods
Direct methods
Indirect methods
Recovery methods
Draw-down methods
Salt methods
Dye methods
Non-discharging apparatus
Discharging apparatus
Non-equilibrium method
Equilibrium method
Electrolytic method
Chemical method
Variable head
Constant head

size" of sand grain, in millimeters (a size such that if all grains were of that diameter the sand would transmit the same amount of water that it actually does—determined by Hazen as the diameter of sand grain such that 10 percent of the material is of smaller grains and 90 percent is of larger grains), h is the loss of head, l is the thickness of sand through which the water passes, and θ is the temperature on the centigrade scale.

The formula may also be written

$$v=\frac{Cd_e^2h}{l}\left(\frac{\theta+10}{60}\right) \qquad (7)$$

in which θ is the temperature on the Fahrenheit scale. It should be noted that the velocity v is not the actual rate of percolation. The actual velocity is greater than v by the ratio $\frac{v}{p}$, where p is the effective porosity of the sand.

In the Hazen formula

$$Cd_e^2\left(\frac{\theta+10}{60}\right)$$

represents a coefficient of permeability which at 50° F. becomes simply Cd_e^2. It may be defined as the flow of water through a square meter of sand, in meters a day, under a hydraulic gradient of 100 percent, at a temperature of 50° F.

Hazen at first stated that the constant C was equal to about 1,000 and that his formula was applicable only to sands having a uniformity coefficient[49] below 5 and an effective size of grain from 0.10 to 3.0 millimeters.[50] Later he indicated that the value of C is not entirely constant but depends upon the uniformity coefficient, upon the shape and chemical composition of the sand grains, and upon the purity and compactness of the sand.[51] He stated that C may be as high as 1,200 for very uniform and perfectly clean sand and as low as 400 for very closely packed sand containing a considerable quantity of alumina or iron. Hazen pointed out that the value of C decreases as the uniformity coefficient increases.

Slichter formula.—Slichter[52] developed a similar formula for the flow of water through sand in which the permeability was also determined by means of a mechanical analysis of the sand. Slichter's formula is

$$Q=0.2012\frac{hd_e^2A}{\mu lC} \qquad (8)$$

[49] The uniformity coefficient of a sand is the ratio of (1) the size of grain which has 60 percent of the sample finer than itself to (2) the size which has 10 percent finer than itself. The uniformity coefficient indicates whether the sand particles are chiefly of the same size or whether there is a great range in their diameters.

[50] Hazen, Allen, op. cit., p. 553.

[51] Hazen, Allen, The filtration of public water supplies: New York, John Wiley & Sons, p. 22, 1901.

[52] Slichter, C. S., Theoretical investigation of the motion of ground waters: U. S. Geol. Survey 19th Ann. Rept., pt. 2, p. 322, 1899.

in which Q is the quantity of water, in cubic feet, transmitted by the column of sand in 1 minute; h is the head under which the flow takes place, measured in feet of water; A is the cross-sectional area of the sand column, in square feet; l is the length of the column; d_e is the "effective size" of sand grain, in millimeters; μ is a coefficient of viscosity; and C is a constant.

In Slichter's equation $0.2012 \frac{d_e^2}{\mu C}$ represents a coefficient of permeability and is Slichter's "transmission constant." For a temperature of 50° F. the equation for the transmission constant becomes

$$P=\frac{0.2012 d_e^2}{0.01315 C}=\frac{15.3 d_e^2}{C} \qquad (9)$$

in which P is the flow of water, in cubic feet a minute, through a cross-sectional area of a square foot, under a gradient of 100 percent at a temperature of 50° F.

Slichter[53] has given values for the coefficient of viscosity, μ, for several temperatures and the values for $\frac{1}{C}$ for several porosities. He also gives the following equation, in which the coefficient of viscosity has been replaced by an expression varying with the temperature similar to that given in the Hazen formula:

$$Q=\frac{11.3 h d_e^2 A}{l C}[1+0.0187(\theta-32)] \qquad (10)$$

This formula, however, does not give the same results as his fundamental formula because the expression $11.3[1+0.0187\ (\theta-32)]$ does not equal for all temperatures the expression $\frac{0.2012}{\mu}$, which it replaces. For example, Slichter's coefficient of viscosity for 50° F. is 0.01315, which substituted in the expression $\frac{0.2012}{\mu}$ gives a value of 15.3; whereas the expression $11.3\ [1+0.0187(\theta-32)]$, when evaluated for a temperature of 50° F., gives a value of 15.1. For a water temperature of 60° F. the values for the two expressions are respectively 17.8 and 17.2. Slichter's "transmission constants" were apparently computed by using for the viscosity correction the expression $\frac{0.2012}{\mu}$[54] and $11.3\ [1+0.0187(\theta-32)]$.[55] Hence the two sets do not agree, after a correction is made to reduce the "transmission constants" given in the latter table, which are computed for a water temperature of 60° F., to those for a water temperature of 50° F.

[53] Slichter, C. S., The motions of underground waters: U. S. Geol. Survey Water-Supply Paper 67, pp. 24-25, 1902.

[54] Slichter, C. S., op. cit., p. 27.

[55] Slichter, C. S., Field measurements of the rate of movement of underground waters: U. S. Geol. Survey Water-Supply Paper 140, p. 12, 1905.

If it is assumed that Slichter's fundamental equation is correct, the "transmission constant" as defined previously for a water temperature of 50° F. is equal to the coefficient of permeability expressed in Meinzer's units divided by 12,500; and if the "transmission constant" is defined for a water temperature of 60° F., it is equal to the coefficient of permeability expressed in Meinzer's units divided by 10,770.

Terzaghi formula.—From a series of experiments Terzaghi [56] developed the following semiempirical formula for determining permeability from an analysis of the character of a sand.

$$P=(800 \text{ to } 460)\frac{\mu_0}{\mu_t}\left(\frac{n-0.13}{\sqrt[3]{1-n}}\right)^2 d_e^2 \qquad (11)$$

In this formula P is a coefficient of permeability, μ_o and μ_t are the coefficients of viscosity of the water at 10° C. and at temperature t respectively, n is the void volume (voids divided by total volume), and d_e is the effective size of grain, in centimeters. The value of 800 was derived from tests on sands whose grains were well-rounded, and the value of 460 was derived from tests on irregular rough sand grains.

The formula is based on the assumption that the widest parts of the capillary channels through which the water percolates have at least five times the cross-sectional area of the narrowest parts. Thus the loss of head per unit of length for a given flow through the narrowest channels will be 25 times the loss of head per unit of length through the widest channels. Terzaghi likens the flow of water through sand to the flow of water through a set of sieves in series. The resistance to percolation is confined to the sieves; and the resistance in the spaces between the sieves is negligible.

Hulbert and Feben formula.—The following formula was proposed by Hulbert and Feben [57] for computing the loss of head of water percolating through rapid sand filters.

$$h=\frac{24.2}{10^5}\left[\frac{lQ(69.43-p)}{d_s^{1.89}(\theta+20.6)}\right] \qquad (12)$$

In this, h is the loss of head in feet, l is the depth of sand in inches, Q is the rate of flow in million gallons per acre per day, p is the porosity (percent void by Jackson Turbidimeter tube method), d_s is the size of sand grains in millimeters (50 percent or median sieve size), and θ is the temperature of the water in degrees Fahrenheit.

Hulbert and Feben's experiments were carried on with graded stratified filter sand used in rapid sand filters in contrast with Hazen's experiments, which were made on an unstratified mixture of coarse sand interspersed with fine sand used for slow sand filters. The above formula is applied separately to the material held on each sieve, and

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[56] Terzaghi, Charles, Principles of soil mechanics: Eng. News-Record, vol. 95, p. 832, 1925.

[57] Hulbert, Roberts, and Feben, Douglas, Hydraulics of rapid filter sand: Am. Water Works Assn. Jour., vol. 25, pp. 19–45, 1933.

the sum of these individual losses of head is taken as the loss of head through the entire sand bed.

In the Hulbert and Feben formula

$$P=\frac{10^5 d_s^{1.89}(\theta+20.6)}{24.2(69.43-p)} \qquad (13)$$

in which P is a coefficient of permeability and the other symbols are those defined above.

Fair and Hatch formula.—Fair and Hatch[58] have published two formulas for computing the loss of head of water percolating through sand filters. The first formula, which pertains to unstratified filter sands, is

$$H=KLTFv\left[\frac{S}{100}\text{ sum of }\frac{P}{d}\right]^2 \qquad (14)$$

and the second formula, which relates to stratified sand beds, is

$$H=KLTFv\left[\frac{S^2}{100}\text{ sum of }\frac{P}{d^2}\right] \qquad (15)$$

In both formulas H is the loss of head of water passing through the filter bed in terms of the water column, K is a filtration constant (according to the authors $K=5/g$), L is the vertical depth of the filter bed, T is a temperature viscosity factor (equal to $\frac{m}{r}$ where m is the viscosity and r is the density), F is a porosity factor (equal to $\frac{(1-f)^2}{f^3}$ where f is porosity), v is the velocity of approach over the gross area of the bed (or rate of discharge per unit of cross-sectional area), S is a sand shape factor, P is the percent of sand held between adjacent sieves, and d is the geometric mean of the rated sizes of adjacent sieves.

The coefficient of permeability as obtained from the formula for unstratified sand beds is

$$P=\frac{1}{KTF\left[\frac{S}{100}\text{ sum of }\frac{P}{d}\right]^2} \qquad (16)$$

and as obtained from the formula for stratified sand beds the coefficient of permeability is

$$P=\frac{100}{KTFS^2\left[\text{sum of }\frac{P}{d^2}\right]} \qquad (17)$$

DIRECT METHODS

Many early investigators, including Hazen, Newell, Seelheim, Wollny, and King, devised apparatus for measuring the flow of water through permeable materials. The apparatus of these investigators

[58] Fair, G. M., and Hatch, L. P., Fundamental factors governing the streamline flow of water through sand: Am. Water Works Assn. Jour., vol. 25, pp. 1551–1563, 1933.

has since been altered and improved, new features have been introduced, and the procedure for making percolation tests has been considerably changed. Whereas the early investigators were apparently interested chiefly in measuring the percolation through sand samples in order to study the Darcy law and to devise and to check indirect percolation formulas, the principal use of the percolation apparatus now is to measure directly the permeability of the material.

There are, of course, many kinds of percolation apparatus in use by investigators, and a description of each will not be practicable in this paper. However, each general type of apparatus—the constant-head discharging apparatus, variable-head discharging apparatus, and the nondischarging apparatus—is used in the hydrologic laboratory of the Geological Survey, so a discussion of the apparatus and procedure used in this laboratory will include the essential features of all.

V. C. Fishel, physicist of the Geological Survey, who has performed most of the work in the hydrologic laboratory since 1929, has kindly prepared the following text on the direct laboratory methods for determining permeability. Most of the methods and apparatus described by him were devised by O. E. Meinzer, geologist in charge, division of ground water, who organized the laboratory in 1923 and who has supervised its operation since that time.

DISCHARGING APPARATUS

By V. C. Fishel

Constant-head apparatus.—The constant-head type of apparatus was devised by O. E. Meinzer [59] in 1923 to measure the rate of flow of water through columns of unconsolidated materials under low heads, such as are found in nature. The method is to allow inflow of water at the bottom of a column of the material of known height and outflow at the top. The difference in head of water at the bottom and the top is regulated by an adjustable supply tank and is indicated by two pressure gages. Observations are made on the rate of discharge and the temperature of the water.

The apparatus is shown in figure 2. The glass cylindrical vessel *a*, which is called the percolation cylinder, is closed at the lower end and has four openings, two at the bottom and two at the top. It is 3 inches in diameter and 8 inches in height. There is one opening near the bottom, *b*, for inflow of water; one near the top, *c*, for discharge of water that has percolated up through the sample; and two, *d* and *d′*, for pressure gages. The pressure gages consist of two glass tubes, *e* and *e′*, each about half an inch in diameter, that indicate the head at the bottom and top of the column of material that is being tested. The glass tubes must be of sufficient diameter to make capillarity in

[59] Stearns, N. D., Physical properties of water-bearing materials: U. S. Geol. Survey Water-Supply Paper 596, pp. 144-147, 1928.

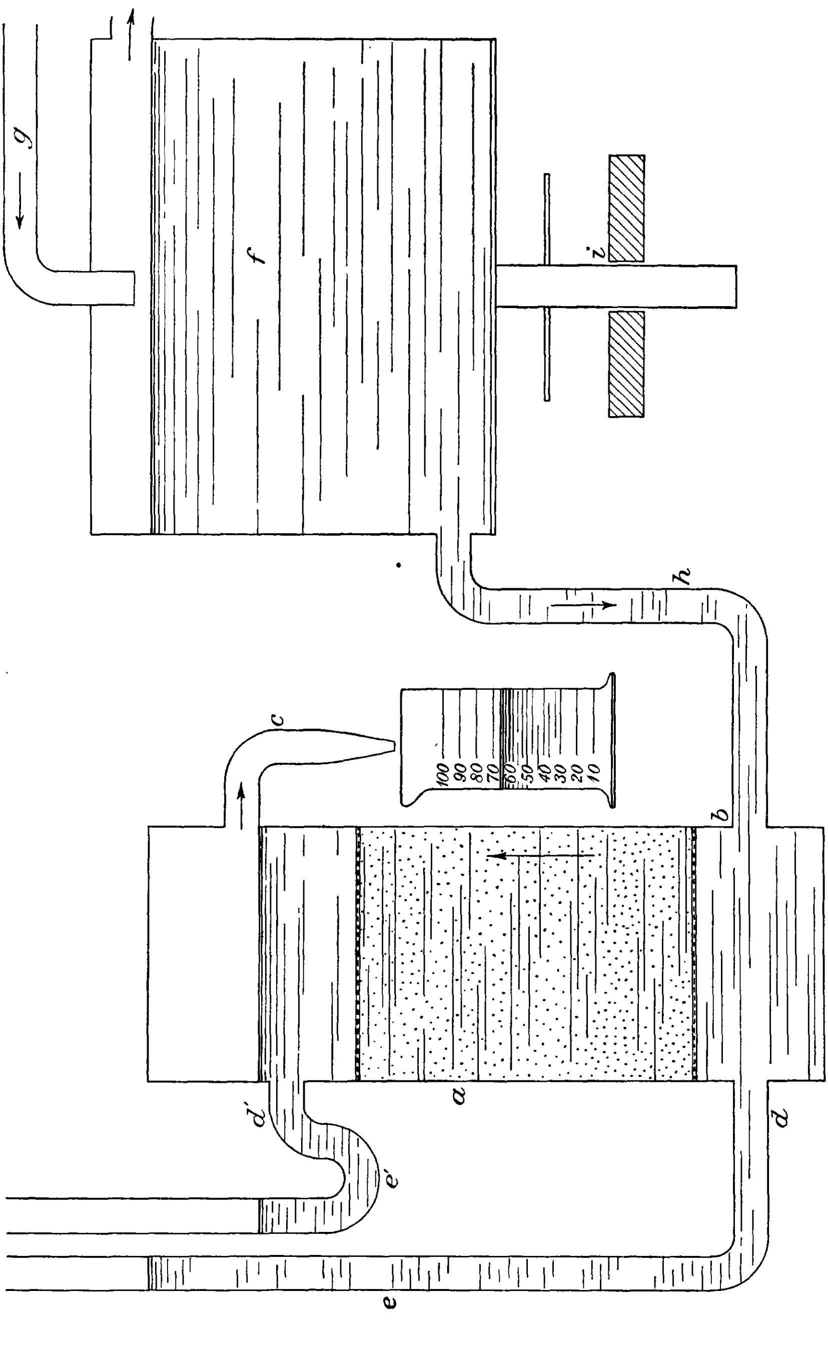

FIGURE 2.—Diagram of constant-head type of discharging permeability apparatus.

them negligible. Another cylindrical vessel, *f*, about 12 inches high and 5 inches in diameter, is used as a water-supply tank. Distilled water enters the supply tank slowly through a glass tube, *g*, from which it passes through a rubber tube, *h*, to the percolation cylinder. The water level in the supply tank is maintained nearly constant by allowing surplus water to leave through an outlet in the side of the tank. The tank can be raised or lowered by means of a screw jack, *i*, with which very fine adjustments of head are possible.

When making a test the apparatus is set up as shown in figure 2, with the material to be tested resting on a fine copper gauze. To prevent entrapping air beneath the screen, water is introduced into the apparatus before the sample is placed in it until the water stands about 1 centimeter above the screen. If the sample was taken volumetrically, the requisite weight of sand to make a column 10 centimeters high, based on the air-dry apparent specific gravity, is slowly poured into the percolation cylinder. Additional water is introduced during the filling process to prevent the water level from dropping below the screen. The sample is shaken, tamped, and jarred in order to reduce it to practically the volume it had in nature. If the sample was not taken volumetrically, the material is packed into the cylinder until a column 10 centimeters high is obtained. It is jarred and tamped to make it as compact as possible, this degree of compaction being assumed to represent that of the natural sample. Serious errors may, of course, result from applying the coefficient of permeability determined in the laboratory to field problems because the natural packing of the formation that was sampled may not be duplicated in the laboratory.

After the percolation cylinder has been filled with the material to be tested, additional water is introduced at the bottom under a low head in order to avoid roiling. Periods of a few minutes to several hours may be required to saturate the sample, depending on whether the material is coarse or fine. The test is begun when water is discharged uniformly from the outlet at the top of the cylinder, and observations are made on the temperature of the water, head, and rate of discharge. After a test has been made at a given head, the supply tank is raised or lowered and a new test is made at a different head. Three to five tests are usually made in order that a considerable range in head will be covered.

According to Darcy's law the volume of water that will percolate through a column of water-bearing material in a given time will be expressed by the equation $Q=PIAt$, in which Q is the volume of percolation, P is the coefficient of permeability, I is the hydraulic gradient, A is the cross-sectional area of the material, and t is the length of the period of flow. The hydraulic gradient under which the constant-head discharging apparatus operates is equal to h (the difference in head at the bottom and top of the water-bearing material), divided by l, the length of the column of material. Hence

$$P=\frac{Ql}{Ath} \quad \text{------------------------} \quad (18)$$

The percolation cylinder has a diameter of 3 inches (7.62 centimeters) and the length of the column of material tested is 10 centimeters. If Q, l, A, and h are measured in centimeters and t in seconds

$$P=\frac{0.2193Q}{ht} \quad \text{--------------------} \quad (19)$$

in which P is the coefficient of permeability expressed as the flow in cubic centimeters per second through a cross-sectional area of 1 square centimeter under a hydraulic gradient of 100 percent. The coefficient of permeability can be expressed in terms of Meinzer's coefficient by multiplying the above metric coefficient by the conversion factor 21,200 (see p. 10). Thus

$$P_m=\frac{4{,}649Q}{ht} \quad \text{-------------------} \quad (20)$$

in which P_m is the flow in gallons per day through a cross-sectional area of 1 square foot under a hydraulic gradient of 100 percent. The coefficient of permeability is defined for a temperature of 60° F. If the test is made at any other temperature a correction factor must be applied according to the procedure explained on page 62.

Permeability tests can be made also on consolidated samples with the constant-head apparatus in the manner described on pages 56–58. The coefficient of permeability expressed in Meinzer's units may be computed by the equation

$$P_m=\frac{21{,}200Ql}{Ath} \quad \text{------------------} \quad (21)$$

in which P_m is the coefficient of permeability, Q is the volume of percolation in cubic centimeters per second, l is the length of the sample in centimeters, A is the cross-sectional area of the sample in centimeters, t is the period of percolation in seconds, and h is the difference in head at the bottom and top of the sample, in centimeters.

Variable-head apparatus.—The variable-head discharging apparatus was designed in 1933 by C. V. Theis primarily for field use in connection with his ground-water investigations in New Mexico. An apparatus of this type, with minor modifications from the original apparatus used by Dr. Theis, is shown in figure 3. It consists of a brass percolation cylinder a, 3.53 centimeters in diameter and 13.25 centimeters high, connected with a manometer tube b, part of which is graduated in centimeters. The inside diameter of the manometer tube is 1.04 centimeters and its height is 35 centimeters. A screen at the base of the percolation cylinder supports the material to be tested. The cylinder is connected with the manometer tube by a copper tube *f*, with suitable packing gland *d*, and pipe reducer *e*. The copper tube is mounted in a lead base *c*. In this type of apparatus the water is forced upward in the percolation cylinder until it spills over the edge. The percolation is caused by a head which is created by initially filling the manometer tube to a higher level than the overflow level of the percolation cylinder. As water flows upward through the sample the water level declines in the manometer tube, with the result that the head which causes the flow diminishes continuously but at a decreasing rate.

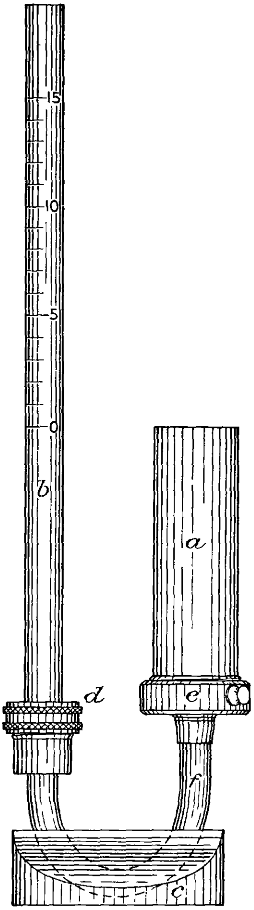

FIGURE 3.—Diagram of variable-head type of discharging permeability apparatus.

In making a test the apparatus is set up as shown in figure 3, with the manometer tube adjusted so that the bottom of the water-level meniscus in the manometer tube is exactly at the zero line at the time water first overflows the percolation cylinder. The level at which water will overflow the percolation cylinder will fluctuate slightly owing to surface tension, but the fluctuation can be eliminated by placing a nail across the top of the cylinder, with the head of the nail about one-sixteenth of an inch from the cylinder. After the zero-level adjustment is completed water is withdrawn from the apparatus until the water level stands about half an inch above the screen in the bottom of the percolation cylinder. Any air bubbles that exist below the screen may be removed by blowing gently into the manometer tube. The material to be tested is then poured into the percolation cylinder until the cylinder is completely filled, care being taken during the process not to allow the water level in the manometer tube to drop out of sight, as an air bubble may be drawn beneath the screen by capilarity. Water is added slowly to the manometer tube to prevent a decline of the water level during the filling process, and the material in the cylinder is compacted either by tamping or by jarring. After the cylinder is filled with material, water is added slowly to the manometer tube until the water level in the manometer tube is raised nearly to the top and the material in the test cylinder becomes saturated. The water level in the tube then declines as the water percolates upward through the material in the percolation cylinder. The test is completed by recording the time at which the water level passes the marked divisions on the manometer tube.

The apparatus used by Dr. Theis was designed particularly for tests on undisturbed samples. One edge of the percolation cylinder is constructed with a cutting edge so that the cylinder can be easily driven into the material to be sampled. However, extreme care must be taken to prevent the entrapping of air beneath the screen when making permeability tests on undisturbed samples. By drilling a small hole in one side of the test cylinder immediately below the screen the entrapped air and some water may be forced out of the cylinder as the water is introduced at the beginning of the test. The hole is closed after all the air is ejected, and the test is then made according to the procedure just described.

According to Darcy's law

$$dQ = PIAdt = \frac{PhAdt}{l} \qquad (22)$$

in which dQ is the volume of percolation through the cylinder in time dt, P is the coefficient of permeability, I is the hydraulic gradient, h is the head under which the percolation is taking place, l is the length of the column of water-bearing material (equal to the length of the test cylinder), and A is the cross-sectional area of the material (equal to the cross-sectional area of the test cylinder).

$$ah_0 - ah = Q \qquad (23)$$

$$h = h_0 - \frac{Q}{a} \qquad (24)$$

and

$$dh = -\frac{dQ}{a} \qquad (25)$$

in which h is the head in the manometer tube at any given time, h_0 is the initial head, Q is the volume of percolation, and a is the cross-sectional area of the manometer tube.

Substituting (25) in (22)

$$-adh = \frac{PhAdt}{l} \qquad (26)$$

$$-\frac{dh}{h} = \frac{PAdt}{al} = \frac{PD^2dt}{d^2l} \qquad (27)$$

in which D is the diameter of the test cylinder and d is the diameter of the manometer tube. By integrating

$$-\log_e h = \frac{PD^2t}{d^2l} + C \qquad (28)$$

When $t=0$, $h=h_0$; hence

$$-\log_e h_0 = C \qquad (29)$$

Substituting (29) in (28)

$$-\log_e h = \frac{PD^2t}{d^2l} - \log_e h_0 \qquad (30)$$

$$\log_e \frac{h_0}{h} = \frac{PD^2t}{d^2l} \qquad (31)$$

$$P = \frac{d^2l \log_e \frac{h_0}{h}}{D^2t} \qquad (32)$$

and

$$P = 2.30259 \frac{d^2}{D^2} \frac{l}{t} \log_{10} \frac{h_0}{h} \qquad (33)$$

The above equation will give the coefficient of permeability expressed as the flow of water in cubic centimeters per second through a cross-sectional area of 1 square centimeter under a hydraulic gradient of 100 percent, if l is measured in centimeters and t in seconds. D, d, h, and h_0 may be measured in any units but D and d must be measured in the same units and h and h_0 must be in the same units. For the apparatus used in the hydrologic laboratory the coefficient of permeability is computed in Meinzer's units by the formula

$$P_m = \frac{56{,}142 \log_{10} \frac{h_0}{h}}{t} \qquad (34)$$

The coefficient of permeability is defined for a water temperature of 60° F. If the test is made at any other temperature, the permeability may be corrected by multiplying the right side of equation 34 by the proper correction factor, which is given below.

Factors for converting coefficients of permeability computed at water temperatures of 40° to 80° F. to coefficients of permeability at water temperature of 60° F.

Water temperature (° F.)	Conversion factor (C_t)	Water temperature (° F.)	Conversion factor (C_t)	Water temperature (° F.)	Conversion factor (C_t)
40	1.37	54	1.09	68	0.89
41	1.35	55	1.08	69	.88
42	1.33	56	1.06	70	.87
43	1.31	57	1.04	71	.86
44	1.28	58	1.03	72	.85
45	1.26	59	1.01	73	.84
46	1.24	60	1.00	74	.83
47	1.22	61	.99	75	.82
48	1.20	62	.97	76	.81
49	1.18	63	.96	77	.80
50	1.16	64	.95	78	.79
51	1.15	65	.93	79	.78
52	1.13	66	.92	80	.77
53	1.11	67	.91		

When permeability tests are made on consolidated samples a glass percolation cylinder is always used in order to facilitate the detection and elimination of air bubbles that may become entrapped beneath the material during the test. The sample to be tested is first cut into a convenient sized cube or core and the sides are carefully coated with paraffin. The paraffin should be warmed to a temperature only slightly above the melting point in order to prevent its penetrating too deeply into the sample. In general the paraffin should penetrate about 2 millimeters into the sample, and a corresponding correction should be made in the cross-sectional area in the permeability formula.

The apparatus is set up in the manner described for making tests on unconsolidated samples and water is introduced into the apparatus until it stands slightly above the screen. The sample is carefully placed on the screen to prevent the entrapping of air beneath the material and additional water is introduced through the manometer tube to replace the water drawn up into the material by capillarity. Paraffin at a temperature just above the melting point then is poured into the annular space between the material and the inner wall of the percolation cylinder. The paraffin, whose base rests on the water surface, soon solidifies and forms a tight seal between the material and the wall of the cylinder. The test is then carried on in the manner described for unconsolidated materials.

For the variable-head apparatus the coefficient of permeability is computed by the equation

$$P_m = \frac{48{,}815al}{At} \log \frac{h_0}{h} \qquad (35)$$

in which P_m is the coefficient of permeability expressed in Meinzer's units, a is the cross-sectional area of the manometer tube in square centimeters, l is the length of the sample in centimeters, A is the cross-sectional area of the sample in square centimeters, t is the time of percolation in seconds, h_0 is the initial head in any unit, and h is the head measured in the same unit as h_0 at any time t.

Whenever possible undisturbed samples of water-bearing material should be collected for permeability tests because changes in the permeability of the samples resulting from a rearrangement of the material are largely eliminated. The apparatus described below, which is a variable-head discharging apparatus, was designed especially for testing undisturbed material and is equipped with convenient parts for collecting samples.

The apparatus for collecting samples (fig. 4) consists of a noncorrosive metal collecting cylinder a, which is 13.25 centimeters high and 3.53 centimeters in diameter; a driving head f; some short lengths of connecting pipe *g*, for collecting samples a few feet below the surface; and two cups *h* for clamping over the ends of the cylinder while the sample is being taken to the laboratory. The collecting cylinder has a sharp cutting edge at one end and is threaded at the other end.

The apparatus for making the permeability test consists of the collecting cylinder *a* (fig. 4), which is now used as the percolation cylinder, a manometer tube *b*, a reducer *c*, for connecting the percolation cylinder with the manometer tube, a screen *d*, supported by a clamp around the edge of the cylinder, and a glass receiving reservoir *e*, which is 15 centimeters in diameter and 20 centimeters high. The screen clamp has four legs, which hold the base of the percolation cylinder about a centimeter above the bottom of the glass reservoir. The glass receiving reservoir has an overflow near the top.

The cylinder, after being connected with the driving head, is driven full length into the material to be tested. The driving head is then disconnected and the sample is cut off flush with both ends of the cylinder. The cups are clamped over the ends of the cylinder to prevent spilling, and the sample is then taken to the laboratory for testing. Several samples may be collected at one time by employing interchangeable cylinders.

The cups on the ends of the cylinder are removed in the laboratory, the manometer tube is connected by a reducer to the threaded end of the cylinder, and a screen is clamped on the other end. The cylinder, with the cutting edge pointing downward, is then carefully lowered into the glass reservoir that is partly filled with water. The trapping of air beneath the cylinder is easily prevented by holding the cylinder in an oblique position when the lower end enters the water. After the sample becomes saturated by the upward percolation of water the zero level on the manometer tube is adjusted to the level of the reservoir overflow. Water is then introduced into the manometer tube, from which it percolates downward through the material and overflows the glass reservoir. The test is completed by recording the time required for the water level to pass between the graduations on the manometer tube.

This apparatus has an advantage over the variable-head apparatus previously described in that the trapping of air beneath the screen is easily prevented. However, because the percolation of water is downward the screen would tend to become clogged if the test was carried on over an extended period.

The coefficient of permeability is computed by the same formulas as those employed for the other variable-head apparatus.

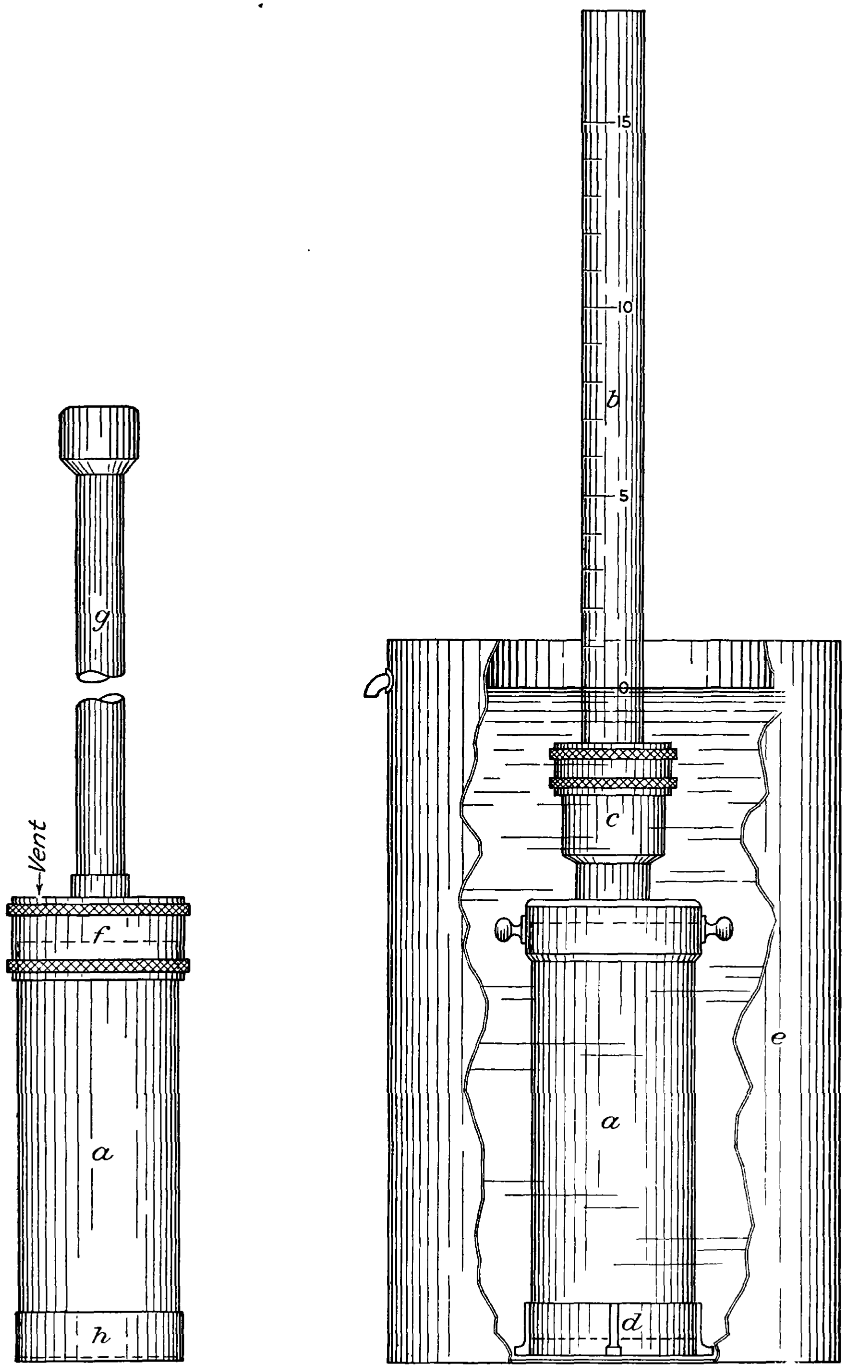

FIGURE 4.—Diagram of apparatus for collecting and making permeability tests of volumetric samples.

NONDISCHARGING APPARATUS

By V. C. Fishel

Apparatus of the nondischarging type was designed by Meinzer [60] in 1933 for making permeability tests under very low hydraulic gradients. It consists of a supply reservoir, a receiving reservoir, and a connecting conduit (percolation tube) containing the sample of material through which the water passes from the supply reservoir to the receiving reservoir (fig. 5). The conduit is a U-tube, constructed from an 8-foot length of ¾-inch copper pipe bent in such a manner that

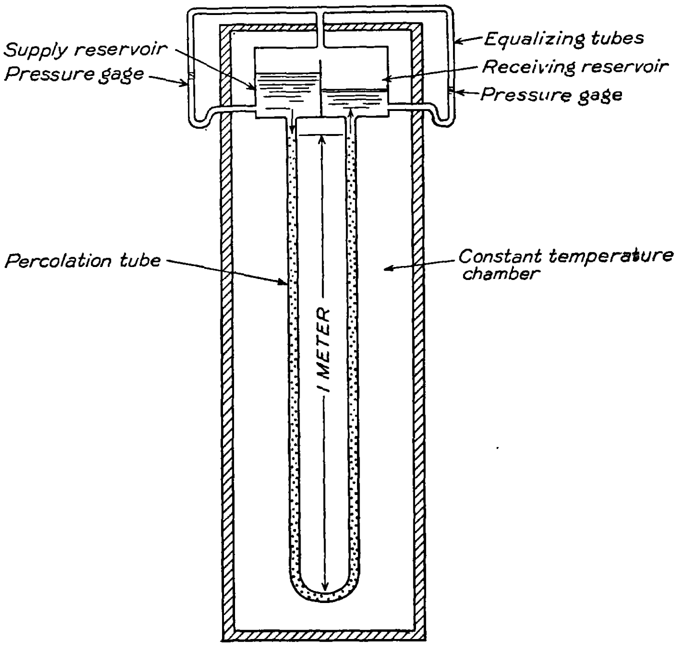

FIGURE 5.—Diagram of nondischarging type of permeability apparatus.

columns of the tube are about 4 inches apart. The length of the sample of sand used in this apparatus is 2 meters. The supply and receiving reservoirs are made of copper sheeting and are 6 inches square. They are tightly covered to prevent evaporation but are connected at the top to insure equal air pressure on the two water surfaces. In the bottom of each reservoir is a compartment 2 inches square with lower walls. By keeping the water levels above the tops of the small compartments, the 6-inch reservoirs may be used, and by lowering the water levels the 2-inch reservoirs may be used. Glass

[60] Meinzer, O. E., and Fishel, V. C., Tests of permeability with low hydraulic gradients: Am. Geophys. Union Trans 1934, pp. 405–09. Fishel, V. C., Further tests of permeability with low hydraulic gradients: Am. Geophys. Union Trans. 1935, pp. 499–503. Meinzer, O. E., Movements of ground water: Am. Assoc. Petroleum Geologists Bull., vol. 20, No. 6, pp. 706–710, 1936.

pressure tubes are connected with each of the reservoirs, and the difference between the water levels in them is obtained with a cathetometer. Pressure tubes 1 centimeter in inside diameter were first originally used, but tubes 1.7 centimeters in diameter were later substituted. The entire apparatus, except the pressure tubes, is enclosed in a constant-temperature chamber, which is kept at a temperature slightly higher than the maximum room temperature. The tubes are connected above with the reservoirs by rubber tubing, to prevent evaporation and to equalize the air pressure in the tubes with that in the reservoirs. Distillation of the water from the reservoirs into the tubes is prevented by inserting a capillary tube in the rubber tubing connecting them.

The test is started with the water level in the supply reservoir at any desired height above the water level in the receiving reservoir. As water flows through the sample the water level declines in the supply reservoir and rises in the receiving reservoir, with the result that the head which causes the flow diminishes continuously but at a decreasing rate. In an apparatus of this type the only observations that are required are the differences in the water levels at stated times and the temperature of the water. The volume of percolation is indicated by the change in water level.

According to Darcy's law the quantity of water dQ that will percolate through the column of water-bearing material in the time dt is

$$dQ=\frac{Pahdt}{l} \qquad (36)$$

in which P is the coefficient of permeability, a is the cross-sectional area of the material, h is the head causing the percolation, and l is the length of the column of water-bearing material.

The drop in water level Z_1 in the supply reservoir in time t will be $Z_1=\frac{Q}{A}$ and the rise of the water level Z_2 in the receiving reservoir will be $Z_2=\frac{Q}{B}$. Q is the volume of percolation, A is the cross-sectional area, of the supply reservoir plus the cross-sectional area of the pressure gage; B is the cross-sectional area of the receiving reservoir plus the cross-sectional area of the pressure gage. If h_o is the initial head and h is the head at any subsequent time

$$h_o-h=Z_1+Z_2=\frac{Q}{A}+\frac{Q}{B}=\frac{Q(A+B)}{AB} \qquad (37)$$

and

$$-dh=\frac{(A+B)dQ}{AB} \qquad (38)$$

Substituting (38) in (36)

$$-\frac{ABdh}{(A+B)h}=\frac{Padt}{l} \qquad (39)$$

Integrating

$$-\frac{AB}{A+B}\log_e h=\frac{Pat}{l}+C \qquad (40)$$

When $t=0$, $h=h_0$, and

$$C=-\frac{AB}{A+B}\log_e h_0 \qquad (41)$$

Substituting (41) in (40)

$$-\frac{AB}{A+B}\log_e h=\frac{Pat}{l}-\frac{AB}{A+B}\log_e h_0 \qquad (42)$$

$$P=\frac{lAB}{at(A+B)}\log_e\frac{h_0}{h} \qquad (43)$$

When the supply reservoir and the receiving reservoir have equal cross-sectional areas

$$P=\frac{A^2l}{2Aat}\log_e\frac{h_0}{h}=\frac{Al}{2at}\log_e\frac{h_0}{h} \qquad (44)$$

and

$$P=\frac{2.30259Al}{2at}\log_{10}\frac{h_0}{h} \qquad (45)$$

If A, l, and a are expressed in centimeters and t is expressed in seconds the coefficient of permeability is the volume of water in cubic centimeters per second that will percolate through a cross-sectional area of 1 square centimeter under a hydraulic gradient of 100 percent. The coefficient of permeability may be expressed in Meinzer's units by multiplying by 21,200 (see p. 10).

$$P_m=\frac{24{,}408Al}{at}\log_{10}\frac{h_0}{h} \qquad (46)$$

COMPARISON OF METHODS

The indirect methods of Hazen, Slichter, and Terzaghi are similar in that the formula for each contains the square of the effective, or 10 percent size, sand grain. Hazen's formula makes no allowance, however, for similar material of different porosities except through the selection of the constant in his equation, whereas the formulas of Slichter and Terzaghi include factors to compensate for the degree of compactness. Hulbert and Feben's formula contains factors for sand size (50 percent or medium-sieve size) and for porosity, and the formula of Fair and Hatch includes factors for porosity, percent of sand held between adjacent sieves, and geometric mean of the rated sizes of adjacent sieves.

Probably the greatest difficulty encountered in developing an accurate and generally applicable indirect formula is the selection of proper factors to represent the variations in flow that result from variations in compactness of similar water-bearing material. A given sample of material may be packed tightly and have a comparatively low porosity or it may be packed loosely and have a relatively high porosity. Slichter's [61] study showed that spheres of the same size can be packed with a minimum porosity of 25.95 percent and a maximum porosity of 47.64 percent. The more recent and exhaustive study of the geometry of aggregates of spheres by Graton and Fraser [62] similarly illustrates the wide range in compactness that may be expected to occur in nature. The permeability of a material changes, of course, with the degree of packing. According to Slichter the flow of water through aggregates of spheres with a porosity of 47 percent will be more than 7 times the flow through aggregates of the same sized spheres packed with a porosity of 26 percent. As the permeability is directly proportional to the percolation under a given head, the range of permeability is as wide as the range of flow. It seems likely that the range will be even greater for material with grains of different sizes and shapes, because a heterogeneous material is not likely to be uniformly packed—an assumption on which all the indirect permeability formulas are based.

It appears probable that neither Hazen nor Slichter contemplated the general use of his formula for a wide range of materials but that each felt that his formula applied merely to water-bearing materials similar to those on which the formula was based. Stearns [63] gives a comprehensive outline of work by Hazen, King, and Slichter on effective size in relation to permeability and concludes—

> It is obvious from the foregoing discussion that an indiscriminate use of the 10-percent size for the effective size in Slichter's formula is not warranted. Such extensive use was doubtless not contemplated by Hazen, who merely found the 10-percent size useful in estimating the permeability of the filter materials with which he worked. Nor did Slichter authorize the use of the 10-percent size for the effective size in his formulas.

Hulbert and Feben [64] in discussing the application of their formula state:

> An inspection of the porosity correction of this [their] formula discloses the fact that a definite loss-of-head value would be calculated for a theoretical condition where the sand mass was impervious, and hence of zero porosity, whereas, in fact, the loss of head would be infinitely great. At the other extreme, a porosity value of 69.43 percent or more would result in a computed loss of head of zero, or a negative quantity, when in fact it should be a definite amount. Hence the formula is limited in its application to filtering materials which show void percentages within or not too far removed from the limits which hold for the sands employed in its derivation.

Fraser [65] gives a table showing a comparison between experimental coefficients of permeability and coefficients computed by the formulas

[61] Slichter, C. S., Theoretical investigation of the motion of ground waters: U. S. Geol. Survey 19th Ann. Rept., pt. 2, p. 323, 1899.

[62] Graton, L. C., and Fraser, H. J., Systematic packing of spheres, with particular relation to porosity and permeability: Jour. Geology, vol. 43, No. 8, pp. 785–909, 1935.

[63] Stearns, N. D., Laboratory tests on physical properties of water-bearing materials: U. S. Geol. Survey Water-Supply Paper 596, pp. 170–176, 1927.

[64] Hulbert, Roberts, and Feben, Douglas, op. cit., p. 40.

[65] Fraser, H. J., Experimental study of the porosity and permeability of clastic sediments: Jour. Geology, vol. 43, No. 8, p. 957, 1935.

of Slichter, Terzaghi, and Fair and Hatch. The computed coefficients agree reasonably well with the experimentally determined coefficients, although those computed by the Fair and Hatch formula are consistently high.

The methods of observing the flow of water through samples of material determine the permeability more directly than the methods based on a mechanical analysis of the materials. The indirect permeability formulas apparently do not give correct values for many of the materials found in the field, hence the direct determination of permeability by observing the flow of water through selected samples is generally preferable.

Direct laboratory methods, however, have many difficulties to overcome. Among these are the prevention of evaporation, the elimination of air and mineral constituents from the water, and the prevention of the growth of organisms in the material. Unless the samples were taken undisturbed, another difficulty is to maintain in the permeability apparatus the original arrangement of the grains in the samples.

A practical difficulty in using either the direct or the indirect laboratory methods is the application to field conditions of the permeabilities so determined. In nature almost all of the water-bearing formations are heterogeneous in character, and as a result their permeabilities may vary greatly in short distances. Thus determinations of permeability made in the laboratory on a few samples of a formation may differ greatly from the average permeability of the formation in the field. For example, a well may penetrate a sand and gravel formation that is 100 feet thick and may draw some water from all parts of the formation; yet the arrangement of the material may be such that most of the water percolates through a thickness of a few feet of the formation. In this formation the permeabilities of only samples of the material with either high or low permeability will be highly misleading. The coefficients of permeability of 18 samples of sand and gravel collected at different depths during the drilling of a well near Grand Island, Nebr., and determined in the laboratory by the short-cylinder discharging-type apparatus, ranged from 150 to 4,350 (see p. 118). This indicates that 29 times as much water percolated through each foot thickness of this material at a depth of 30 to 39 feet as percolated through each foot thickness of material at a depth of 42 to 46 feet. Between the depths at which these samples were obtained was a 1-foot layer of clay with a coefficient of permeability of only 2. The movement of water through this compact material is almost negligible. The average permeability throughout the entire thickness of 99 feet as computed by the laboratory method is about 1,200.

The collection of clean samples presents another problem inherent in both direct and indirect laboratory methods. Where the samples are obtained in connection with drilling operations, care must be taken that material is not contaminated by other parts of the formation, that the finer material is not washed out of the sample or added to it, and that the coarser material is included in the sample. Where samples are taken from outcrops it is essential to ascertain whether the material so collected is altered from the material whose permeability is being determined. Weathering may greatly alter the permeability of the material. Consideration should be given to the direction of movement of the water in stratified material because the permeability of some stratified material is different in different directions.

If laboratory methods are used, as they necessarily must be in many tests because other methods are not practicable, determinations of permeability should be made on enough samples of the material to represent the entire formation, so that parts differing greatly in permeability will not be overlooked.

FIELD METHODS

GROUND-WATER VELOCITY METHODS

The velocity of ground water can be measured by introducing some substance in a well situated upgradient from the well in which the arrival of the substance is to be detected. Inasmuch as the velocity of ground water is directly proportional to the permeability and porosity of the material through which it moves and to the hydraulic gradient, the coefficient of permeability may be computed if the ground-water velocity, porosity of the material, and the hydraulic gradient are known. The quantity of water flowing through a given cross-sectional area of water-bearing material is computed by the formula

$$Q=pAv \qquad (47)$$

in which Q is the quantity of water, p is the porosity of the material, A is the cross-sectional area, and v is the average velocity of the ground water.

The coefficient of permeability of the water-bearing material is computed by equating equations (47) and (1):

$$pAv=PIA \qquad (48)$$

$$P=\frac{pAv}{IA}=\frac{pv}{I} \qquad (49)$$

This is a general formula. If P is defined in Meinzer's units (i. e.—P_m), p is expressed as a ratio of the volume of voids to the total volume of material, v is given in feet a day, C_t is the temperature correction, and I is in feet per foot, the equation is

$$P_m=\frac{7.48pvC_t}{I} \qquad (50)$$

For example, if the measured velocity of ground water in a certain formation is 3 feet a day, the porosity of the material 25 percent, the water temperature 50° F., and the natural hydraulic gradient 10 feet a mile, the coefficient of permeability is

$$P_m=\frac{7.48\times0.25\times3\times1.16}{0.00189}=3{,}440 \qquad (51)$$

The hydraulic gradient of an aquifer should not be confused with the slope of dip of the aquifer. The slope of an aquifer between two points may be defined as the ratio of the difference in elevation of the two points to the horizontal distance between the two points. The hydraulic gradient is the ratio of the difference in the level between the points to the length of the saturated material instead of to the horizontal distance between the points. Thus the slope is the tangent of an angle, and the hydraulic gradient is the sine of the angle. For some purposes the slope of the aquifer may be substituted for the hydraulic gradient as the tangent and sine of small angles are almost equal.

DYE METHODS

Probably the first coloration experiments were made in 1882 by Dr. Dionis des Carrières.[66] The tests were made during a severe typhoid epidemic at Auxerre, a city about 85 miles southeast of Paris, to establish the water origin of the disease. Since these experiments were made, dyes have been frequently used for tracing underground movements of water, especially in limestone terranes.

A. Trillat [67] in 1899 made elaborate investigations into the use of certain dyes as flow indicators and the effect on the dyes of passage through common soils. The fluroscope, which is capable of detecting fluorescein as dilute as 1 part in 10,000,000,000, was invented by him. The naked eye can detect fluorescein as dilute as 1 part in 40,000,000. Dole [68] gave an account of the use of fluorescein, described its application and detection, and gave a brief discussion regarding its fitness for use under various conditions. The results of some practical experiments were cited, and a partial bibliography was included.

Fluorescein may be used to measure the velocity of ground water or to trace the source of water. The velocity of the water between two wells parallel with the direction of flow of the ground water can be determined by introducing the dye in the upstream well and noting the time that elapses before the dye appears in the other well. The

[66] Dionis des Carrières, Étiologie de l'épidémie typhoïde qui a éclaté à Auxerre en septembre 1882: Soc. Mid. des Hôpitaux de Paris, Bul. et Mém., 2d ser., vol. 19, pp. 277–286, 1882

[67] Trillat, A., Sur l'emploi des matieres colorantes pour la recherche de l'origine des sources et des eaux d'infiltration [Use of dyes to locate origin of underground water]: Acad. sci. Paris Comptes rendus, vol. 128, pp. 698–700, 1899.

[68] Dole, R. B., Use of fluorescein in the study of the motion of underground waters: U. S. Geol. Survey Water Supply Paper 160, pp. 73–85, 1906.

arrival of the dye at the down-stream well is detected by periodic sampling of the water for color. One difficulty involved in the use of the dye method is the steepening of the gradient and the resultant increase in the velocity of the ground water when a sample is taken from a well. If the upstream and downstream wells are not far apart, the error so introduced may be large. The dye method for determining ground-water velocity in the above manner has been somewhat replaced by the more refined electrolytic method. Dye is employed most for determining the source of ground water and for tracing the underground route that it follows.

A dye was used by Stiles, Crohurst, and Thomson [69] in investigating pollution of ground water at Fort Caswell, N. C. The investigation was made to determine the distance, rate, and conditions of movement of *Bacillus coli* through ground water. A trench 25 feet long, 1.5 feet wide, and 0.6 foot deep was dug below the water table, which was temporarily very high. This trench was dosed with uranin and fecal material. Parallel to the trench, lines of sterilized pipe wells were placed. From October 13, 1922, to May 31, 1923, 1,313 water samples were examined from a total of 122 wells arranged in 21 parallel lines spaced 2 to 115 feet downgradient from the trench. Uranin and *B. coli* moved out gradually at the water table, or very close to it, and both were recovered in water samples taken from wells 2 to 65 feet downgradient from the trench; uranin was recovered from wells as far as 115 feet downgradient from the trench. In another experiment uranin was detected in wells 450 feet downgradient from the trench; *B. coli* was eventually recovered 228 feet downgradient.

SALT METHODS

Chemical method.—According to Meinzer [70] the pioneer in developing field methods for measuring the flow of ground water was Adolph Thiem, whose first paper on the subject was published in 1879. His method was to construct two wells parallel to the direction of ground-water movement and to treat the upgradient well with salt. The time of arrival of the salt solution in the lower well was determined by periodically testing samples of the water for salt content. The velocity of the water was determined by dividing the distance between the two wells by the elapsed time between the introduction of the salt in the upgradient well and its detection in the downgradient well.

As in the dye method, a difficulty inherent in the use of the chemical method is the steepening of the gradient and the resultant increase in the velocity of the ground water when a sample is taken from a well.

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[69] Stiles, C. W., Crohurst, H. R., and Thomson, G. E., Experimental bacterial and chemical pollution of wells via ground water, and the factors involved: U. S. Public Health Service Hygienic Lab. Bull. 147, 166 pp., 1927.

[70] Meinzer, O. E., The history and development of ground-water hydrology: Washington Acad. Sci. Jour., vol. 24, No. 1, p. 25, 1934.

Electrolytic method.—Slichter developed a method for measuring ground-water velocities in which the arrival of a salt in a downgradient well is detected electrically.[71] Several small wells are driven into the water-bearing material in such a manner that the water moves from an upgradient well toward one or more of the downgradient wells. The movement of the salt from the upgradient well to the downgradient wells is observed by means of an electric circuit that utilizes the conductivity of the ground water between the casings of the upgradient and downgradient wells. As the salt moves toward the lower well the conductivity of the water increases. Another electric circuit within each downgradient well is utilized for detecting the time of arrival of the salt. The amount of current that will flow in this circuit depends on the conductivity of the water in the well and is observed by measuring the current that will flow between two electrodes, one in the well and the other in the well casing. The rate of movement of the salt and hence the rate of movement of the ground water is computed from the time elapsing between the introduction of the salt in the central, or upgradient, well and its detection in a well located downgradient. Slichter found by experiment that ammonium chloride was a satisfactory salt for this method. He and others have made satisfactory field tests of ground-water velocities by this method.[72]

There are difficulties in the use of the electrolytic method, many of which also apply to the dye and chemical methods. The method is not satisfactorily adaptable to localities where the ground water has low velocity, because the salt solution, whose specific gravity is somewhat higher than that of the natural water, sinks rather rapidly and may not reach the downgradient wells. In using this method in such a locality, the wells are located comparatively close to one another—usually about 4 feet apart. Under these conditions errors in determining the velocity of the ground water are often introduced by failure to sink the wells exactly plumb, by the diffusion of the salt solution, and by increase in the hydraulic gradient caused by the rise of water in the upgradient well at the time the salt is introduced. Jacob [73] has used two receiving wells as a means of overcoming the increase in hydraulic gradient caused by the introduction of the salt.

[71] Slitchter, C. S., The motions of underground waters: U. S. Geol. Survey Water-Supply Paper 67, p. 48, 1902.

[72] Slichter, C. S., Field measurements of the rate of movement of underground waters: U. S. Geol. Survey Water-Supply Paper 140, 122 pp. 1905; Hamlin, Homer, Underflow tests in the drainage basin of Los Angeles River: U. S. Geol. Survey Water-Supply Paper 112, 54 pp. 1905; Veach, A. C., Slichter, C. S., Bowman, Isaiah, Crosby, W. O., and Horton, R. E., Underground water resources of Long Island, N. Y.: U. S. Geol. Survey Prof. Paper 44, pp. 88-99, 1906; Slichter, C. S., The underflow in Arkansas Valley in western Kansas: U. S. Geol. Survey Water-Supply Paper 153, 90 pp. 1906; Slichter, C. S., and Wolff, H. C., The underflow of the South Platte Valley: U. S. Geol. Survey Water-Supply Paper 184, 42 pp. 1906; Wolff, H. C., The utilization of the underflow near St. Francis, Kans.: U. S. Geol. Survey Water-Supply Paper 258, pp. 98-119, 1911; Jacob, C. E., Ground water underflow in Croton Valley, New York: Am. Geophys. Union Trans. 1938, pp. 419-430.

[73] Jacob, C. E., op. cit., pp. 422-424.

The wells are located on a line with the salt well, and the arrival of the salt solution in both receiving wells is detected electrically. The solution is forced out of the salt well by pouring in water in order to assure its introduction to the ground-water stream. The natural rate of movement is computed from the time elapsing between the arrival of the salt solution in the first receiving well and the second.

It appears reasonable that Slichter's electrolytic method could be applied to the determination of ground-water velocities in the vicinity of discharging wells. Where observation wells are located directly upgradient from the discharging well, salt could be introduced in one of the upgradient observation wells during the time that the main well was discharging and could be detected in one or more of the downgradient observation wells. The velocity so determined can be substituted in equation 49 together with the average hydraulic gradient under which it moved. This gradient can be determined from a profile of the cone of depression.

The velocity determined by any of the methods just outlined will probably be the maximum velocity of the ground water in the particular section tested and therefore may give results for permeability that are too high for the average of the entire section tested. For this reason and also because the ground-water velocities vary considerably in short distances, tests should be made at as many places as possible and the entire thickness of the material should be tested.

DISCHARGING-WELL METHODS

Several formulas that are based on the flow of water into discharging wells can be used either directly or indirectly for the determination of permeability. A basic assumption of the formulas is that the cone of depression around the discharging well has reached equilibrium (steady-state flow of water), and hence these formulas may be called equilibrium formulas. The formulas for some time were used chiefly to determine the amount of water that could be expected to be withdrawn from a well penetrating a formation with a known or assumed permeability and were not used for the direct determination of permeability. However, the formulas are essentially the same as those used later for determining permeability and probably should so be recognized. Thiem [74] apparently was the first hydrologist to determine permeability with this type of formula. Since then several other investigators have developed formulas, all of them practically the same but designed primarily for the determination of permeability.

Theis's formula [75] for determining the draw-down of the cone of depression at any distance from a discharging well is based on an

[74] Thiem, Gunter, Hydrologische Methoden, 56 pp., Leipzig, J. M. Gebhardt, 1906.

[75] Theis, C. V., The relation between the lowering of the piezometric surface and the rate and duration of a well using ground-water storage: Am. Geophys. Union Trans. 1935, pp. 519–524.

analogy between hydrologic conditions in an aquifer and thermal conditions in a similar thermal system. His formula introduced the important factor of time, which was not contained in the formulas of previous investigators, except for the amount of time taken for the cone of depression to reach approximate equilibrium. The permeability of the water-bearing material can be determined by this formula. The formula may be termed a non-equilibrium formula in contrast with the equilibrium formulas because it does not depend on the cone of depression reaching approximate equilibrium. Jacob [76] recently developed the non-equilibrium formula directly from hydrologic concepts. Theis [77] also published a formula for determining permeability from the recovery of the water level in the vicinity of a discharging well after the discharge of the well has stopped.

DRAW-DOWN METHODS

EQUILIBRIUM METHODS

FUNDAMENTAL PRINCIPLE OF EQUILIBRIUM FORMULA

The equilibrium formula is based on the form of the water table or piezometric surface around a discharging well that is supplied by water from a formation whose permeability is to be determined. Ground water obeys the law of fluids in that it always flows away from a point of high head toward one of low head. In other words, the direction of flow is shown by the hydraulic gradient. When a well is pumped some water inevitably is taken out of storage from the well and from the material surrounding it. This reduces the head, creates a hydraulic gradient toward the well, and causes ground water to flow into the well. If the water-bearing formation has a water table, considerable ground water may have to be removed from storage before the gradient will be steep enough to allow the water to flow toward the well at the rate at which it is pumped, thus establishing approximate equilibrium. If the formation is filled with water under pressure only a comparatively small amount of water has to be removed from storage in order to give the required gradient, and hence the draw-down will be more rapid and approximate equilibrium will be more quickly established.

When, with a constant rate of pumping, approximate equilibrium is established, very little water is removed from storage close to the well. If the water table or piezometric surface in a homogeneous formation is horizontal before pumping begins, water percolates toward the pumped well equally from all directions, and the same quantity of water percolates toward the pumped well through each of the

[76] Jacob, C. E., On the flow of water in an elastic artesian aquifer: Am. Geophys. Union Trans. 1940, pp. 574–586.

[77] Theis, C. V., op. cit., p. 522.

indefinite series of concentric cylindrical sections around the pumped well.

According to Darcy's fundamental law the discharge through any of the concentric cylindrical sections of water-bearing material, Q, is equal to PiA, and the permeability of the material, P, equals $\frac{Q}{iA}$. The symbol i is used to represent the hydraulic gradient at a point on the cone of depression around a well that is discharging water, and the symbol I is used to represent the natural hydraulic gradient of the water table or piezometric surface when the well is idle. The two symbols are interchangeable, their use depending upon whether the water table or piezometric surface is cone-shaped or is approximately a plane. As previously explained, after approximate equilibrium has been reached the discharge through all concentric cylindrical sections of water-bearing material is about the same, and the total discharge is approximately equal to the quantity of water being pumped from the well. The hydraulic gradient at a given distance from the pumped well can be determined from the slope of the water table or piezometric surface. For artesian conditions the area of the cylindrical section through which the ground water percolates at that distance from the pumped well is equal to $2\pi rm$ if r is the distance from the pumped well and m is the thickness of the saturated water-bearing material. For water-table conditions the area is equal to $2\pi r(m-s)$, where s is the draw-down at the distance r from the pumped well. Thus the permeability of the water-bearing material can be computed by substituting these figures in the equation $P=\frac{Q}{iA}$.

SIMPLE DEVELOPMENT OF GENERAL EQUILIBRIUM FORMULA

The general equilibrium formula is based on the fundamental principle just outlined, but as a result of the mathematical treatment the determination of the hydraulic gradient, i, is made unnecessary by the substitution for it of a factor involving the draw-down of the water table at two places on the cone of depression.

A water-bearing bed of uniform permeability is assumed to rest on a relatively impervious formation of indefinite areal extent. A well equipped with a pump extends to the bottom of the water-bearing material, and two observation wells are placed on a line with the pumped well (fig. 6). The pump is operated at a uniform rate during a period in which the water table declines and takes a form similar to an inverted cone around the pumped well. The nonpumping water table and the underlying impervious bed are assumed to be horizontal.

The following symbols and nomenclature are used:

Q=discharge of pumped well;
P=coefficient of permeability;
i=hydraulic gradient at any point, J, on the cone of depression;
A=area of any designated cyclindrical section through which the water percolates on its way to the pumped well;
x and y=coordinates of any point, J, on the cone of depression with reference to the point of intersection of the impermeable bottom of the formation with the axis of the well as the origin;
m=thickness of the saturated part of the water-bearing formation;
h_1 and h_2=depth of water in two observation wells during pumping;
r_1 and r_2=distances from pumped well to two observation wells.

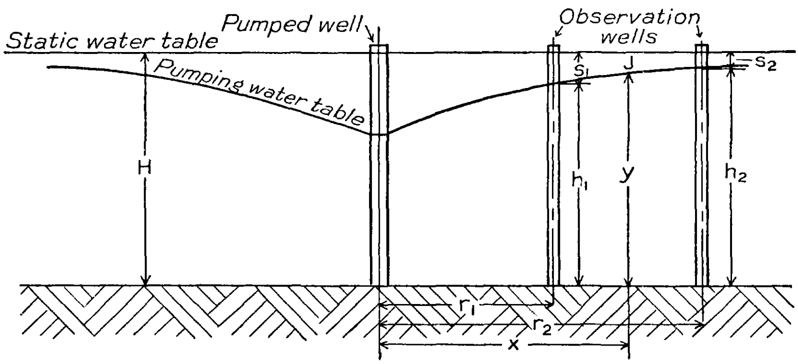

FIGURE 6.—Section showing assumed ground-water conditions for development of the equilibrium formula from water-table conditions.

At any distance from the pumped well the flow Q toward the well through a cylindrical section of the water-bearing material equals $P\,i\,A$.

The hydraulic gradient at any distance, x, from the pumped well is equal to $\frac{dy}{dx}$. The total area through which the flow, Q, takes place is $2\pi xy$.

Therefore

$$Q=P\frac{dy}{dx}2\pi xy \qquad (52)$$

$$\frac{dx}{x}=\frac{2\pi Pydy}{Q} \qquad (53)$$

By integrating between the limits, $x=r_1$, $x=r_2$, and $y=h_1$, $y=h_2$.

$$\int_{r_1}^{r_2}\frac{dx}{x}=\frac{2\pi P}{Q}\int_{h_1}^{h_2}y\,dy \qquad (54)$$

$$\log_e r_2 - \log_e r_1 = \frac{2\pi P}{Q}\left(\frac{h_2^2 - h_1^2}{2}\right) \quad (55)$$

$$P = \frac{Q(\log_e r_2 - \log_e r_1)}{\pi(h_2^2 - h_1^2)} \quad (56)$$

$$h_2^2 - h_1^2 = (h_2 + h_1)\ (h_2 - h_1) \quad (57)$$

$(h_2 - h_1)$ is equal to the difference of draw-downs $(s_1 - s_2)$. Thus

$$h_2^2 - h_1^2 = (h_2 + h_1)\ (s_1 - s_2) \quad (58)$$

$$P = \frac{Q \log_e \frac{r_2}{r_1}}{\pi(h_2 + h_1)\ (s_1 - s_2)} \quad (59)$$

This is the general equilibrium formula for determining permeabilities of water-bearing materials where the water is not confined under

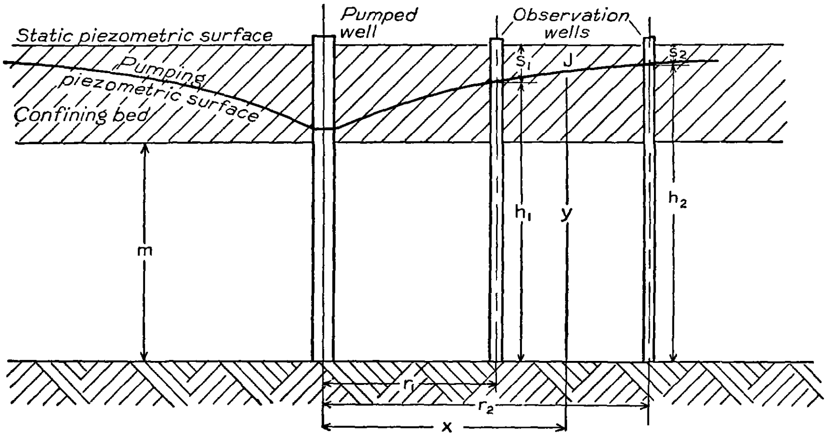

FIGURE 7.—Section showing assumed ground-water conditions for the development of the equilibrium formula from artesian conditions.

artesian pressure. By a similar development [78] the general equilibrium formula for artesian conditions (fig. 7) is found to be

$$P = \frac{Q \log_e \frac{r_2}{r_1}}{2\pi m(s_1 - s_2)} \quad (60)$$

EQUILIBRIUM FORMULAS

Slichter formula.—The Slichter formula [79] for artesian conditions, which is based on the assumptions outlined on page 77, is

$$Q = \frac{2\pi s P m}{\log_e\left(1 + \frac{R}{r}\right)} \quad (61)$$

[78] Wenzel, L. K., The Thiem method for determining permeability of water-bearing materials: U. S. Geol. Survey Water-Supply Paper 679, pp. 17–18, 1937.

[79] Slichter, C. S., Theoretical investigation of the motion of ground waters: U. S. Geol. Survey 19th Ann. Rept., pt. 2, p. 360, 1899.

where Q is the quantity of water discharged by the well, s is the amount the water is lowered in the well by pumping; P is a coefficient of permeability—Slichter's "transmission constant"; m is the thickness of water-bearing material; R is the distance from the wall of the well at which the draw-down may be assumed to be zero; and r is the radius of the pumped well.

Slichter solved his formula for Q, having determined the "transmission constant" by means of the formula based on the effective size of the sand grains and the porosity of the material (p. 53).

Solving Slichter's formula for P,

$$P=\frac{Q \log_e\left(1+\frac{R}{r}\right)}{2\pi s m} \qquad (62)$$

which is equivalent to the general equilibrium formula for artesian conditions (p. 79). The draw-down in the near observation well is taken as the draw-down in the pumped well, and the draw-down in the far observation well is considered to be zero.

Turneaure and Russell formula.—The Turneaure and Russell formula,[80] based on the assumptions outlined on page 77, is

$$Q=\frac{(H^2-h^2)(\pi C p)}{\log_e \frac{R}{r}} \qquad (63)$$

where Q is the discharge of the pumped well, H is the original depth of water in the pumped well, h is the thickness of saturated water-bearing material at the wall of the pumped well, C is a constant that depends on the character of the material, p is the porosity of the material, R is the distance from the axis of the well at which the change in water level is inappreciable, and r is the radius of the pumped well.

This formula, like Slichter's, was solved for the quantity of water that could be pumped from the well, and the constants C and p were determined by a mechanical analysis of the water-bearing material. Solving the above equation for Cp (a coefficient of permeability)

$$Cp=\frac{Q \log_e \frac{R}{r}}{\pi (H^2-h^2)} \qquad (64)$$

which is equivalent to the general equilibrium formula for water-table conditions except that the thickness of the saturated water-bearing material at the near observation well is replaced by the thickness of the saturated material at the casing of the well, and the thickness of the saturated material at the far observation well is replaced by the

[80] Turneaure, F. E., and Russell, H. L., Public water supplies, 1st ed., p. 269, New York, John Wiley & Sons, Inc., 1901.

thickness of the saturated material at the distance R, where the draw-down of the water table is inappreciable.

Thiem formula.—The Thiem formula [81] for water-table conditions is

$$P=\frac{Q\,(\log_e r_2-\log_e r_1)}{\pi(h_2+h_1)(s_1-s_2)} \qquad (65)$$

in which P is a coefficient of permeability, Q is the discharge of the pumped well, h_1 is the saturated thickness of the water-bearing material at the near observation well at distance r_1 from the pumped well, h_2 is the thickness of the saturated water-bearing material at the far observation well at a distance r_2 from the pumped well, and s_1 and s_2 are the draw-downs in the observation wells. (See fig. 6.)

The formula differs from that for artesian conditions only in that $(h_2 + h_1)$ is replaced by $2m$. If m is defined as the average of the thickness of the saturated part of the water-bearing material at the two observation wells, the equation for both water-table and artesian conditions may be expressed

$$P=\frac{Q\,(\log_e r_2-\log_e r_1)}{2\pi m(s_1-s_2)} \qquad (66)$$

Converting the logarithm with base e to one with base 10, and expressing the rate of pumping in gallons a minute

$$P_f=\frac{527.7q\log\frac{r_2}{r_1}}{m(s_1-s_2)} \qquad (67)$$

which is Thiem's formula in modified form for both water table and artesian conditions, for convenient use in the United States.

The conditions assumed by Thiem for the development of his formula differed somewhat from the assumptions stated on page 77. Thiem assumed an initial sloping water table or piezometric surface and developed the formula from that assumption.[82] Unfortunately, however, Thiem changed from a system of oblique coordinates to a system of rectangular coordinates and by so doing vitiated the assumption of an initial slope, and hence, as in the case of the Slichter and the Turneaure and Russell formulas, the final equation applies only to horizontal conditions. Thiem apparently was the first to use the equilibrium formula for determining permeability and the first to utilize two observation wells instead of two less definite points on the cone of depression. Hence it seems proper that this method should be known as the Thiem method and the formulas as the Thiem formula although other investigators prior to Thiem's work had utilized the same general formula.

[81] Thiem, Gunter, Hydrologische Methoden, 56 pp., Leipzig. J. M. Gebhardt, 1906.

[82] Wenzel, L. K., op. cit., pp. 10–15.

Israelsen formula.—The Israelsen formula[83] for artesian conditions, which is based on the assumptions outlined on page 77, is

$$P=\frac{2.303Q\,\log_{10}\frac{r_2}{r_1}}{2\pi gm(s_1-s_2)} \qquad (68)$$

in which P is a coefficient of permeability—Israelsen's "specific water-conductivity;" g is the acceleration due to gravity; m is the average thickness of the formation in feet; Q is the discharge of the pumped well in cubic feet a second; s_1 is the draw-down of the piezometric surface at the distance r_1 from the axis of the pumped well in feet; and s_2 is the draw-down of the piezometric surface at the distance r_2 from the axis of the pumped well in feet.

This formula is essentially the same as the general equilibrium formula except for the change in units and the introduction of the gravity factor, which otherwise is included in the coefficient of permeability.

Wyckoff, Botset, and Muskat formula.—The Wyckoff, Botset, and Muskat formula[84] was developed from laboratory experiments on the flow of water through sand in which ground-water conditions around a pumped well were reproduced. The draw-down of the water table and piezometric surface were observed at several distances from the well under various rates of flow, and the following formula with the nomenclature altered somewhat was found to express the flow into the well.

$$Q=\frac{\pi P\rho g(h_2^2-h_1^2)}{\log_e\frac{r_2}{r_1}} \qquad (69)$$

Q is the flow in the well, P is a coefficient of permeability, ρ is the density of the fluid, g is the acceleration due to gravity, and h_1 and h_2 are the fluid pressures at the respective distances r_1 and r_2 from the pumped well. The equation may be written

$$P\rho g=\frac{Q\,\log_e\frac{r_2}{r_1}}{\pi(h_2^2-h_1^2)} \qquad (70)$$

This is essentially the same as the formula given on page 79 except for the inclusion of the gravity and density factors. In this formula the fluid pressures represented by h_1 and h_2, which are measured at the bottom of the formation, are probably equivalent for most conditions found in nature to the fluid heights in the observation wells.

[83] Israelsen, O. W., Irrigation principles and practices, New York, John Wiley & Sons, Inc., pp. 189-211, 1932.

[84] Wyckoff, R. D., Botset, H. G., and Muskat, M., Flow of liquids through porous media under the action of gravity: Physics, vol. 3, No. 2, pp. 90-113, 1932.

Limiting formula.—The writer made a rather intensive pumping test near Grand Island, Nebr., in 1931 [85] (see pp. 117–122) from which a method was derived for empirically applying the equilibrium formula to field conditions. The differences between the assumed conditions on which the formula is based and those found in nature are usually of sufficient magnitude to vitiate entirely the results obtained when the equilibrium formula is indiscriminately applied. The effects of differences between assumed conditions and field conditions on the permeability formulas are described later in this paper (pp. 102–112).

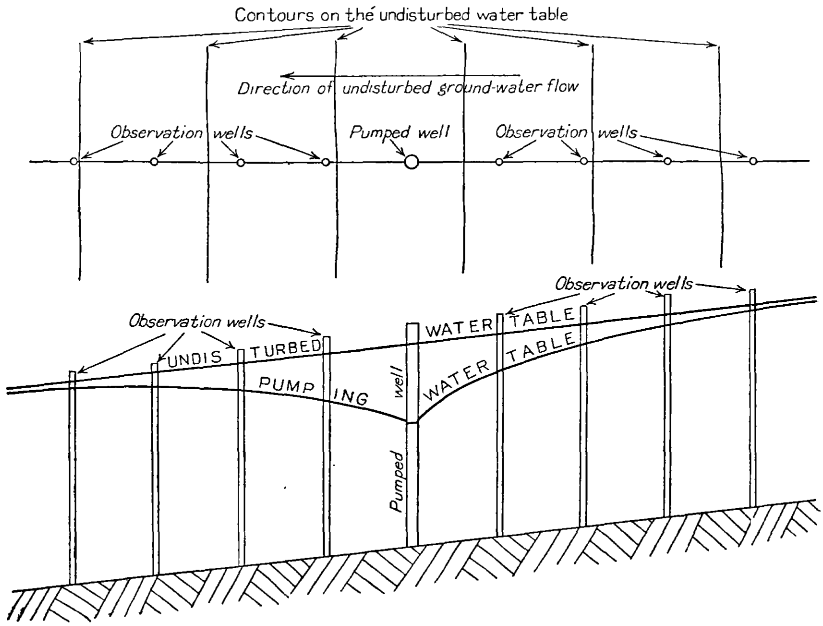

FIGURE 8.—Plan and section showing location of observation wells in relation to discharging well and contours on the undisturbed water table for obtaining data for the computation of permeability by the limiting formula.

A study of the data collected during the Grand Island test showed that consistent results could be obtained with the equilibrium formula by following an empirical procedure: (1) using for the draw-down of the water level s_1 the average of the draw-downs on opposite sides of the pumped well—preferably upgradient and downgradient—at the distance r_1 from the pumped well. Similarly the draw-down s_2 is taken as the average of the draw-downs at the distance r_2 on opposite sides of the pumped well; (2) using only those draw-downs that are obtained from observation wells situated on a straight line through the pumped well (fig. 8); (3) using only the draw-downs in observation wells situated within the part of the cone of depression that by the

[85] Wenzel, L. K., The Thiem method for determining permeability of water-bearing materials: U. S. Geol. Survey Water-Supply Paper 679, pp. 1–57, 1937.

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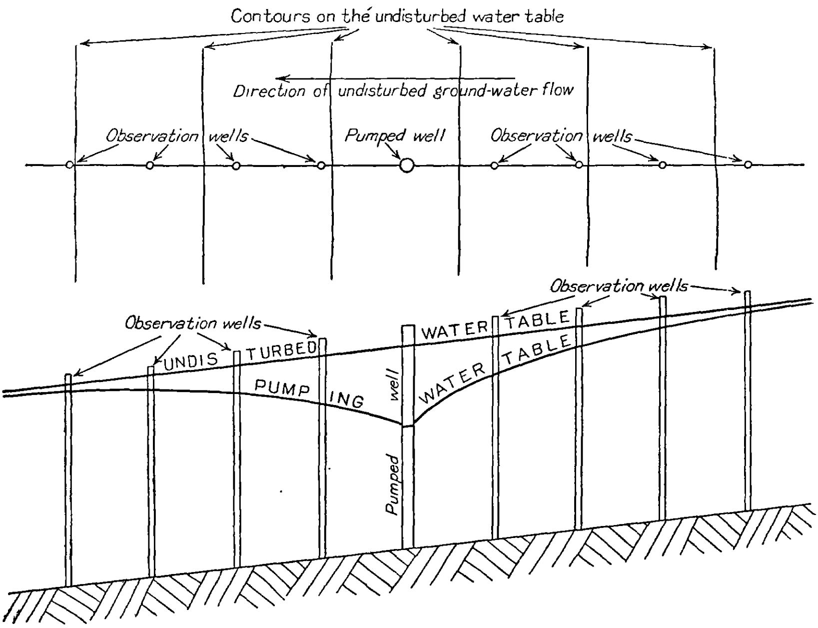

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[85] Wenzel, L. K., The Thiem method for determining permeability of water-bearing materials: U. S. Geol. Survey Water-Supply Paper 679, pp. 1–57, 1937.

end of the period of pumping has reached approximate equilibirum in form; (4) using only draw-downs in observation wells situated sufficiently far from the pumped well that the effects of vertical ground-water movement, changes in permeability of the water-bearing material due to well development, and the failure of the well to penetrate the entire thickness of material are inappreciable; and (5) using draw-downs obtained at more than two distances from the pumped well.

By taking this procedure into account the following limiting equilibrium formula is developed:

$$P_f = 527.7qC \qquad (71)$$

In this formula P_f is the field coefficient expressed in Meinzer's units, q is the discharge of the pumped well in gallons a minute, and C is a constant, equal to $\frac{A}{B}$, that is determined graphically. A is equal to

$$\frac{\log_{10}\frac{r_2}{r_1}}{0.25M} \qquad (72)$$

and B is equal to

$$\frac{1}{2}(s_{1u}+s_{1d}-s_{2u}-s_{2d}) \qquad (73)$$

in which r_1 and r_2 are distances, in feet, to two points on the cone of depression that lie on a straight line through the pumped well; s_{1u} is the draw-down, in feet, on the line at the distance r_1 upgradient from the well; s_{1d} is the draw-down, in feet, on the line at distance r_1 downgradient from the pumped well; s_{2u} is the draw-down, in feet, at the distance r_2 upgradient; s_{2d} is the draw-down, in feet, at the distance r_2 downgradient; and M is the sum of the saturated thicknesses of water-bearing material, in feet, at the locations of the four draw-downs. For artesian conditions $M=4m$; and for water-table conditions

$$M=4m-(s_{1u}+s_{1d}+s_{2u}+s_{2d}) \qquad (74)$$

where m is equal to the saturated thickness of water-bearing material before pumping starts.

To obtain C all possible values of A should be plotted against the corresponding values of B and a straight line drawn through the plotted points (see figs. 11, 13, 14, 15, and 17). More than one point is necessary, of course, to determine the plotted line and hence at least six observation wells—three upgradient and three downgradient—are needed. C is equal to the slope of the straight line. If most of the points do not fall approximately on a straight line through the origin the equilibrium formula cannot be used. Examples of the application of this method to the four pumping tests in Nebraska and the one in Kansas are given later in this paper.

Gradient formula.—The gradient formula simply applies the fundamental principle of the equilibrium formula outlined on page 76 to field conditions. As previously stated, when with a constant rate of pumping approximate equilibrium is established, very little water is taken from storage close to the well. If the water table or piezometric surface in a homogeneous formation is horizontal before pumping begins, water percolates toward the pumped well equally from all directions, and the same quantity of water percolates toward the pumped well through each of the indefinite series of concentric cylindrical sections around the well.

The area of each concentric cylindrical section is $A=2\pi rh$, where r is the radius of the cylinder and h is the thickness of the saturated water-bearing material. Thus, according to Darcy's law

$$Q=PiA=2\pi Pirh \qquad (75)$$

and

$$Q=2\pi Pi_1r_1h_1=2\pi Pi_2r_2h_2=2\pi Pi_3r_3h_3 \qquad (76)$$

where Q is the discharge of the pumped well; P is the coefficient of permeability; i_1, i_2, and i_3 are the hydraulic gradients at distances r_1, r_2, and r_3 respectively from the pumped well; and h_1, h_2, and h_3 are the respective saturated thicknesses of material at the three distances.

In nature the initial water table or piezometric surface generally has a slope, and as a result the flow of water to a discharging well is not everywhere normal to cylindrical sections around the well. The flow is normal only along a line through the well that extends directly upgradient and downgradient to the ground-water divide. The flow through a given cross-sectional area at a specified distance upgradient from the well will be greater than the flow through an equal cross-sectional area at the same distance downgradient. As a result, the hydraulic gradient causing the flow is approximately equal to the average of the gradients upgradient and downgradient from the well. Thus

$$Q=2\pi Pr\left(\frac{h_u+h_d}{2}\right)\left(\frac{i_u+i_d}{2}\right)=\frac{\pi Pr}{2}(h_u+h_d)(i_u+i_d) \qquad (77)$$

and

$$P=\frac{2Q}{\pi r(h_u+h_d)(i_u+i_d)} \qquad (78)$$

where i_u is the gradient and h_u is the thickness of the saturated water-bearing material at the distance r upgradient from the well; and i_d is the gradient and h_d is the thickness of the saturated water-bearing material at the distance r downgradient from the well.

The hydraulic gradient cannot, of course, be determined from the draw-down in an observation well, but it can be ascertained closely by graphical methods. A profile of the cone of depression is first constructed by plotting the elevations of the water levels in the observation wells located on a straight line through the discharging well against the distances of the wells from the discharging well and by connecting the plotted points with a smooth curve, thus showing the cone of depression from the farthest upgradient well to the farthest downgradient well at some time, t, after the discharge is started. A profile of the initial water table or piezometric surface should be constructed also. From these profiles the drawn-down of the water level and the altitude of the water level at the time t may be determined for any distance upgradient and downgradient.

The hydraulic gradient at any distance, r, from the discharging well is approximately equal to the difference in altitude between two points at distance b on each side of point r divided by the distance between the points—that is $2b$. Thus

$$i=\frac{f_{(r+b)}-f_{(r-b)}}{2b} \qquad (79)$$

in which $f_{(r-b)}$ is the altitude of the water level at the distance r-b from the pumped well and $f_{(r+b)}$ is the altitude of the water level at the distance $r+b$ from the pumped well.

Substituting in equation (78)

$$P=\frac{2Q}{\pi r(h_u+h_d)\left(\frac{f_{(r+b)u}-f_{(r-b)u}}{2b}+\frac{f_{(r+b)d}-f_{(r-b)d}}{2b}\right)} \qquad (80)$$

$$P=\frac{4bQ}{\pi r(h_u+h_d)(f_{(r+b)u}+f_{(r+b)d}-f_{(r-b)u}-f_{(r-b)d})} \qquad (81)$$

in which $f_{(r+b)u}$ and $f_{(r+b)d}$ are the respective altitudes of the water level at the distance $r+b$ upgradient and downgradient and $f_{(r-b)u}$ and $f_{(r-b)d}$ are the respective altitudes of the water level at the distance r-b upgradient and downgradient from the discharging well.

For many field tests b may be taken as 10 feet; thus in Meinzer's units

$$P_f=\frac{18{,}335q}{r(h_u+h_d)(f_{(r+10)u}+f_{(r+10)d}-f_{(r-10)u}-f_{(r-10)d})} \qquad (82)$$

This is the gradient formula pertaining to water-table conditions, in which P_f is expressed in Meinzer's units, q is measured in gallons a minute, and the rest of the factors are measured in feet.

The corresponding formula for artesian conditions is

$$P_f=\frac{9{,}168q}{rm(f_{(r+10)u}+f_{(r+10)d}-f_{(r-10)u}-f_{(r-10)d})} \qquad (83)$$

in which m is the average thickness of the formation in feet, and the other symbols are those given for the formula pertaining to water-table conditions.

The application of the gradient formula to the four Nebraska tests and the Kansas test is given later in this report.

NON-EQUILIBRIUM METHOD

A non-equilibrium formula was recently developed under the direction of Theis.[86] It is based on the assumption that Darcy's law is analogous to the law of the flow of heat by conduction and thus the mathematical theory of heat-conduction is largely applicable to hydraulic theory. The following formula is the final equation for the draw-down of the water level in the vicinity of a discharging well, as developed from an equation expressing the changes in temperature due to a type of source, or sink, that is analogous to a recharging or discharging well under certain conditions.

$$s=\frac{114.6q}{T}\int_{\frac{1.87r^2S}{Tt}}^{\infty}\frac{e^{-u}}{u}du \qquad (84)$$

in which s is the draw-down in feet at any point in the vicinity of a well discharging at a uniform rate, q is the discharge of a well in gallons a minute; T is the coefficient of transmissibility of the aquifer (see p. 10) in gallons a day, through each strip extending the height of the aquifer, under a unit gradient—this is the average field coefficient of permeability as used by the Geological Survey multiplied by the thickness of the aquifer; r is the distance of the discharge well to the point of observation in feet; S is the coefficient of storage,[87] as a decimal fraction; and t is the time the well has been pumped in days.

$$\int_{\frac{1.87r^2S}{Tt}}^{\infty}\frac{e^{-u}}{u}du=-Ei(-u) \qquad (85)$$

$$-Ei(-u)=-0.577216-\log_e u+u-\frac{u^2}{2\cdot 2!}+\frac{u^3}{3\cdot 3!}-\frac{u^4}{4\cdot 4!}\cdots\cdots \qquad (86)$$

Values of $-Ei\ (-u)$ for values of u between 10^{-15} and 9.9 are given in the table facing page 89.

The non-equilibrium formula is based on the following assumptions: (1) the water-bearing formation is homogeneous and isotropic, (2) the formation has an indefinite areal extent, (3) the discharge well

[86] Theis, C. V., The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage: Am. Geophys. Union Trans. 1935, pp. 519–524.

[87] The coefficient of storage is the cubic feet of water discharged from each vertical column of the aquifer with a base 1 foot square as the water level falls 1 foot. For water-table conditions S is equal to the specific yield of the material unwatered during the pumping; for artesian conditions S is equal to the water obtained from storage by the compression of a column of water-bearing material whose height equals the thickness of the water-bearing material and whose base is 1 foot square.

penetrates the entire thickness of the formation, (4) the coefficient of transmissibility is constant at all places and all times, (5) the discharge well has an infinitesimal diameter, and (6) water taken from storage by the decline in water level is discharged instantaneously with the decline in head.

The formula may be used in two ways. If the coefficient of transmissibility and the coefficient of storage are known, the draw-down can be computed for any time and any point on the cone of depression. If the draw-downs are known, the coefficients of transmissibility and storage can be computed. If the draw-down is known T and S can be computed either from the draw-down curve of one well or from the draw-downs that are observed at any one time in a line of wells—that is, from the form of the cone of depression.

As the coefficient of transmissibility appears on both sides of the equation, the formula cannot be solved directly for T and S. However, T and S may be conveniently determined by the following graphical method suggested by Theis.[88] The non-equilibrium formula may be written

$$s=\frac{114.6q}{T}W(u) \qquad (87)$$

in which $W(u)$ may be read as "well function of u" and the other terms as previously defined.

$$W(u)=-0.577216-\log_e u+u-\frac{u^2}{2\cdot 2!}+\frac{u^3}{3\cdot 3!}-\frac{u^4}{4\cdot 4!}\cdots\cdots \qquad (88)$$

and

$$u=\frac{1.87r^2S}{Tt} \qquad (89)$$

When T and S are to be determined from observations on the draw-down in one well, the log of the draw-down is plotted against the log of the reciprocal of the time since pumping began (s against $\frac{1}{t}$). When T and S are to be determined from the draw-downs in a line of wells, the log of the draw-down is plotted against the log of $\frac{r^2}{t}$. If the formation was entirely homogeneous and the water was discharged instantaneously with the fall in pressure all points so plotted, for all times and all wells, would fall on a smooth curve. The curve so determined is a segment of the type curve produced by plotting the log of the value of the integral, $W(u)$, against the log of the quantity u (pl. 1). If, therefore, (1) the type curve is plotted on logarithmic

[88] Theis, C. V., personal communication, 1937.

Values of $W(u)$ and u for non-equilibrium formula [1]

$[W(u) = -Ei(-u)]$

N \ u	$N \times 10^{-15}$	$N \times 10^{-14}$	$N \times 10^{-13}$	$N \times 10^{-12}$	$N \times 10^{-11}$	$N \times 10^{-10}$	$N \times 10^{-9}$	$N \times 10^{-8}$	$N \times 10^{-7}$	$N \times 10^{-6}$	$N \times 10^{-5}$	$N \times 10^{-4}$	$N \times 10^{-3}$	$N \times 10^{-2}$	$N \times 10^{-1}$	N
1.0	33.9616	31.6590	29.3564	27.0538	24.7512	22.4486	20.1460	17.8435	15.5409	13.2383	10.9357	8.6332	6.3315	4.0379	1.8229	0.2194
1.1	33.8662	31.5637	29.2611	26.9585	24.6559	22.3533	20.0507	17.7482	15.4456	13.1430	10.8404	8.5379	6.2363	3.9436	1.7371	.1860
1.2	33.7792	31.4767	29.1741	26.8715	24.5689	22.2663	19.9637	17.6611	15.3586	13.0560	10.7534	8.4509	6.1494	3.8576	1.6595	.1584
1.3	33.6992	31.3966	29.0940	26.7914	24.4889	22.1863	19.8837	17.5811	15.2785	12.9759	10.6734	8.3709	6.0695	3.7785	1.5889	.1355
1.4	33.6251	31.3225	29.0199	26.7173	24.4147	22.1122	19.8096	17.5070	15.2044	12.9018	10.5993	8.2968	5.9955	3.7054	1.5241	.1162
1.5	33.5561	31.2535	28.9509	26.6483	24.3458	22.0432	19.7406	17.4380	15.1354	12.8328	10.5303	8.2278	5.9266	3.6374	1.4645	.1000
1.6	33.4916	31.1890	28.8864	26.5838	24.2812	21.9786	19.6760	17.3735	15.0709	12.7683	10.4657	8.1634	5.8621	3.5739	1.4092	.08631
1.7	33.4309	31.1283	28.8258	26.5232	24.2206	21.9180	19.6154	17.3128	15.0103	12.7077	10.4051	8.1027	5.8016	3.5143	1.3578	.07465
1.8	33.3738	31.0712	28.7686	26.4660	24.1634	21.8608	19.5583	17.2557	14.9531	12.6505	10.3479	8.0455	5.7446	3.4581	1.3098	.06471
1.9	33.3197	31.0171	28.7145	26.4119	24.1094	21.8068	19.5042	17.2016	14.8990	12.5964	10.2939	7.9915	5.6906	3.4050	1.2649	.05620
2.0	33.2684	30.9658	28.6632	26.3607	24.0581	21.7555	19.4529	17.1503	14.8477	12.5451	10.2426	7.9402	5.6394	3.3547	1.2227	.04890
2.1	33.2196	30.9170	28.6145	26.3119	24.0093	21.7067	19.4041	17.1015	14.7989	12.4964	10.1938	7.8914	5.5907	3.3069	1.1829	.04261
2.2	33.1731	30.8705	28.5679	26.2653	23.9628	21.6602	19.3576	17.0550	14.7524	12.4498	10.1473	7.8449	5.5443	3.2614	1.1454	.03719
2.3	33.1286	30.8261	28.5235	26.2209	23.9183	21.6157	19.3131	17.0106	14.7080	12.4054	10.1028	7.8004	5.4999	3.2179	1.1099	.03250
2.4	33.0861	30.7835	28.4809	26.1783	23.8758	21.5732	19.2706	16.9680	14.6654	12.3628	10.0603	7.7579	5.4575	3.1763	1.0762	.02844
2.5	33.0453	30.7427	28.4401	26.1375	23.8349	21.5323	19.2298	16.9272	14.6246	12.3220	10.0194	7.7172	5.4167	3.1365	1.0443	.02491
2.6	33.0060	30.7035	28.4009	26.0983	23.7957	21.4931	19.1905	16.8880	14.5854	12.2828	9.9802	7.6779	5.3776	3.0983	1.0139	.02185
2.7	32.9683	30.6657	28.3631	26.0606	23.7580	21.4554	19.1528	16.8502	14.5476	12.2450	9.9425	7.6401	5.3400	3.0615	.9849	.01918
2.8	32.9319	30.6294	28.3268	26.0242	23.7216	21.4190	19.1164	16.8138	14.5113	12.2087	9.9061	7.6038	5.3037	3.0261	.9573	.01686
2.9	32.8968	30.5943	28.2917	25.9891	23.6865	21.3839	19.0813	16.7788	14.4762	12.1736	9.8710	7.5687	5.2687	2.9920	.9309	.01482
3.0	32.8629	30.5604	28.2578	25.9552	23.6526	21.3500	19.0474	16.7449	14.4423	12.1397	9.8371	7.5348	5.2349	2.9591	.9057	.01305
3.1	32.8302	30.5276	28.2250	25.9224	23.6198	21.3172	19.0146	16.7121	14.4095	12.1069	9.8043	7.5020	5.2022	2.9273	.8815	.01149
3.2	32.7984	30.4958	28.1932	25.8907	23.5881	21.2855	18.9829	16.6803	14.3777	12.0751	9.7726	7.4703	5.1706	2.8965	.8583	.01013
3.3	32.7676	30.4651	28.1625	25.8599	23.5573	21.2547	18.9521	16.6495	14.3470	12.0444	9.7418	7.4395	5.1399	2.8668	.8361	.008939
3.4	32.7378	30.4352	28.1326	25.8300	23.5274	21.2249	18.9223	16.6197	14.3171	12.0145	9.7120	7.4097	5.1102	2.8379	.8147	.007891
3.5	32.7088	30.4062	28.1036	25.8010	23.4985	21.1959	18.8933	16.5907	14.2881	11.9855	9.6830	7.3807	5.0813	2.8099	.7942	.006970
3.6	32.6806	30.3780	28.0755	25.7729	23.4703	21.1677	18.8651	16.5625	14.2599	11.9574	9.6548	7.3526	5.0532	2.7827	.7745	.006160
3.7	32.6532	30.3506	28.0481	25.7455	23.4429	21.1403	18.8377	16.5351	14.2325	11.9300	9.6274	7.3252	5.0259	2.7563	.7554	.005448
3.8	32.6266	30.3240	28.0214	25.7188	23.4162	21.1136	18.8110	16.5085	14.2059	11.9033	9.6007	7.2985	4.9993	2.7306	.7371	.004820
3.9	32.6006	30.2980	27.9954	25.6928	23.3902	21.0877	18.7851	16.4825	14.1799	11.8773	9.5748	7.2725	4.9735	2.7056	.7194	.004267
4.0	32.5753	30.2727	27.9701	25.6675	23.3649	21.0623	18.7598	16.4572	14.1546	11.8520	9.5495	7.2472	4.9482	2.6813	.7024	.003779
4.1	32.5506	30.2480	27.9454	25.6428	23.3402	21.0376	18.7351	16.4325	14.1299	11.8273	9.5248	7.2225	4.9236	2.6576	.6859	.003349
4.2	32.5265	30.2239	27.9213	25.6187	23.3161	21.0136	18.7110	16.4084	14.1058	11.8032	9.5007	7.1985	4.8997	2.6344	.6700	.002969
4.3	32.5029	30.2004	27.8978	25.5952	23.2926	20.9900	18.6874	16.3848	14.0823	11.7797	9.4771	7.1749	4.8762	2.6119	.6546	.002633
4.4	32.4800	30.1774	27.8748	25.5722	23.2696	20.9670	18.6644	16.3619	14.0593	11.7567	9.4541	7.1520	4.8533	2.5899	.6397	.002336
4.5	32.4575	30.1549	27.8523	25.5497	23.2471	20.9446	18.6420	16.3394	14.0368	11.7342	9.4317	7.1295	4.8310	2.5684	.6253	.002073
4.6	32.4355	30.1329	27.8303	25.5277	23.2252	20.9226	18.6200	16.3174	14.0148	11.7122	9.4097	7.1075	4.8091	2.5474	.6114	.001841
4.7	32.4140	30.1114	27.8088	25.5062	23.2037	20.9011	18.5985	16.2959	13.9933	11.6907	9.3882	7.0860	4.7877	2.5268	.5979	.001635
4.8	32.3929	30.0904	27.7878	25.4852	23.1826	20.8800	18.5774	16.2748	13.9723	11.6697	9.3671	7.0650	4.7667	2.5068	.5848	.001453
4.9	32.3723	30.0697	27.7672	25.4646	23.1620	20.8594	18.5568	16.2542	13.9516	11.6491	9.3465	7.0444	4.7462	2.4871	.5721	.001291
5.0	32.3521	30.0495	27.7470	25.4444	23.1418	20.8392	18.5366	16.2340	13.9314	11.6289	9.3263	7.0242	4.7261	2.4679	.5598	.001148
5.1	32.3323	30.0297	27.7271	25.4246	23.1220	20.8194	18.5168	16.2142	13.9116	11.6091	9.3065	7.0044	4.7064	2.4491	.5478	.001021
5.2	32.3129	30.0103	27.7077	25.4051	23.1026	20.8000	18.4974	16.1948	13.8922	11.5896	9.2871	6.9850	4.6871	2.4306	.5362	.0009086
5.3	32.2939	29.9913	27.6887	25.3861	23.0835	20.7809	18.4783	16.1758	13.8732	11.5706	9.2681	6.9659	4.6681	2.4126	.5250	.0008086
5.4	32.2752	29.9726	27.6700	25.3674	23.0648	20.7622	18.4596	16.1571	13.8545	11.5519	9.2494	6.9473	4.6495	2.3948	.5140	.0007198
5.5	32.2568	29.9542	27.6516	25.3491	23.0465	20.7439	18.4413	16.1387	13.8361	11.5336	9.2310	6.9289	4.6313	2.3775	.5034	.0006409
5.6	32.2388	29.9362	27.6336	25.3310	23.0285	20.7259	18.4233	16.1207	13.8181	11.5155	9.2130	6.9109	4.6134	2.3604	.4930	.0005708
5.7	32.2211	29.9185	27.6159	25.3133	23.0108	20.7082	18.4056	16.1030	13.8004	11.4978	9.1953	6.8932	4.5958	2.3437	.4830	.0005085
5.8	32.2037	29.9011	27.5985	25.2959	22.9934	20.6908	18.3882	16.0856	13.7830	11.4804	9.1779	6.8758	4.5785	2.3273	.4732	.0004532
5.9	32.1866	29.8840	27.5814	25.2789	22.9763	20.6737	18.3711	16.0685	13.7659	11.4633	9.1608	6.8588	4.5615	2.3111	.4637	.0004039
6.0	32.1698	29.8672	27.5646	25.2620	22.9595	20.6569	18.3543	16.0517	13.7491	11.4465	9.1440	6.8420	4.5448	2.2953	.4544	.0003601
6.1	32.1533	29.8507	27.5481	25.2455	22.9429	20.6403	18.3378	16.0352	13.7326	11.4300	9.1275	6.8254	4.5283	2.2797	.4454	.0003211
6.2	32.1370	29.8344	27.5318	25.2293	22.9267	20.6241	18.3215	16.0189	13.7163	11.4138	9.1112	6.8092	4.5122	2.2645	.4366	.0002864
6.3	32.1210	29.8184	27.5158	25.2133	22.9107	20.6081	18.3055	16.0029	13.7003	11.3978	9.0952	6.7932	4.4963	2.2494	.4280	.0002555
6.4	32.1053	29.8027	27.5001	25.1975	22.8949	20.5923	18.2898	15.9872	13.6846	11.3820	9.0795	6.7775	4.4806	2.2346	.4197	.0002279
6.5	32.0898	29.7872	27.4846	25.1820	22.8794	20.5768	18.2742	15.9717	13.6691	11.3665	9.0640	6.7620	4.4652	2.2201	.4115	.0002034
6.6	32.0745	29.7719	27.4693	25.1667	22.8641	20.5616	18.2590	15.9564	13.6538	11.3512	9.0487	6.7467	4.4501	2.2058	.4036	.0001816
6.7	32.0595	29.7569	27.4543	25.1517	22.8491	20.5465	18.2439	15.9414	13.6388	11.3362	9.0337	6.7317	4.4351	2.1917	.3959	.0001621
6.8	32.0446	29.7421	27.4395	25.1369	22.8343	20.5317	18.2291	15.9265	13.6240	11.3214	9.0189	6.7169	4.4204	2.1779	.3883	.0001448
6.9	32.0300	29.7275	27.4249	25.1223	22.8197	20.5171	18.2145	15.9119	13.6094	11.3068	9.0043	6.7023	4.4059	2.1643	.3810	.0001293
7.0	32.0156	29.7131	27.4105	25.1079	22.8053	20.5027	18.2001	15.8976	13.5950	11.2924	8.9899	6.6879	4.3916	2.1508	.3738	.0001155
7.1	32.0015	29.6989	27.3963	25.0937	22.7911	20.4885	18.1860	15.8834	13.5808	11.2782	8.9757	6.6737	4.3775	2.1376	.3668	.0001032
7.2	31.9875	29.6849	27.3823	25.0797	22.7771	20.4746	18.1720	15.8694	13.5668	11.2642	8.9617	6.6598	4.3636	2.1246	.3599	.00009219
7.3	31.9737	29.6711	27.3685	25.0659	22.7633	20.4608	18.1582	15.8556	13.5530	11.2504	8.9479	6.6460	4.3500	2.1118	.3532	.00008239
7.4	31.9601	29.6575	27.3549	25.0523	22.7497	20.4472	18.1446	15.8420	13.5394	11.2368	8.9343	6.6324	4.3364	2.0991	.3467	.00007364
7.5	31.9467	29.6441	27.3415	25.0389	22.7363	20.4337	18.1311	15.8286	13.5260	11.2234	8.9209	6.6190	4.3231	2.0867	.3403	.00006583
7.6	31.9334	29.6308	27.3282	25.0257	22.7231	20.4205	18.1179	15.8153	13.5127	11.2102	8.9076	6.6057	4.3100	2.0744	.3341	.00005886
7.7	31.9203	29.6178	27.3152	25.0126	22.7100	20.4074	18.1048	15.8022	13.4997	11.1971	8.8946	6.5927	4.2970	2.0623	.3280	.00005263
7.8	31.9074	29.6048	27.3023	24.9997	22.6971	20.3945	18.0919	15.7893	13.4868	11.1842	8.8817	6.5798	4.2842	2.0503	.3221	.00004707
7.9	31.8947	29.5921	27.2895	24.9869	22.6844	20.3818	18.0792	15.7766	13.4740	11.1714	8.8689	6.5671	4.2716	2.0386	.3163	.00004210
8.0	31.8821	29.5795	27.2769	24.9744	22.6718	20.3692	18.0666	15.7640	13.4614	11.1589	8.8563	6.5545	4.2591	2.0269	.3106	.00003767
8.1	31.8697	29.5671	27.2645	24.9619	22.6594	20.3568	18.0542	15.7516	13.4490	11.1464	8.8439	6.5421	4.2468	2.0155	.3050	.00003370
8.2	31.8574	29.5548	27.2523	24.9497	22.6471	20.3445	18.0419	15.7393	13.4367	11.1342	8.8317	6.5298	4.2346	2.0042	.2996	.00003015
8.3	31.8453	29.5427	27.2401	24.9375	22.6350	20.3324	18.0298	15.7272	13.4246	11.1220	8.8195	6.5177	4.2226	1.9930	.2943	.00002699
8.4	31.8333	29.5307	27.2282	24.9256	22.6230	20.3204	18.0178	15.7152	13.4126	11.1101	8.8076	6.5057	4.2107	1.9820	.2891	.00002415
8.5	31.8215	29.5189	27.2163	24.9137	22.6112	20.3086	18.0060	15.7034	13.4008	11.0982	8.7957	6.4939	4.1990	1.9711	.2840	.00002162
8.6	31.8098	29.5072	27.2046	24.9020	22.5995	20.2969	17.9943	15.6917	13.3891	11.0865	8.7840	6.4822	4.1874	1.9604	.2790	.00001936
8.7	31.7982	29.4957	27.1931	24.8905	22.5879	20.2853	17.9827	15.6801	13.3776	11.0750	8.7725	6.4707	4.1759	1.9498	.2742	.00001733
8.8	31.7868	29.4842	27.1816	24.8790	22.5765	20.2739	17.9713	15.6687	13.3661	11.0635	8.7610	6.4592	4.1646	1.9393	.2694	.00001552
8.9	31.7755	29.4729	27.1703	24.8678	22.5652	20.2626	17.9600	15.6574	13.3548	11.0523	8.7497	6.4480	4.1534	1.9290	.2647	.00001390
9.0	31.7643	29.4618	27.1592	24.8566	22.5540	20.2514	17.9488	15.6462	13.3437	11.0411	8.7386	6.4368	4.1423	1.9187	.2602	.00001245
9.1	31.7533	29.4507	27.1481	24.8455	22.5429	20.2404	17.9378	15.6352	13.3326	11.0300	8.7275	6.4258	4.1313	1.9087	.2557	.00001115
9.2	31.7424	29.4398	27.1372	24.8346	22.5320	20.2294	17.9268	15.6243	13.3217	11.0191	8.7166	6.4148	4.1205	1.8987	.2513	.000009988
9.3	31.7315	29.4290	27.1264	24.8238	22.5212	20.2186	17.9160	15.6135	13.3109	11.0083	8.7058	6.4040	4.1098	1.8888	.2470	.000008948
9.4	31.7208	29.4183	27.1157	24.8131	22.5105	20.2079	17.9053	15.6028	13.3002	10.9976	8.6951	6.3934	4.0992	1.8791	.2429	.000008018
9.5	31.7103	29.4077	27.1051	24.8025	22.4999	20.1973	17.8948	15.5922	13.2896	10.9870	8.6845	6.3828	4.0887	1.8695	.2387	.000007185
9.6	31.6998	29.3972	27.0946	24.7920	22.4895	20.1869	17.8843	15.5817	13.2791	10.9765	8.6740	6.3723	4.0784	1.8599	.2347	.000006439
9.7	31.6894	29.3868	27.0843	24.7817	22.4791	20.1765	17.8739	15.5713	13.2688	10.9662	8.6637	6.3620	4.0681	1.8505	.2308	.000005771
9.8	31.6792	29.3766	27.0740	24.7714	22.4688	20.1663	17.8637	15.5611	13.2585	10.9559	8.6534	6.3517	4.0579	1.8412	.2269	.000005173
9.9	31.6690	29.3664	27.0639	24.7613	22.4587	20.1561	17.8535	15.5509	13.2483	10.9458	8.6433	6.3416	4.0479	1.8320	.2231	.000004637

[1] Values of argument between 10^{-15} and 10^{-3} were computed by R. G. Kazmann with the assistance of Miss M. M. Evans. Values between 10^{-3} and 9.9 were adapted from Tables of Exponential and Trigonometric Integrals published by the Project for the Computation of Mathematical Tables of the Federal Works Agency in 1940.

paper and (2) the observed draw-down values are plotted on transparent paper against $\frac{1}{t}$ for one observation well or $\frac{r^2}{t}$ for a line of observation wells to a logarithmic scale the same as that used for plotting the type curve (see pls. 2–6), (3) the observed curve can be fitted to the type curve in only one place. Then (4) from this fit the value of $W(u)$ and the corresponding value of u may be determined from the type curve for any selected point on the observed curve, which (5) may be used in conjunction with the observed values for that point to determine T and S.

The coefficient of transmissibility is then computed by the formula

$$T=114.6q\frac{W(u)}{s} \qquad (90)$$

and the field coefficient of permeability

$$P_f=\frac{114.6q}{m}\frac{W(u)}{s} \qquad (91)$$

in which m is the average thickness of the water-bearing material. The coefficient of storage is computed by the formula

$$S=\frac{uTt}{1.87r^2} \qquad (92)$$

Values of $W(u)$—that is, $-Ei(-u)$— and u, which are used for plotting the type curve, are given in the table facing this page.

The writer has applied this method for determining permeability to the four Nebraska tests and to the Kansas test (pp. 146–147). The coefficients of permeability determined from the draw-downs in wells located on a line through the pumped well and averaged in the same manner as those in the limiting formula check very closely the permeabilities computed by both the limiting and the gradient formulas. However, the permeabilities computed by the non-equilibrium method using the draw-downs in any one well differed considerably from the permeabilities computed by the other methods and varied considerably, depending on which well was selected for the computation. This variation apparently was the result of the slow draining of the unwatered material (see p. 110), which altered the form of the draw-down curve from its theoretical form by making it relatively too steep for a time after pumping began and relatively too flat toward the end of the period of pumping. It is tentatively concluded, therefore, that at least for water-table conditions the coefficient of permeability should be determined by the non-equilibrium method only from the draw-downs in observation wells located on a line through the pumped well, i. e., from the shape of the cone of depression rather than from the shape of the draw-down curve.

RELATION BETWEEN EQUILIBRIUM AND NON-EQUILIBRIUM FORMULAS

The relation between the equilibrium and non-equilibrium formulas may be shown by the following analysis. The draw-downs s_1 and s_2 at two distances r_1 and r_2, respectively, on the cone of depression at time t are given by the non-equilibrium formula

$$s_1=\frac{114.6q}{T}W(u_1) \qquad (93)$$

$$s_2=\frac{114.6q}{T}W(u_2) \qquad (94)$$

Hence

$$s_1-s_2=\frac{114.6q}{T}\Big(W(u_1)-W(u_2)\Big) \qquad (95)$$

$$u_1=\frac{1.87r_1^2S}{Tt} \qquad (96)$$

and

$$u_2=\frac{1.87r_2^2S}{Tt} \qquad (97)$$

Let $\frac{1.87S}{Tt}=a$; then, $u_1=ar_1^2$ and $u_2=ar_2^2$.

$$W(u_1)=-0.577216-\log_e ar_1^2+ar_1^2-\frac{ar_1^2}{2\cdot 2!}+\frac{a^2r_1^4}{3\cdot 3!}-\frac{a^3r_1^6}{4\cdot 4!}\ \cdots \qquad (98)$$

$$W(u_2)=-0.577216-\log_e ar_2^2+ar_2^2-\frac{ar_2^2}{2\cdot 2!}+\frac{a^2r_2^4}{3\cdot 3!}-\frac{a^3r_2^6}{4\cdot 4!}\ \cdots \qquad (99)$$

Let
$$A_1=ar_1^2-\frac{ar_1^2}{2\cdot 2!}+\frac{a^2r_1^4}{3\cdot 3!}-\frac{a^3r_1^6}{4\cdot 4!}\ \cdots, \text{ and}$$

$$A_2=ar_2^2-\frac{ar_2^2}{2\cdot 2!}+\frac{a^2r_2^4}{3\cdot 3!}-\frac{a^3r_2^6}{4\cdot 4!}\ \cdots$$

Then

$$W(u_1)-W(u_2)=-\log_e ar_1^2+A_1+\log_e ar_2^2-A_2 \qquad (100)$$

$$=\log_e\frac{r_2^2}{r_1^2}+A_1-A_2 \qquad (101)$$

$$=2.30259\log_{10}\frac{r_2^2}{r_1^2}+A_1-A_2 \qquad (102)$$

$$=4.60518\log_{10}\frac{r_2}{r_1}+A_1-A_2 \qquad (103)$$

Substituting equation (103) in equation (95)

$$s_1-s_2=\frac{527.7q}{T}\log_{10}\frac{r_2}{r_1}(A_1-A_2) \qquad (104)$$

Since $P_f m=T$

$$s_1-s_2=\frac{527.7q}{P_f m}\log_{10}\frac{r_2}{r_1}(A_1-A_2) \qquad (105)$$

The equilibrium formula may be written

$$s_1 - s_2 = \frac{527.7q}{P_f m} \log_{10} \frac{r_2}{r_1} \qquad (106)$$

Hence the non-equilibrium formula differs from the equilibrium formula only by $A_1 - A_2$. When the time of discharge t is large $A_1 - A_2$ becomes practically negligible and the two formulas become essentially equal.

METHODS BASED ON CHANGE IN RATE OF DISCHARGE FROM WELLS

It is sometimes possible to determine the permeability of water-bearing materials in areas where the withdrawal of water from wells must be almost continuous and therefore where the undisturbed water level cannot be ascertained, for example, in cities where wells cannot be shut down except for short periods. Neither the equilibrium nor non-equilibrium formulas can be directly applied under such conditions because the draw-down of the water level resulting from the withdrawal cannot be determined. However, application of the formulas with modification can be made providing the withdrawal from the well or group of wells can be maintained at a constant rate for an appreciable time and then changed to another rate that can be maintained uniformly for a similar period. The permeability is computed by utilizing the change in the draw-down of the water level in observation wells caused by the change in rate of withdrawal from the discharging wells. Where water is withdrawn from only one well the center of pumping may, of course, be considered at that well, but where the withdrawal is from a group of wells the center of pumping must be computed from the location of the wells and from the relative discharge of each well.

Application of equilibrium method.—For the use of the equilibrium method it is necessary that the withdrawal from the discharging well be kept at a constant rate Q_1 until the cone of depression reaches essential equilibrium in form from the discharging well to the farthest observation well—that is, to the distance r_2. The withdrawal then is changed to a constant rate Q_2 and is maintained at this rate until the cone of depression again reaches essential equilibrium in form to the farthest observation well. The change in rate of withdrawal can, of course, be from a selected rate to either a higher or lower rate. For the withdrawal rate Q_1, let z_1 and z_2 be the depths in feet below established measuring points of the water levels in two observation wells located at distances r_1 feet and r_2 feet from the discharging well, and for the withdrawal rate Q_2 let Z_1 and Z_2 be the corresponding depths to the water level, in feet, below the same measuring points. The depths to the water level for both rates of withdrawal must be measured after the cone of depression has reached essential equilibrium in form.

The difference between the two withdrawal rates $(Q_1 - Q_2)$ in gallons a minute causes the water level in the near observation well to change (z_1-Z_1) feet and the water level in the distant well to change (z_2-Z_2) feet. Thus by the equilibrium formula

$$P_f=\frac{1{,}055.4\ (Q_1-Q_2)\ \log_{10}\frac{r_2}{r_1}}{(m_1+m_2)(z_1-Z_1-z_2+Z_2)} \qquad (107)$$

where P_f is the field coefficient of permeability in Meinzer's units; m_1 is the average thickness in feet of the water-bearing material at the two observation wells for the withdrawal rate Q_1; m_2 is the average thickness, in feet, of the water-bearing material at the two observation wells for the withdrawal rate Q_2, and the other symbols are those described above.

Application of non-equilibrium method.[89]—Permeability may be computed by the non-equilibrium method from the change in draw-down in one well caused by the change in rate of withdrawal from the discharging well, or from the change in draw-downs that occur in a line of wells due to the change in rate of withdrawal.

For the computation with one observation well periodic measurements of the depth to the water level below an established point are made in the well during the period with the rate of withdrawal Q_1 and also during the period with the rate of withdrawal Q_2. A curve similar to that shown by the solid line in figure 9 is obtained. The draw-down curve corresponding to the rate Q_1 is extrapolated through the period of withdrawal corresponding to Q_2, as is shown by the dashed line. The draw-down Z_1, due to the difference in rates of withdrawal (Q_1-Q_2) is equal to the vertical distance between the extrapolated and observed curves. Hence, by the non-equilibrium formula

$$T=P_fm=114.6\ (Q_1-Q_2)\left(\frac{W(u)}{Z_1}\right), \qquad (108)$$

in which T is the coefficient of transmissibility; P_f is the field coefficient of permeability in Meinzer's units; m is the average thickness of water-bearing material, in feet; $W(u)$ is the "well function"; and the other symbols are those defined above. The well function is obtained by plotting values of Z_1 against corresponding values of $\frac{1}{t}$ on log log paper (where t is the time after the rate of withdrawal Q_2 began, in days) and matching this curve with the type curve also plotted to the same scale on log log paper. The value of $W(u)$ corresponding to some value of Z_1 is obtained from the type curve. (See pp. 88-89.) This value of $W(u)$ is substituted in the above equation to obtain P_f.

[89] Jacob, C. E., personal communication, 1938.

For the computation with a line of observation wells the depths to water level during the two periods of withdrawal Q_1 and Q_2 are measured periodically as for the computation with one observation well. Also, the draw-down curve for each well for the withdrawal rate Q_1 is extrapolated throughout the period of withdrawal Q_2 in the manner previously described. Then the draw-down in each observation well caused by the difference in rates Q_1-Q_2 at any time t days after the beginning of the rate of withdrawal Q_2 is equal to the vertical distance between the observed and extrapolated curves for that well (fig. 9)

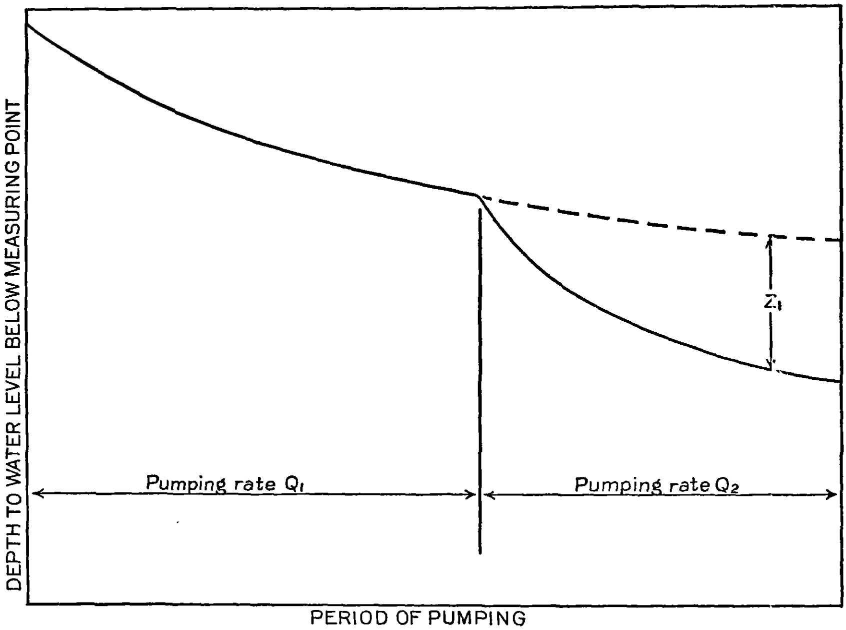

FIGURE 9.—Diagram showing method of obtaining the draw-down Z_1 caused by a change in rate of withdrawal.

Let these draw-downs be Z_1, Z_2, Z_3, and the corresponding distances to the observation wells from the discharging well be r_1, r_2, r_3. Then $\frac{r_1^2}{t}$, $\frac{r_2^2}{t}$, and $\frac{r_3^2}{t}$ are plotted on log log paper against corresponding values of Z_1, Z_2, Z_3, and the curve drawn through the plotted points is fitted to the type curve to obtain a value for $W(u)$ corresponding to one of the values of Z (see pp. 88–89). The field coefficient of permeability P_f, expressed in Meinzer's units, is then determined from the formula

$$T=P_f m=114.6\ (Q_1-Q_2)\left(\frac{W(u)}{Z}\right) \qquad (109)$$

in which the symbols are those given above.

RECOVERY METHODS

Many investigators have observed the recovery of the water level or pressure head in a well after the discharge from it has stopped. The recovery curve obtained from observations of this kind by plotting the residual draw-down against time since the discharge stopped is generally a very smooth curve that approaches zero residual draw-down when the time is long. Obviously, the rate of recovery of the water level in a well is related to the permeability of the water-bearing material through which the water percolates to the well and to the specific yield or elasticity of the formation. The rate of recovery also depends on the rate of discharge and on the period of time the well was operated prior to the shut-down. The quantitative inter-relation of these factors, together with the complexity of the problem of radial flow as it occurs under field conditions, has as yet not been completely evaluated.

Slichter [90] published a formula for determining the specific capacity of a well from observations on the recovery of the water level. This formula might be utilized to determine the permeability of the water-bearing materials, but such use was not suggested by Slichter. Theis [91] has proposed a very promising method but one whose application to field conditions requires further study. Muskat [92] recently published a formula similar to that of Slichter, but for determining permeability. An outline of these methods is given below.

Slichter formula for determining specific capacities of wells.—Slichter [93] gives the following formula for computing the specific capacity of a well from observations on the recovery of the water level in it after pumping has stopped.

$$C=17.25\,\frac{A}{t}\log_{10}\frac{s_1}{s_2} \qquad (110)$$

in which C is the specific capacity of the well, in gallons a minute per foot of draw-down; A is the cross-sectional area of the well casing, in square feet; t is the time after pumping stopped, in minutes; s_1 is the draw-down of the water level just before pumping stopped, in feet; and s_2 is the residual draw-down, in feet at time t.

Slichter found that, with the same draw-down at the end of the period of pumping, the recovery was much slower after a long period of pumping at a slow rate than after a short period of pumping at a more rapid rate. He explains this as follows: [94] "* * * during the short period of pumping * * * the cone of influence had not

[90] Slichter, C. S., The underflow in Arkansas Valley in western Kansas: U. S. Geol. Survey Water-Supply Paper 153, p. 61, 1906.

[91] Theis, C. V., The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage: Am. Geophys. Union Trans. 1935, p. 522.

[92] Muskat, Morris, Use of data on the build-up of bottom-hole pressures: Am. Inst. Min. Met. Eng. Trans., vol. 123, pp. 44–48, 1937.

[93] Slichter, C. S., op. cit., p. 61.

[94] Slichter, C. S., op. cit., p. 72.

extended as far as in the first case, and there was therefore less unsaturated soil to fill with water and a steeper slope of the ground-water surface." As a result, the specific capacity of the well as computed from the recovery curve of the first test differed from the value computed from the second test.

Theis formula.—The Theis formula for determining permeability from the recovery of the water level in a well is based on the assumption that if a well is pumped, or allowed to flow, for a known period and then left to recover the residual draw-down at any instant will be the same as if the discharge of the well had been continued but a recharge well with the same (flow) had been introduced at the same point at the instant the discharge actually stopped.

The residual draw-down at any instant after discharge has stopped is expressed by Theis [95] as follows:

$$s=\frac{114.6q}{T}\left[\int_{\frac{1.87r^2S}{Tt}}^{\infty}\frac{e^{-u}}{u}du-\int_{\frac{1.87r^2S}{Tt'}}^{\infty}\frac{e^{-u}}{u}du\right] \qquad (111)$$

in which s is the residual draw-down in feet; q is the discharge of the pumped well in gallons a minute; T is the coefficient of transmissibility (see p. 10); r is the distance in feet from the axis of the pumped or flowing well to the point on the cone of depression where the recovery is being computed; S is the coefficient of storage (see p. 87); t is the time since pumping began in hours; and t' is the time since pumping stopped in hours.

Theis states that in and very close to the discharging well the quantity

$$\frac{1.87r^2S}{Tt'} \qquad (112)$$

will be very small as soon as t' ceases to be small, because r is very small, and therefore that the value of the integral will be given very closely by the first two terms of

$$-0.577216-\log_e u+u-\frac{u^2}{2\cdot 2!}+\frac{u^3}{3\cdot 3!}-\frac{u^4}{4\cdot 4!} \qquad (86)$$

Hence if

$$L=\frac{1.87r^2S}{T} \qquad (113)$$

$$s=\frac{114.6q}{T}\left[-0.577216-\log_e\frac{L}{t}-\left(0.577216-\log_e\frac{L}{t'}\right)\right] \qquad (114)$$

$$s=\frac{114.6q}{T}\left[\log_e\frac{tL}{t'L}\right] \qquad (115)$$

and

$$T=\frac{264q}{s}\log_{10}\frac{t}{t'} \qquad (116)$$

[95] Theis, C. V., op. cit., p. 522.

The value of $\frac{\log_{10}\frac{t}{t'}}{s}$ should be determined graphically by plotting $\log_{10}\frac{t}{t'}$ against s. If most of the points do not fall on a straight line the formula cannot be used.[96] If they do, the presumption is that it probably can be, although it is also possible that the line will remain straight although the transmissibility computed thereby may be in error. According to Theis, if the points plot as a straight line, the value for $\frac{\log_{10}\frac{t}{t'}}{s}$ should be taken as the slope of the line.

The straight line obtained by plotting $\log_{10}\frac{t}{t'}$ against s should pass through the origin. In some instances, however, such as for the Grand Island and Scottsbluff tests, it does not do so (see pp. 125, 141). In these tests the coefficient of transmissibility computed by using the slope of the line does not agree with that computed by the limiting formula, gradient formula, or non-equilibrium formula, all of which give very nearly the same value. However, by empirically applying a factor to the Theis formula to make the straight line pass through the origin, values for transmissibility were computed that agreed closely with those determined by the other methods. With the empirical correction factor the Theis formula is as follows:

$$T=\frac{264q}{s}\log_{10}\frac{t\pm c}{t'} \qquad (117)$$

where c is the value whose magnitude is such that the straight line determined by plotting $\log_{10}\frac{t\pm c}{t'}$ against s will pass through the origin.

It may be fortuitous that such a correction gives transmissibility values that check with those computed by the other formulas, and more tests must be made before such a correction can be applied with assurance.

Muskat formula.—Muskat[97] gives the following formula for determining permeability from the recovery in a well.

$$P=\frac{C\mu\log_e\frac{r_e}{r_w}}{2\pi m} \qquad (118)$$

in which P is the sand permeability; m is the sand thickness; μ is the viscosity of the fluid; r_w is the well radius; and r_e is the distance at

[96] Theis, C. V., personal communication, 1937.

[97] Muskat, Morris, op. cit., p. 46.

which the draw-down is inappreciable at the time the well is discharging. This formula is similar to the general equilibrium formula for artesian conditions (p. 79) except that $\frac{Q}{s_1-s_2}$ is replaced by C.

C is computed by the formula

$$C=\frac{a}{\rho g t}\log_e\frac{h_e-h_i}{h_e-h} \qquad (119)$$

in which a is the cross-sectional area of the well; ρ is the density of the fluid; g is gravity; t is the time since pumping stopped; h_e is the initial water level, h_i is water level at the end of the pumping period—that is, when $t=0$; and h is the water level at time t.

Muskat states that the plot of t against the log of h_e—h should be a straight line whose slope equals $\frac{\rho g C}{a}$. Unless the points plot approximately on a straight line the method cannot be used. This method, like Slichter's, does not take into consideration the length of time that the well discharged prior to the time of shut-down.

ADVANTAGES AND DISADVANTAGES OF DISCHARGING-WELL METHODS

The discharging-well methods, in attempting to determine permeability of the water-bearing material in place, possess a large advantage over laboratory methods, in which the material must necessarily be removed and in many instances rearranged before tests are made. Moreover, if the permeabilities are determined by the form of the cone of depression over a relatively large area they represent the average permeability of the formation, taking into consideration the many vertical and horizontal variations in the arrangement of the water-bearing material. The permeabilities so determined are more applicable to rather wide areas than determinations made on a less comprehensive scale.

On the other hand, the several discharging-well formulas are based on the assumption of ideal conditions that generally are not found in nature. All of the methods assume an initial water table or piezometric surface that is horizontal and a water-bearing material that is homogeneous, whereas the water level in most areas has an original slope and probably all formations are at least somewhat heterogeneous in character. The equilibrium formula assumes a condition of equilibrium over the whole cone of depression, a condition that presumably will never occur. All methods assume that the pumped well penetrates completely through the water-bearing formation and that water can enter the well through the water-bearing material at any point opposite the casing and below the water level while the pump is discharging, whereas some wells do not extend through the formation and many are not perforated or screened through the entire aquifer. All methods assume a constant thickness of water-bearing material resting on a horizontal confining layer, but most formations vary in thickness and have a dip. The non-equilibrium formula assumes that water taken from storage in the formation, either as a result of a decline of the water table or by the compaction of an artesian aquifer and the associated beds of fine-grained materials, is removed instantaneously, whereas the material generally yields water slowly. The non-equilibrium formula assumes a constant thickness of saturated water-bearing material, but where there is a water table this thickness is reduced by the decline of the water table due to pumping. All the formulas assume that water percolates to the well horizontally and that there is no vertical movement, whereas vertical movement must occur under water-table conditions and under artesian conditions if the discharging well is not entirely open opposite the water-bearing material or if the well does not completely penetrate the material.

The effects of these differences between theoretically assumed conditions and those actually found in nature may be of sufficient magnitude to vitiate the results obtained by an indiscriminate use of many of the formulas for determining permeability. Several investigators have found the formulas unsatisfactory, chiefly because of these differences. However, it is often possible to obtain consistent results if allowances are made for the various differences, as is done in the limiting formula.

BEHAVIOR OF THE WATER LEVEL IN THE VICINITY OF A DISCHARGING WELL

As soon as a pump begins discharging water from a well that penetrates a water-bearing formation with a water table, a hydraulic gradient from all directions is established toward the well and the water table is lowered around the well. The water table soon assumes a form comparable to an inverted cone, although it is not a true cone. Where the water-bearing material is homogeneous, this cone of depression will be circular if the initial or static water table is horizontal but somewhat elliptical if the initial water table has a slope. Some water-bearing material will be unwatered by the decline of the water table, and the water drained from this material will percolate to the pumped well. Thus for a short time after pumping begins most of the water that is pumped from a well comes from the unwatered sediments comparatively close to the pumped well, and temporarily very little water may be drawn to the well from greater distances. However, as pumping continues, a hydraulic gradient that is essentially an equilibrium gradient will be established close to the pumped well, and water will be transmitted to the well through the water bearing material in approximately the amount that is being pumped.

The decline of the water table and the resultant unwatering of material in this area will then be much slower. This necessitates the percolation of more water from greater distances, and the cone of depression will expand, gradually draining material at greater distances. Thus as the pumping of the well continues, more of the formation will gradually be unwatered, an equilibrium gradient which will transmit to the well approximately the amount of water that is being pumped will be established at increasing distances from the well, and an appreciable draw-down of the water table will be noted farther from the well. Inasmuch as an equilibrium gradient can be established at increasing distances from the pumped well only by steepening the hydraulic gradient, which in turn can be created only by an increase in draw-down, the water table near the pumped well, in order to maintain an approximate equilibrium form, will continue to lower indefinitely, but at a decreasing rate. If no water is added to the formation, the water table will continue to decline, so long as the well is pumped, and the cone of depression will eventually extend to the limits of the formation. Recharge to the formation may, however, halt the development of the cone of depression by furnishing additional water, which will become a supply for the pumped well.

Under artesian conditions the piezometric surface behaves in a manner very similar to its behavior under water-table conditions. However, water is not generally removed from storage by the unwatering of a part of the formation but presumably by the compaction of the aquifer and associated beds of fine-grained material due to the reduction in pressure head. Whether the compaction of the aquifer and associated beds is strictly proportional to the decline in pressure is not known, but probably the compaction increases with the decline in pressure, and thus the compaction is greatest near the discharging well. Hence the quantity of water squeezed out of the formation is greatest near the well. The squeezing out of water from the formation by compaction delays the development of the cone of depression in much the same way that the development of the cone of depression for water-table conditions is delayed by the unwatering of part of the formation. However, the quantity of water removed from an artesian aquifer by compaction is in most instances much less than the quantity of water removed by the unwatering of a part of a formation, and the draw-down of the piezometric surface and development of the cone of depression under artesian conditions usually is more rapid than under water-table conditions.

One distinct difference exists between the removal of water from storage from artestian aquifers by compaction and the removal of water from storage from a formation in which a water table exists by the unwatering of a part of the formation. The specific yield [98] of the formation is not related to the thickness of the formation, hence lowering of the water table a given amount will release the same quantity of water to the pumped well regardless of the thickness of the formation. On the other hand, the amount of compaction of an aquifer and associated beds depends on their thickness, and hence a lowering of the water level of a given amount in a well discharging from an artesian aquifer will release more water to the well if the beds are thick than if they are thin.

It has been found by many investigators that a material after being saturated and allowed to drain will yield water for a considerable period. Although the material may yield a very large percentage of the water in it in a few hours or days, it may continue to yield small amounts for several years. The sand and gravel unwatered during a pumping test near Grand Island, Nebr., drained in such a manner that the computed specific yield of the material was 9.2 after 6 hours of pumping, 11.7 after 12 hours, 16.1 after 24 hours, 18.5 after 36 hours, and 20.1 after 48 hours of pumping.[99] A much longer period of pumping would be required before the true specific yield of the material would have been reached. The true specific yield was estimated to lie between 22 and 23.

Where the initial water table or piezometric surface is horizontal and the ideal conditions outlined on page 77 exist, water percolates to a discharging well from all directions, moving on about straight lines. Equal quantities of water percolate to the well through concentric cylindrical cross sections. In most places, however, the initial water level is not horizontal and as a result water percolates to the discharging well in somewhat circuitous paths. Because the slope of the cone of depression is steeper upgradient from the discharging well than downgradient, more water percolates to the well from the upgradient side. The slope of the cone downgradient becomes progressively less than the slope at the corresponding distance upgradient, and at some distance downgradient from the well the water table or piezometric surface is horizontal. This point lies on the ground-water divide. The ground-water divide extends upgradient in the general form of a parabola and separates the water that eventually percolates to the well from that which percolates downgradient

[98] The specific yield of a formation is defined by Meinzer as the ratio of (1) the volume of water which, after being saturated, it will yield by gravity to (2) its own volume. (U. S. Geol. Survey Water-Supply Paper 494, p. 28, 1923.)

[99] Wenzel, L. K., The Thiem method for determining permeability of water-bearing materials: U. S. Geol. Survey Water-Supply Paper 679, p. 55, 1937.

past the well.[1] All the water below the divide percolates away from the discharging well and all water above it percolates toward the well. If withdrawal of water from the well continues at a uniform rate, the cone of depression gradually becomes larger, and the ground-water divide gradually moves downgradient but at a decreasing rate.

BEHAVIOR OF THE WATER LEVEL IN THE VICINITY OF A WELL AFTER ITS DISCHARGE HAS STOPPED

After the discharge of a well is stopped, water momentarily continues to percolate toward the well under the hydraulic gradient set up during the period that the well was discharging, but instead of being discharged by the well it refills the well and the interstices of the material that were unwatered, or, under artesian conditions, it expands the aquifer and associated beds to about their original capacity. As the formation near the well is gradually refilled, the hydraulic gradient toward the well is decreased and the recovery becomes progressively slower. At distances comparatively far from the well the water level may continue to lower for a considerable time after the discharge ceases because at those distances water still is taken from the interstices of the material to supply the water that refills the sediments around the well. In time there is a general equalization of water levels over the entire region, and the water table or piezometric surface will assume a form similar to that it had under the initial conditions, although it may remain temporarily or permanently somewhat lower than before water was withdrawn.

In the Grand Island test,[2] as well as in the other Nebraska tests, the water table very close to the pumped well approximately regained its initial slope very soon after pumping stopped. Even though the water table close to the pumped well at first had a greater amount to recover, the rate of rise after a certain time reduced to about the rate of rise of the water table at greater distances and the remaining draw-down at both distances became approximately the same. Thus 12 hours after pumping stopped in the Grand Island test the remaining draw-down was 0.77 foot at 24.9 feet, 59.9 feet, and 114.4 feet from the pumped well, although at the time pumping stopped the draw-downs were respectively 4.03, 2.81, and 2.03 feet. Presumably, at some later time the rate of recovery out to a distance greater than 115 feet would become the same.

[1] Contours on the water table and the position of the ground-water divide for five different times after pumping began in the Grand Island test are shown in U. S. Geol. Survey Water-Supply Paper 679, plate 6. The lines of flow of ground water toward a discharging well in a region with an initial sloping water level is shown in U. S. Geol. Survey 19th Ann. Rept. pt. 2, pl. 17, 1898.

[2] Wenzel, L. K., The Thiem method for determining permeability of water-bearing materials: U. S. Geol. Survey Water-Supply Paper 679, p. 35, 1937.

EFFECT OF DIFFERENCES BETWEEN THEORETICAL ASSUMPTIONS AND FIELD CONDITIONS ON PERMEABILITY METHODS

INITIAL SLOPING WATER TABLE OR PIEZOMETRIC SURFACE

A fundamental assumption on which the discharging-well methods are based is that the initial water table or piezometric surface is horizontal and hence that no movement of ground water exists prior to the time that the well is pumped or allowed to flow. Such a condition is not generally found in nature. As previously stated, if the initial water level was horizontal, water particles would percolate to the discharging well from all directions on more or less straight lines, but if the initial water level was sloping, the water particles would take a more circuitous path. In the first case the movement of water will be normal to concentric cylindrical cross-sectional areas around the discharging well, whereas in the second case the movement of water will be normal to irregular-shaped cross-sectional areas. With an initial sloping water table or piezometric surface the movement of water presumably is normal to cylindrical cross-sectional areas at only two places—directly upgradient and directly downgradient from the discharging well. The limiting formula attempts to compensate for this by averaging the draw-downs at equal distances upgradient and downgradient from the discharging well, and the gradient formula does likewise by averaging the gradients.

Some investigators believe that an initial sloping water table has no effect on the permeability formulas. Slichter[3] states that "the flow into the well is unmodified by the general motion [initial movement] of the ground water, for the loss of velocity on one side of the well is just balanced by the gain of velocity on the other side." This presumably infers that the draw-down of the water level will be the same regardless of whether the initial water level is sloping or is horizontal.

Turneaure and Russell[4] utilize the quantity of water normally flowing in the ground in computing for their formula (p. 80) the value of R, the distance from the well at which the draw-down is inappreciable. They state that "Assuming that all the water in the circle of influence flows into the well, the width of the strip of the ground-water stream tributary to the well will be $2R$, and the original cross-section of this portion of the ground-water stream is $2RH$." Then

$$Q=2CIRHp \qquad (120)$$

[3] Slichter, C. S., Theoretical investigation of the motion of ground waters: U. S. Geol. Survey 19th Ann. Rept., pt. 2, p. 371, 1899.

[4] Turneaure, F. E., and Russell, H. L., Public water Supplies, 3d ed., p. 258, New York, John Wiley & Sons, Inc., 1924.

in which Q is the flow in cubic feet a day, C is a coefficient of permeability, I is the slope of the initial water level in feet per foot, H is the thickness of saturated water-bearing material in feet, and p is the porosity expressed as a ratio.

$$R=\frac{Q}{2CIHp} \quad (121)$$

By substituting the value of Q from their equilibrium formula (equation 63)

$$R=\frac{\pi(H^2-h^2)}{2IH \log_e \frac{R}{r}} \quad (122)$$

in which h is the thickness of the saturated water-bearing material at the wall of the pumped well in feet; r is the radius of the well in feet; and the other factors are those given above.

This procedure is based on the assumption that a condition of equilibrium will result when the cone of depression extends to a width of $2R$, a premise that appears to be open to question. Prior to development, natural recharge to the water-bearing formation probably about balances the natural discharge—that is, over a period of years there is no net increase or decrease in ground-water storage. The withdrawal of water from a well, however, represents an additional draft on the supply that disturbs the balance between recharge and discharge. Equilibrium now can be obtained only if the natural recharge is increased by an amount equal to the withdrawal from the well or if the discharge from the formation is decreased by that amount. Thus it is obvious that the cone of depression resulting from the discharge of the well must ultimately extend to either the part of the formation where natural recharge occurs or to the part where natural discharge occurs, or both, and that these parts of the formation may be many times the distance R, as computed by the Turneaure and Russell formula.

In each of the five pumping tests described later in this report (pp. 117-146) the draw-downs of the water table in observation wells situated upgradient differed somewhat from the draw-downs at the corresponding distances downgradient. Whether the differences are due in part to the effect of an initial sloping water table is not known. In the Kearney, Scottsbluff, and Wichita tests most of the draw-downs upgradient were greater than those at corresponding distances downgradient, whereas in the Grand Island and Gothenburg tests the reverse was true (see following table).

Observed draw-down in feet, of the water level

Distance from pumped well	Grand Island (48 hours)		Kearney (24 hours)		Gothenburg (24 hours)		Scott's Bluff (15 hours)		Wichita (18 days)	
	Up-gradient	Down-gradient	Up-gradient	Down-gradient	Up-gradient	Down-gradient	Up-gradient	Down-gradient	Up-gradient	Down-gradient
50	3.14	2.93	3.97	3.88	5.16	5.13	6.69	6.93	5.91	5.48
100	2.11	2.20	2.99	2.91	3.88	3.85	4.87	4.73	4.58	4.31
150	1.57	1.68	2.47	2.38	3.01	3.25	4.03	3.95		
200	1.22	1.33	2.12	1.97	[1] 2.53	[1] 2.82	3.55	3.40	[1] 3.42	[1] 3.19
250	.95	1.06	1.78	1.70	2.04	2.28				
300	.74	.73					2.86	2.61		
400	.46	.44					2.36	2.06		
500	.29	.28					1.99	1.62		
600	.20	.20					1.67	1.36		

[1] 190 feet from pumped well.

An inspection of the draw-downs given in the table indicates clearly that a wide range in computed coefficients of permeability can be obtained by indiscriminately substituting in the permeability formulas the draw-downs on opposite sides of the pumped well. For example, in the Kearney test, the difference in draw-down between 200 feet upgradient and 250 feet downgradient is 0.42 foot, whereas the difference between 200 feet downgradient and 250 feet upgradient is only 0.19 foot. Computations based on the latter value will give a coefficient that is about 220 percent greater than the coefficient computed by the larger difference in draw-downs. The range in coefficients computed in this manner may be very much wider than that in the example given above, and when the draw-down on one side of the discharging well is less than the draw-down at a greater distance on the other side of the well the computed coefficient will, of course, be negative. This further emphasizes the necessity of adhering rather rigorously to the system of average draw-downs that is used in the limiting formula or the system of average gradients that is used in the gradient formula.

HETEROGENEITY OF WATER-BEARING MATERIAL

All the permeability methods depend for their precise application on the assumption that the water-bearing material is entirely homogeneous in character or that the material has an average homogeneity that is proportional to the average coefficient of permeability that is computed from several individual determinations. Thus the average coefficient of permeability of a material is taken as the average of the determinations made in the laboratory on several samples of the material or as the average of individual values weighted according to the proportion of thickness or width of the material that each sample represents. Similarly, the average coefficient of permeability determined from tests of ground-water velocity is usually taken as the average permeability computed from the several velocities and from the average of porosity determinations. The methods based on the discharge of wells also assume a homogenous water-bearing material.

That most water-bearing formations are more or less heterogeneous in character is widely recognized. The percolation through a water-bearing material is directly proportional to the character and arrangement of the material—that is, to its permeability—and thus the range in ground-water percolation may be equivalent to the range in permeability. It has already been pointed out that coefficients of permeability for different materials have a wide range—that for a gravel determined in the hydrologic laboratory of the Geological Survey is 450,000,000 times that of a clay—and hence the range in percolation through the material is proportional. The range in the permeability of similar materials is, of course, less than that given above, but it may still be very large, especially in alluvium and other rather heterogeneous deposits. The failure to recognize a comparatively small cross section of material of extremely high permeability may result in an average value for permeability that is much too low and accordingly the computed percolation will be correspondingly low. Thus it is essential that the heterogeneity of the water-bearing materials be carefully taken into consideration.

The water-bearing material may be so heterogeneous in character that the discharging-well methods cannot be applied. In such material, the resulting draw-down and recovery of the water level may be very erratic and the permeabilities computed therefrom may have very little relation to the actual permeability of the formation. Although some investigators have taken the average of permeabilities computed by substituting combinations of erratic draw-down values in the permeability formulas to represent the average permeability of the water-bearing material, such a procedure does not appear likely to yield reliable results.

If permeability is computed by laboratory methods, samples of material should be collected from all parts of the formation in order that material of very high or very low permeability will not be overlooked. Consideration should also be given to the collection of the samples. Samples taken during the drilling of a well may not represent the arrangement and character of the material in place and thus the permeabilities determined from them may not be strictly applicable to the undisturbed material. Although discrepancies of this kind are probably largely compensated by collecting a considerable number of samples, it is not likely that clean material of very high permeability, especially that consisting of coarse gravel, will be brought to the surface as such, and thus the likelihood of obtaining samples of very high permeability is not great. Moreover, in most laboratory methods, very coarse material is eliminated because of the undesirable effect on the determinations.

Permeabilities determined by tests of ground-water velocity are likely to be maximum rather than average values in areas where the water-bearing material is heterogeneous. The movement of water will, of course, be much more rapid through the parts of the material that are comparatively permeable than through the parts that are less permeable. The substance used for measuring the rate of percolation will move accordingly and thus the ground-water velocity determined from the lapse of time between the introduction of the substance in the upgradient well and its detection in a receiving well is likely to be the velocity through the more permeable part of the material. Slichter observed two or more velocities in some tests made by the electrolytic method. For example, on Long Island, N. Y., two velocities, one 96 feet a day and the other 6.9 feet a day, were recorded in the same test.[5]

In the immediate vicinity of wells the permeability of the water-bearing material is likely to be different from that in other parts of the formation. During the withdrawal of water some clay, silt, and sand are usually removed from the part of the formation around the well by the movement of water to the well. Definite efforts are often made to remove this finer material after construction of wells by pumping the wells at rates greater than those at which they are to be operated. Gravel and sand are packed around the casings of some wells. In all such well development or gravel-packing the intent is to increase the permeability of the material around the well and thus to decrease for a short distance from the well the hydraulic gradient toward the well. This in turn reduces the draw-down in the well from that which would have occurred for the same discharge had the character of the material around the well remained unchanged. Gravel packing and well development increase the effective radius of the well, the direct determination of which is not possible.

The change in permability of the water-bearing material around the well is, of course, reflected by a change in the draw-down of the water level for a short distance from the well and constitutes one of the reasons why draw-downs close to discharging wells should not be used in the discharging-well formulas. Because of the change in permeability of the material around a well, the draw-down of the water level in the well is not likely to be closely related to the permeability of the undisturbed material. This is reflected by the large range in yields of wells of the same diameter that is often observed in developed areas. As a result, there appears little justification for the determination of permeability by substituting in the permeability formulas either the draw-down in the discharging well or the draw-down at the wall of the well for the draw-down at one point on the cone of depression.

[5] Slichter, C. S., Field measurements of the rate of movement of underground waters: U. S. Geol. Survey Water-Supply Paper 140, p. 78, 1905.

Some formations consist of alternate layers of clay, silt, sand, and gravel. Where such stratification exists the permeability parallel to the bedding may differ greatly from the permeability in other directions, and the percolation of water in one direction under a given head may greatly exceed the percolation under the same head in other directions. Consideration should be given to whether the natural ground-water movement is parallel, across, or perpendicular to the stratification of the formation, and the permeability to be used in computations is that corresponding to the direction of natural movement.

EXTENT OF CONE OF DEPRESSION

Until very recently little attention was given to the effect of the length of the period of pumping or flow on hydrologic problems dealing with wells. The length of time that wells are pumped or allowed to flow necessarily enters almost all computations of ground-water flow, but in many computations it has been included implicitly—usually in an assumption. A factor for time does not appear in any of the equilibrium formulas, yet it is included in the assumption that the ground-water system has reached a condition of equilibrium. In such formulas only the ultimate condition of the ground-water system is considered; thus the period of discharge is infinite, and no consideration is given to the differing hydrologic conditions that exist prior to stability.

The disregard for the nonstable conditions of ground-water flow probably has been due, at least in part, to the difficulties involved in mathematical treatment. The recent introduction of the nonequilibrium method by Theis [6] has materially aided the formulation of correct concepts, but precise mathematical treatment of all factors involved in a nonstable system has not yet been accomplished.

Observations on the behavior of the water table around pumped wells made in connection with pumping tests in Nebraska show that the form of the cone of depression reaches essential stability in a small area around a pumped well in a relatively short time after pumping begins. However, the area of essential stability expands very slowly and a considerable period of pumping is necessary for the cone to reach approximate equilibrium in form very far from the pumped well. The basic assumption of the equilibrium formulas—that equilibrium is reached—is for practical purposes valid for only a short distance from a pumped well. Beyond this short distance the assumption is far from true.

There is, of course, an appreciable drawn-down of the water level far beyond the distance from a discharging well to which the cone of

[6] Theis, C. V., The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage: Am. Geophys. Union Trans. 1935, pp. 519-524.

depression attains an essential equilibrium form. For example, a draw-down in the water table of 0.06 foot occurred 1,050 feet from the pumped well after 48 hours of pumping in the Grand Island test, but the cone of depression had reached essential equilibrium only to about 200 feet. Doubtless a measurable drawn-down existed at that time at points beyond 1,050 feet. The Nebraska pumping tests indicate that the cone of depression reaches essential stability in form to a distance from the discharging well that is only a very small proportion of the distance to which the effect of the discharge is transmitted. This observed condition is significant because it definitely limits the rigorous use of the equilibrium formulas to a very short distance from a discharging well and virtually invalidates the use of the formulas to greater distances unless the period of discharge is very long.

Several of the equilibrium formulas involve the determination of R, the distance from the discharging well at which the draw-down of the water level is inappreciable. Such formulas also assume that a condition of equilibrium exists over the entire area of influence—that is, from the discharging well to the distance R. This, as has just been pointed out, is far from true.

Several investigators have given arbitrary values to be used for R. Slichter [7] gives 600 feet; Muskat,[8] 500 feet; and Tolman,[9] 1,000 feet. Slichter and Muskat give values for R in connection with discussions of artesian conditions, and Tolman gives his value for both water table and artesian conditions. Turneaure and Russell determine R by a formula involving the initial slope of the water table (see p. 102).

Although it is obvious that the use of R in the equilibrium formula will generally result in determinations that are more or less in error, criticism of its use is probably based more on the implication that R actually represents the distance from a discharging well at which the effect of the discharge is negligible. The extent of the cone of depression is of very practical significance in determining the spacing of wells and in the solving of many quantitative problems. It also has been the crux of important legal controversies. Because empirical values for R, presumably intended chiefly for the solving of formulas for the discharge of wells in areas of known or assumed permeability, appear so persistently in the literature, it has generally been assumed that the cone of depression does not extend beyond the distance R. That the cone of depression may extend far beyond 500, 600, or 1,000 feet is shown both by theoretical deduction and by field observations. Leggette [10] recently observed appreciable fluctuations of water level

[7] Slichter, C. S., Theoretical investigation of the motion of ground waters: U. S. Geol. Survey 19th Ann. Rept., pt. 2, p. 360, 1899.

[8] Muskat, Morris, Flow of homogeneous fluids through porous media, p. 95, New York, McGraw-Hill Book Co., Inc., 1937.

[9] Tolman, C. F., Ground water, p. 387, New York, McGraw-Hill Book Co., Inc., 1937.

[10] Leggette, R. M., The mutual interference of artesian wells on Long Island, N. Y.: Am. Geophys. Union Trans. 1937, p. 493.

in wells as much as 7.1 miles distant from wells in which pumping was discontinued.

PARTIAL WELL PENETRATION

That the discharging well penetrates the total thickness of water-bearing material is assumed in the development of all discharging-well formulas. Many wells, however, penetrate only a part of the formation and as a result some of the water that enters the well must percolate upward from the material situated below the bottom of the well. Thus a vertical movement of ground-water is produced that is not in accordance with the assumption of horizontal movement on which the formulas are based (see p. 77). The water that percolates upward to the well necessarily moves a greater distance to the well than if it had percolated horizontally and thus more head is lost. The effect of this upward percolation will be reflected in the draw-down of the water level close to the discharging well—probably in most cases by an increase in draw-down over that which would occur had the well completely penetrated the formation.

The distance from the discharging well that the draw-down of the water level will be appreciably affected by partial penetration of the well will, in general, vary inversely with the amount of penetration.

Slichter [11] gives the following formula for computing the flow into an artesian well that does not pass through the water-bearing stratum.

$$Q=\frac{2\pi s P(m-r)}{\log_e\left(1+\frac{600}{r}\right)}+2.5\pi Psr \qquad (123)$$

Q is the discharge of the well, in cubic feet a minute; s is the draw-down in the well, in feet; P is a coefficient of permeability (Slichter's transmission constant); m is the thickness of the water-bearing material, in feet; and r is the radius of the well, in feet.

Muskat [12] gives the following correction to be made to the equilibrium formula for partially penetrating wells.

$$C=\frac{fractional\ penetration}{Q/Q_0} \qquad (124)$$

C is the correction factor; Q is discharge of the partially penetrating well; and Q_0 is the discharge of the completely penetrating well. According to Muskat, the coefficient of permeability computed by the equilibrium formulas using m as the thickness of sand opposite the well casing is multiplied by C to obtain the true value for per-

[11] Slichter, C. S., Theoretical investigation of the motion of ground waters: U. S. Geol. Survey 19th Ann Rept., pt. 2, p. 365, 1899.

[12] Muskat, Morris, The flow of homogeneous fluids through porous media, p. 97, New York, McGraw-Hill Book Co., Inc., 1937.

meability. Muskat also states [13] that the flow around partially penetrating wells will become almost exactly radial in character at a distance from the well equal to twice the thickness of the sand. At this distance the observed draw-down should equal the theoretical draw-down.

Of the four tests made in Nebraska, the pumped well completely penetrated the water-bearing material in the Kearney and Gothenburg tests and only partially penetrated it in the Grand Island and Scottsbluff tests. A study of the draw-down of the water table in these tests indicates that the draw-down differed from its theoretical value to a distance of about 5 b/c feet from the pumped well, where b is the thickness of the water-bearing formation below the bottom of the well in feet and c is the distance from the bottom of the well to the stage of the water table immediately outside the casing of the well while the pump is being operated. If this relation holds for artesian conditions, c presumably will be the distance from the bottom of the well to the top of the aquifer, that is $m-b$.

SLOW DRAINING OF WATER FROM WATER-BEARING MATERIAL

It is generally recognized that saturated water-bearing materials when allowed to drain, may yield water rather slowly. Investigations have shown that a sample of material after being saturated may continue to drain for several years, although most of the water in it may drain out in a much shorter time. Thus the value for the specific yield of a material, as ordinarily determined in the laboratory, is not likely to be reached under conditions found in nature except when the water-bearing material is permanently unwatered. Hence, material that is unwatered and then saturated again may hold in the period when it is unwatered considerably more water than is represented by the specific retention of the material.

The slow draining of water-bearing material in the vicinity of a pumped well causes the water table to decline rapidly at first and then more slowly as draining proceeds. As a result, the draw-down of the water table occurs at a different rate than if all the water is drained out instantaneously. This does not appear to have much effect on the determination of permeability by the equilibrium formulas because the quantity of water drained from unwatered material between two observation wells, when the observation wells are situated within the part of the cone of depression that has reached essential equilibrium in form, is small as compared with the quantity of lateral percolation. Slow draining, on the other hand, greatly affects the determination of permeability by the non-equilibrium formula because it also involves a determination of specific yield, which varies with the time of draining. As previously stated, the non-equilibrium formula, when applied

[13] Muskat, Morris, op. cit., p. 283.

to the draw-down of the water table, appears to give inconsistent values—probably because of the slow draining of the material. However, consistent values result when permeability is determined by the non-equilibrium formula from the draw-downs in observation wells located on a line—that is from the form of the cone of depression at one time. The effect of slow draining is minimized by this method.

Recent investigations indicate that artesian aquifers and their associated beds of fine-grained material do not compress and expand immediately in response to changes in pressure. The effect of this lag in response on the computation of permeability by the discharging-well formulas is similar to that caused by the slow draining of water-bearing material in areas where there is a water table.

VERTICAL PERCOLATION

Muskat,[14] in discussing the equilibrium method as it pertains to water-table conditions—which he calls the Dupuit-Forchheimer theory of gravity flow systems—points out that the method assumes that all water particles move horizontally to the pumped well, whereas, because of the lowering of the water table due to pumping, some of the water particles must also move vertically. He further states that it is fortuitous, because of this vertical movement, that the equilibrium equation predicts accurately the flow observed with radial flow models.

It seems reasonable that the effect of vertical movement on the draw-down of the water table will gradually become less as the distance from the pumped well increases and that the effect will be greater in thin water-bearing formations than in thick ones. The Nebraska tests appear to indicate that the effect of vertical velocities due to the lowering of the water table are dissipated within a short distance from the pumped well.

MISCELLANEOUS DIFFERENCES

There are many differences between theoretical assumptions and field conditions other than those mentioned above that in some areas may affect the application of the permeability methods adversely whereas in other areas the differences are of but little importance. Where the thickness of the water-bearing material varies considerably over the part of the cone of depression that is being used to determine permeability, the draw-down of the water table or piezometric surface obviously will not be equal to the theoretical draw-down computed on the assumption of uniform thickness. The effect of a dipping formation probably will not be significant except where the dip is steep.

Where there is a water table there is doubtless some percolation to pumped wells through the capillary fringe but unless the fringe is thick in proportion to the zone of saturation, the flow through it can

[14] Muskat, Morris, op. cit., pp. 359–365.

be disregarded. In some areas, such as near Gothenburg and Scottsbluff, Nebr., the water table stands in relatively impermeable material and most of the water discharged by wells percolates through material of much higher permeability at greater depths. Where the water table during pumping is not lowered below the impermeable material, the artesian formulas for computing permeability should be used, although water-table conditions exist. The formulas pertaining to water-table conditions are based on the assumption that when the water table is lowered by pumping, the cross-sectional area through which percolation to the well takes place is reduced by the amount of the draw-down. Where the water table fluctuates within the limits of a relatively impermeable zone, the draw-down of the water table does not affect the area through which most of the water passes.

The value to be substituted in the discharging-well formulas for the thickness of the water-bearing material may sometimes be questionable, especially where permeable material in the geologic section is separated by more or less impermeable material. If the value for the total thickness of water-bearing material is used the computed permeability will be that for the average of the entire section, whereas if the value for only the thickness of permeable material is used the computed permeability will be that for only the more permeable material.

In some areas it may be difficult to conduct pumping tests without some interference from nearby discharging wells. The draw-down of the water level around the well used for the test will then be different from the draw-down of a similar well that has no interference. Corrections to the observed draw-downs can sometimes be applied from observations of the extent of interference when the test well is idle. The gradient formula may often be used with assurance where the draw-down is affected by other discharging wells because this formula does not depend on the draw-down of the water level but rather on its slope. It is obvious that the average slope of the cone of depression will be practically unchanged by the interference because the average gradient required to transmit a given quantity of water to the discharging well will be virtually the same irrespective of the interference.

PROCEDURE FOR DETERMINING PERMEABILITY BY DISCHARGING-WELL METHODS

COLLECTION OF FIELD DATA

Choice of site.—Careful consideration should be given to the site for making permeability tests by the discharging-well methods. The discharge well should be selected where observation wells may be constructed as shallow as possible. On the other hand if water-table conditions exist and the water table stands very close to the land surface, from 1 to 10 feet, it may fluctuate daily in response to the use of water by vegetation. The location of wells in alfalfa fields is especially undesirable because this phreatophyte uses considerable ground water.

A discharge well should be selected in the open where little difficulty will be experienced in constructing observation wells at any desired place in the vicinity of the well. Locations very near groves of trees, rivers, lakes, roads, and hills should be avoided if possible. A well that is soundly constructed and, if a nonflowing well, equipped with a suitable powered pump should be selected to avoid possible interruptions in pumping. Preference should be given to wells equipped with electric pumps. A site near the edge or limit of a formation should not be chosen because the cone of depression may be altered in form if it extends to the limit of the formation during the period of the test. A site should be selected where the water from the discharging well can be disposed of without some of it returning to the zone of saturation. The water may be spread on a field at some appreciable distance from the area in which the observation wells are located or may be discharged into a ditch that will carry it to a stream or other body of surface water. As the period of discharge in most tests is at least 24 hours, the quantity of water that must be disposed of may be rather large. If possible, a well that penetrates the entire thickness of saturated water-bearing material should be selected. Locations should be avoided where other discharging wells are situated nearby, or arrangements should be made to have other wells shut down during the test and for several days prior to the test.

Preliminary test.—Unless the information is already known a brief preliminary test should be made to determine the draw-down and the approximate discharge of the discharging well. With these data the depths to which the observation wells must be sunk can be approximated, the size and kind of device for measuring the discharge can be ascertained, and if the well is pumped the approximate discharge at which the pump can be operated without an excessive decline of the water level can be determined.

Location of line of observation wells.—From three to six observation wells located on a line through the discharge well should be constructed upgradient from the well and an equal number should be constructed on the same line downgradient. The distance from the discharge well to each upgradient well should be equal to the distance from the discharge well to a corresponding downgradient well.

The approximate slope of the natural water table or piezometric surface should be determined before the observation wells are constructed. If the water table is shallow a few holes may be bored with a post-hole auger to the water table. The altitude of the water level in each hole may be ascertained by instrumental leveling, and a contour map of the water table may then be constructed. The observation wells should be located on a line through the discharge well perpendicular to the contour lines, that is, on a line parallel to the maximum slope of the water table.

In artesian areas the determination of the slope of the water level by boring holes may not be practicable. The direction of maximum slope may be determined from a map showing the slope of the regional piezometric surface, or it may be estimated for some localities from a knowledge of the intake and discharge areas of the formation.

Method of locating observation wells on a line.—A transit should be set up over the discharge well and directed parallel to the determined maximum slope of the water level. The distance from the axis of the discharge well to the first observation well should then be measured and a stake should be driven on the line, the line being determined by the transit. The locations of the other observation wells on the same side of the discharge well should be determined in this manner. The line then should be extended to the other side of the discharge well by means of the transit and the distances to the observation wells laid off in the manner described.

Construction of observation wells.—There are, of course, many different methods for constructing wells and most of these methods may be applied satisfactorily to the construction of the observation wells for a permeability test by the discharing-well methods. The chief requisite of the method used is that each well be constructed in such a manner that the water level in it will reflect closely the water level and the changes in the water level that occur in the formation.

The Nebraska tests were made in areas where water-table conditions exist and where the water table was at no place more than 20 feet below the land surface. Holes were bored by hand with a post-hole auger to the water table and 1-inch or 1¼-inch galvanized iron pipes, fitted with screen strainers, were then driven to desired depths with a maul. This method was found to be both economical and rapid. A few of the observation wells used in the Grand Island test were jetted into place by means of a hydraulic-rotary drilling rig. Three-inch iron pipe was used and clear water instead of a mud solution was used to prevent the formation and the well from becoming clogged with mud.

Cleaning observation wells.—After the observation wells have been constructed each well should be pumped or allowed to flow until it yields clear water freely, thus indicating that water can readily move into the well or out of it. Where the water table is about 20 feet or less below the top of the well, the well usually can be pumped with an ordinary pitcher pump either by connecting the pump directly to the top of the pipe or by connecting it to a small pipe and lowering the end of the pipe into the water surface in the observation well. Where the water level lies deeper a deep-well pump necessarily must be used.

Where it is not feasible to pump a well, water can be forced into it from the top and out at the bottom to ascertain whether it is open.

Measuring points.—A point from which measurements of water level can be made should be established at each observation well and at the discharge well. The points should be definite, permanent, and clear cut in order that the measurements may be accurate, and the points should be situated so that a steel tape or other measuring device may be lowered vertically into the well. The top of the pipe or well casing is usually a satisfactory measuring point. In flowing-well areas the artesian pressure may be measured by pressure gages, the measuring points being the points at which the gages measure the pressures.

The altitude of each measuring point with respect to a nearby permanent point should be carefully determined to the nearest hundredth of a foot by means of instrumental leveling before the pumping test is made. The altitude of the water level in any well at any time can be determined from these data and the water-level measurements. The altitude of each measuring point should be checked by instrumental leveling after the pumping test is run in order to ascertain whether any of the wells settled during the test. Where pressure gages are used the altitudes of the points at which the gages record the artesian pressures should be determined.

Making water-level measurements.—There are many methods that can be used for making measurements of water levels in wells. The method found most satisfactory in Nebraska, and the one used generally by the Federal Geological Survey, consists of coating several feet of the lower end of a steel tape with blue carpenter's chalk and lowering the tape into the water. A piece of lead at the end of the tape will hold it taught. An even foot mark is usually held at the measuring point and the depth of immersion of the tape into the water in the well is indicated by the wetted length of chalked tape. When using ordinary tapes the depth to water level is, of course, equal to reading of the tape at the measuring point minus the depth of the immersion of the tape in the water.

Making preliminary water-level measurements.—Periodic measurements of the water levels in the observation wells and the discharge well should be made several days before the test is begun. The measurements should be recorded systematically in order that they can be easily inspected at any time. If the water levels fluctuate from time to time before the test is begun the amount and periodicity of this fluctuation must be determined in order that a correction can be applied to the water-level fluctuations that occur during the test. If the regional water level should be declining slowly, the normal rate of decline should be determined and subtracted from the measurements made during the test. Also corrections may have to be made for fluctuations due to transpiration or changes in atmospheric pressure.

Determining the thickness of water-bearing material.—The thickness of the water-bearing material in the vicinity of the discharge well must be ascertained in order to determine the permeability of the formation. The thickness can be taken as the average thickness of the formation penetrated by nearby wells but preferably it should be determined by one or more test holes drilled at the location selected for the test.

Observations during test.—Measurements of the water levels should begin as soon as the discharge of water begins. A measurement should be made, of course, just before the discharge begins to determine the initial water level. The water level in the wells should be measured as often as practicable for the first few hours of the test, when the draw-down of the water level is most rapid, and then less frequently, when the draw-down is slower. Measurements should be made periodically for the entire period of the test.

Frequent measurements should be made also of the discharge of the well and of the water level in the discharging well. The discharge of the well should be maintained at a constant rate. It is not usually possible to apply the formulas for determining permeability if the discharge is stopped during a test and then restarted.

The period of pumping or flow that is necessary to produce draw-downs that will yield satisfactory results varies with the character of the formation and the rate of discharge. For artesian aquifers, the period is generally shorter than for formations in which the water is not confined under pressure because less water is taken from storage and hence the cone of depression reaches approximate equilibrium more quickly. The time that is required for the cone of depression to reach approximate equilibrium under water-table conditions varies greatly in different materials because the amount of water that must be taken from storage may differ considerably. Therefore, it is difficult to anticipate before the test is run how much time the test will require. During the test, however, the water-level measurments will indicate the part of the cone of depression around the discharge well that has reached essential equilibrium in form. This part of the cone will include all observation wells in which the rate of decline of the water level is approximately the same. In the Nebraska tests, which were made in areas where water-table conditions occur, the cone of depression reached approximate equilibrium in form to a distance of 200 feet from the pumped well about 12 to 48 hours after pumping began.

Observations after test.—The continuation of measurements of water level after the discharge of water has stopped may provide valuable information for studying the behavior of the water level in the formation and also make possible the use of the recovery formula for determining permeability (p. 95).

INTERPRETATION OF DATA

Draw-down curves.—A continuous curve representing the decline of the water level or pressure head in a well during the period of discharge is called a draw-down curve. A draw-down curve should be constructed for each observation well by plotting the draw-down measurements—initial water level minus water level during the test—against the time the measurement was made and by constructing a smooth curve as nearly as possible through the points so plotted. The scale should be sufficiently large to readily show small differences in draw-downs. The draw-down of water level at selected times, such as for every 2 hours after pumping began, should then be determined from the draw-down curves and these values should be tabulated. The plotting of draw-down curves subdues irregularities caused by inaccurate measurements and small irregularities in the rate of discharge.

Profiles of the cone of depression.—The draw-downs in each observation well at selected times obtained in the manner described above can be subtracted from the altitude of the initial water level to obtain the altitude of the water level at the selected times. Profiles of the cone of depression for the selected times can be constructed by drawing a smooth curve between the plotted draw-downs. The draw-down at any point on the profile can then be determined from the profiles. If the observation wells are located at equal distances on each side of the discharge well, the plotting of profiles of the cone of depression is not essential. However, if the wells are at different distances, the draw-downs at equal distances can be obtained from the profiles so prepared.

Computation of permeability.—The average coefficient of permeability of the water-bearing material may, of course, be computed by several of the formulas given in this paper. If the data mentioned above are collected, the limiting, gradient, non-equilibrium, and recovery formulas may all be applied. Examples of the use of these formulas are given in this paper in connection with descriptions of the four Nebraska tests and the Kansas test.

PUMPING TESTS IN NEBRASKA AND KANSAS

TEST NEAR GRAND ISLAND

In 1931 two intensive pumping tests were made in the Platte River Valley near Grand Island from which many valuable data were collected on the behavior of the ground water in the vicinity of a pumped well.[15] The tests were made on the farm of Fred Meyer, about 4 miles east of Grand Island, in the NW¼ sec. 17, T. 11 N., R. 8 W. The first test provided adequate data for determining the permeability of the water-bearing sand and gravel but the second test did not because the pump was unavoidably stopped several times, and as a result the form of the cone of depression was altered considerably from the form that it would have possessed had the pump been operated continuously.

About 80 observation wells were constructed in the vicinity of an existing irrigation well (fig. 10). The wells were located from about 3 to more than 1,200 feet from the central well, and thus the fluctuations of the water table over a large area were observed during the test. The thickness of the saturated water-bearing sand and gravel, which is 100 feet, was determined from a well drilled about 25 feet from the irrigation well. Samples of the material collected during the drilling of this well were sent to the hydrologic laboratory of the Geological Survey in Washington, D. C., for mechanical analysis and for determinations of porosity, moisture equivalent, and permeability (see table below).

The irrigation well used for the test was 24 inches in diameter, 39.5 feet deep, and was equipped with a 6-inch horizontal centrifugal pump. The pump was operated continuously for 48 hours for the test, from 6:05 a. m., July 29, to 6:04 a. m., July 31, 1931. During this time the pump discharged water at an average rate of 540 gallons a minute.

Physical properties of samples of alluvium taken from a well near Grand Island, Nebr.

[Determined in the hydrologic laboratory of the Geological Survey by V. C. Fishel]

Depth (feet)	Mechanical analysis (percent by weight)								Apparent specific gravity	Porosity (percent)	Moisture equivalent		Coefficient of permeability, P_m
	Larger than 2.0 mm.	2.0–1.0 mm.	1.00–0.50 mm.	0.50–0.25 mm.	0.25–0.125 mm.	0.125–0.062 mm.	0.062–0.005 mm.	Less than 0.005 mm.			Percent by weight	Percent by volume	
6 to 10	29.7	16.9	18.9	17.1	15.4	1.3	0.4	0.2	1.90	27.1	1.4	2.6	480
10 to 16	14.1	17.9	31.2	30.4	5.5	.3	.2	.1	1.84	30.9	1.5	2.7	1,685
16 to 20	16.8	15.2	25.8	29.4	10.5	1.6	.5	.1	1.80	32.3	1.1	2.0	1,460
20 to 25	18.6	18.8	21.3	24.8	13.8	1.9	.6	.2	1.89	28.5	1.4	2.6	1,095
25 to 30	7.5	17.2	25.0	30.0	16.0	3.4	.8	.3	1.83	31.0	1.4	2.6	1,095
30 to 39	36.4	20.8	21.4	15.0	4.7	.8	.5	.1	1.81	30.6	1.0	1.9	4,350
39 to 40	3.4	3.6	1.8	4.7	26.0	14.0	31.5	13.6	1.56	40.3	17.4	27.1	2
40 to 42	15.9	11.0	20.1	33.4	15.4	2.6	.4	.2	1.83	31.2	1.5	2.7	925
42 to 46	15.4	15.2	20.2	19.5	16.4	7.0	4.5	1.5	1.92	26.3	1.6	3.0	150
46 to 51	17.3	10.7	13.1	29.4	24.4	3.2	1.0	.4	1.84	30.2	1.6	3.0	350
51 to 55	39.6	12.8	9.5	15.7	13.5	4.7	2.5	1.0	1.94	26.2	1.7	3.3	780
55 to 61	27.4	14.9	16.3	22.4	11.8	3.7	2.1	1.0	1.92	25.6	1.6	3.0	730
61 to 66	20.6	19.6	19.7	19.1	9.7	4.3	4.4	.9	1.92	25.0	1.4	2.8	2,095
66 to 71	18.1	18.0	17.7	23.7	14.0	3.3	3.0	1.9	1.94	26.3	1.6	3.0	1,050
71 to 78	[1] 79.3	3.5	3.9	6.3	4.0	1.5	1.0	.3	2.02	22.8	------	------	2,185
78 to 86	14.3	11.9	18.2	25.1	18.7	6.5	3.0	1.7	1.88	41.8	1.6	3.1	220
86 to 92	36.2	10.3	14.6	17.1	11.6	4.3	3.4	2.3	1.97	21.5	1.9	3.9	495
92 to 99	15.1	10.4	22.8	31.1	13.9	3.0	2.5	1.0	1.86	29.9	1.2	2.1	430
99 to 105	25.8	13.3	13.7	21.9	14.3	5.2	3.5	2.0	1.90	27.6	1.5	2.9	285

[1] 76.0 percent larger than 5 mm.

[15] Wenzel, L. K., The Thiem method for determining permeability of water-bearing material: U. S. Geol. Survey Water-Supply Paper 679, pp. 1–57, 1937.

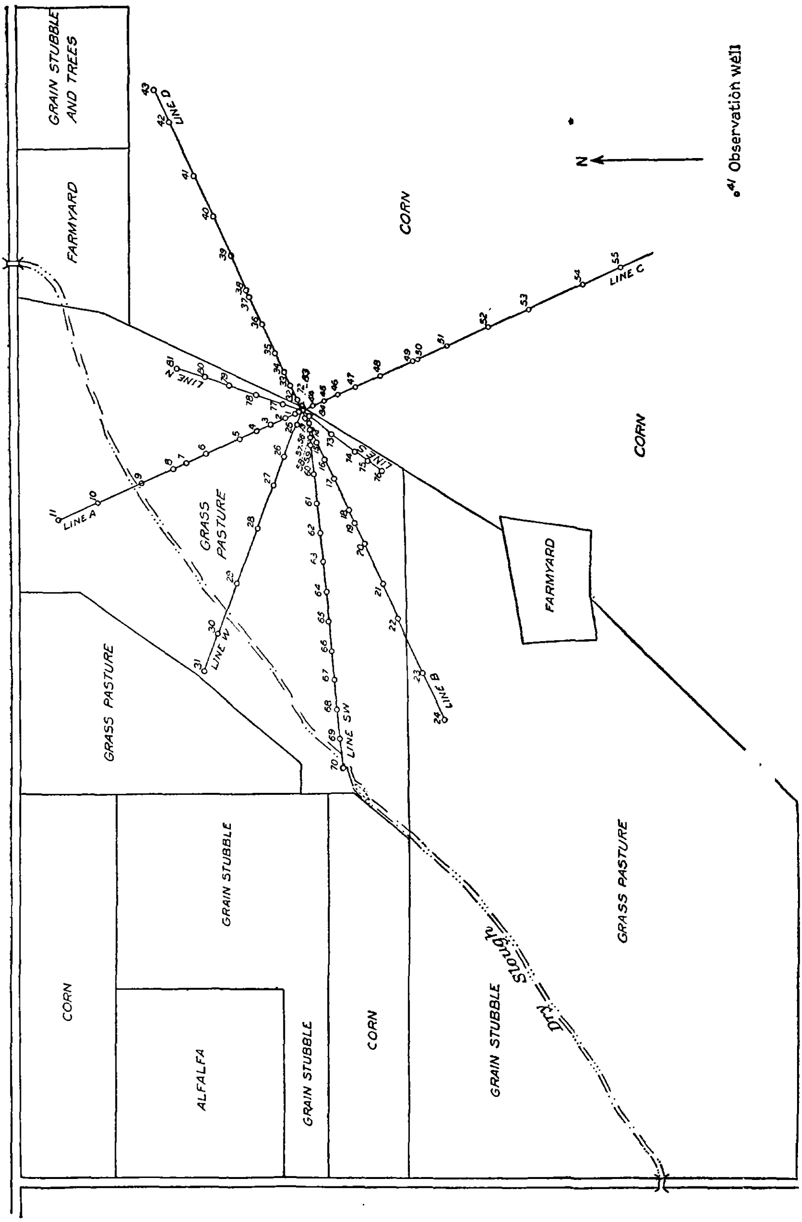

FIGURE 10.—Map showing location of wells used in pumping test near Grand Island.

Location, diameter, depth, and altitude of wells used in the pumping test near Grand Island, Nebr.

Well No.	Line	Diameter (inches)	Depth of well below measuring point (feet)	Distance of measuring point above land surface (feet)	Altitude of measuring point (feet)	Distance from pumped well 83 (feet)
1	A	3	21.4	0.7	1,814.59	24.9
2	A	3	10.3	.1	1,815.66	59.9
3	A	3	10.1	0	1,815.26	114.4
4	A	3	10.3	.1	1,814.63	164.2
5	A	1	11.5	1.4	1,815.83	229.0
6	A	1	6.5	.5	1,812.35	354.1
7	A	3	10.2	.2	1,815.39	429.3
8	A	1	11.4	1.2	1,815.52	478.9
9	A	3	10.3	.1	1,814.97	604.0
10	A	3	10.3	.1	1,814.73	754.6
11	A	3	10.5	.4	1,814.05	903.8
13	B	3	21.4	.2	1,814.84	29.9
14	B	3	10.9	.3	1,815.17	70.0
15	B	1	11.5	1.3	1,816.10	120.0
16	B	3	9.9	.1	1,815.67	184.9
17	B	3	9.9	.2	1,815.46	254.7
18	B	3	10.2	.3	1,815.08	375.3
19	B	3	10.3	.5	1,815.86	424.6
20	B	3	10.2	.4	1,816.30	499.7
21	B	3	9.9	.3	1,816.32	649.7
22	B	3	9.6	.3	1,816.39	775.3
23	B	1	11.5	1.9	1,816.95	974.3
24	B	3	10.6	.1	1,817.12	1,149.3
25	W	3	10.3	.3	1,815.39	49.7
26	W	3	10.3	.3	1,814.78	170.0
27	W	3	10.2	.3	1,815.33	270.0
28	W	3	10.6	.1	1,813.46	430.0
29	W	3	10.1	.3	1,815.68	625.0
30	W	3	10.7	.3	1,815.39	804.5
31	W	3	10.1	.1	1,815.06	939.7
32	D	1	21.5	1.2	1,820.42	40.1
33	D	1	16.5	1.0	1,819.17	95.1
34	D	1	16.5	1.2	1,818.99	144.7
35	D	1	16.5	1.2	1,818.93	214.3
36	D	1	16.5	.9	1,818.31	323.8
37	D	1	16.5	.9	1,818.27	423.2
38	D	1	16.5	1.1	1,818.33	448.2
39	D	1	16.5	1.0	1,818.05	572.9
40	D	1	16.5	1.2	1,818.83	722.7
41	D	1	12.7	1.8	1,818.08	872.2
42	D	1	----------	----------	1,817.19	1,072.5
43	D	1	12.7	.5	1,816.73	1,197.0
44	C	1	23.0	1.0	1,820.12	39.3
45	C	1	17.2	.5	1,818.37	80.5
46	C	1	11.1	.5	1,818.02	130.3
47	C	1	12.7	.5	1,817.37	195.6
48	C	1	12.6	.8	1,817.90	285.6
49	C	1	11.4	.4	1,818.36	410.2
50	C	1	12.3	.5	1,818.30	425.2
51	C	1	12.4	.4	1,818.80	535.4
52	C	1	12.7	.7	1,819.45	685.3
53	C	1	12.6	.4	1,818.01	834.6
54	C	1	12.7	.5	1,817.99	1,034.7
55	C	1	12.6	.6	1,817.37	1,174.9
56	SW	1	11.0	.5	1,814.97	46.7
57	SW	1	10.5	.9	1,815.98	69.5
58	SW	1	10.6	.8	1,815.29	93.6
59	SW	1	11.0	.7	1,816.18	118.0
60	SW	1	11.0	.8	1,815.88	216.9
61	SW	1	10.6	.9	1,816.14	316.6
62	SW	1	10.9	.9	1,816.19	416.5
63	SW	1	10.7	.8	1,816.47	516.5
64	SW	1	10.8	2.1	1,816.93	616.5
65	SW	1	10.9	2.4	1,817.55	716.5
66	SW	1	12.5	2.6	1,817.42	816.6
67	SW	1	10.9	2.4	1,818.39	916.6
68	SW	1	11.1	2.2	1,816.54	1,016.6
69	SW	1	6.1	1.3	1,815.37	1,116.9
70	SW	1	11.4	2.0	1,817.83	1,217.1
71	A	1	----------	----------	1,812.89	2.6
72	A	1	----------	----------	1,814.74	12.3
73	S	1	11.1	.9	1,815.94	130.1
74	S	1	12.0	.7	1,815.90	225.2

Location, diameter, depth, and altitude of wells used in the pumping test near Grand Island, Nebr.—Continued

Well No.	Line	Diameter (inches)	Depth of well below measuring point (feet)	Distance of measuring point above land surface (feet)	Altitude of measuring point (feet)	Distance from pumped well 83 (feet)
75	S	1	12.6	0.5	1,816.05	279.9
76	S	1	13.0	2.3	1,817.74	382.7
77	N	1	6.1	.8	1,813.08	63.2
78	N	1	12.8	1.7	1,815.32	160.0
79	N	1	13.0	.7	1,815.48	261.5
80	N	1	12.3	1.2	1,816.13	342.0
81	N	1	11.8	1.3	1,816.41	445.8
83	------	24	39.5	−.5	1,812.66	0
84	SW	12	102.0	−3.0	1,814.90	24.8

Water levels, in feet below measuring points, in wells just before pumping started in pumping test near Grand Island, Nebr.

Well No.	Water level	Well No.	Water level	Well No.	Water level
1	4.30	30	4.45	57	5.64
2	5.39	31	4.00	58	4.91
3	4.97	32	10.23	59	5.78
4	4.33	33	9.02	60	5.35
5	5.53	34	8.91	61	5.50
6	2.07	35	8.93	62	5.43
7	5.12	36	8.46	63	5.60
8	5.25	37	8.55	64	5.95
9	4.72	38	8.65	65	6.44
10	4.48	39	8.52	66	6.19
11	3.82	40	9.48	67	7.03
13	4.53	41	8.91	68	5.07
14	4.81	42	8.27	69	3.76
15	5.68	43	7.98	70	6.10
16	5.18	44	9.87	71	2.61
17	4.86	45	8.12	72	4.46
18	4.32	46	7.77	73	5.51
19	5.03	47	7.11	74	5.34
20	5.38	48	7.60	75	5.43
21	5.20	49	8.03	76	7.01
22	5.10	50	7.97	77	2.86
23	5.40	51	8.44	78	5.18
24	5.33	52	9.03	79	5.44
25	5.09	53	7.58	80	6.17
26	4.36	54	7.47	81	6.55
27	4.82	55	6.80	83	2.38
28	2.82	56	4.67	84	4.61
29	4.88				

Measurements of water levels in the observation wells were made periodically during the pumping period and for about 24 hours after the pump was shut down. The observed draw-downs in the observation wells appear at the end of this report.

Draw-down curves and profiles of the cone of depression were constructed according to the procedure outlined on page 117. The drawdown of the water table and the thickness of the saturated water-bearing material at 50, 100, 150, and 200 feet from the pumped well on lines *B* and *D* after 36 and 48 hours of pumping are given in the table below.

Draw-down of the water table and thickness of saturated water-bearing material, in feet, in the test near Grand Island, Nebr., after 36 and 48 hours of pumping

Distance upgradient from pumped well (feet)	Draw-down		Thickness of saturated material		Distance downgradient from pumped well (feet)	Draw-down		Thickness of saturated material	
	36 hours	48 hours	36 hours	48 hours		36 hours	48 hours	36 hours	48 hours
50	3.02	3.14	96.98	96.86	50	2.81	2.93	97.19	97.07
100	1.99	2.11	98.01	97.89	100	2.07	2.20	98.93	97.80
150	1.45	1.57	98.55	98.43	150	1.56	1.68	98.44	98.32
200	1.11	1.22	98.89	98.78	200	1.22	1.33	98.78	98.67

COMPUTATIONS OF PERMEABILITY

LIMITING FORMULA

The pumping rate for the Grand Island test was 540 gallons a minute, hence by the limiting formula

$$P_f = 527.7 \times 540 \times C = 284{,}958\ C \qquad (125)$$

in which P_f is the field coefficient of permeability expressed in Meinzer's units and $C = \frac{A}{B}$, a constant to be determined graphically (see p. 84). The following table gives values for A and B for 48 hours of pumping computed when r_1 (distance from the pumped well to the nearest observation well) = 50, 100, 150, and 200 feet, and for r_2 (distance from the pumped well to a more distant observation well) = 100, 150, 200, 300, 400, 500, 600, 700, 800, 900, and 1,000 feet. The large number of values are given to illustrate the effect of using draw-downs beyond the distance from the pumped well that the cone of depression has attained essential equilibrium in form.

Values of A and B for test near Grand Island, Nebr.

r_1	r_2	$\log\frac{r_2}{r_1}$	$0.25M$	A	B
50	100	0.301	97.41	0.0031	0.88
	150	.477	97.67	.0049	1.41
	200	.602	97.85	.0062	1.76
	300	.778	98.08	.0079	2.24
	400	.903	98.23	.0092	2.53
	500	1.000	98.32	.0102	2.71
	600	1.079	98.37	.0110	2.82
	700	1.146	98.41	.0116	2.89
	800	1.204	98.43	.0122	2.94
	900	1.255	98.44	.0127	2.96
	1,000	1.301	98.45	.0132	2.98
100	150	.176	98.11	.0018	.53
	200	.301	98.29	.0031	.88
	300	.477	98.52	.0048	1.36
	400	.602	98.67	.0061	1.65
	500	.699	98.76	.0071	1.83
	600	.778	98.81	.0079	1.94
	700	.845	98.85	.0085	2.01
	800	.903	98.87	.0091	2.06
	900	.954	98.88	.0096	2.08
	1,000	1.000	98.89	.0101	2.10
150	200	0.125	98.55	0.0013	0.35
	300	.301	98.79	.0030	.83
	400	.426	98.93	.0043	1.12
	500	.523	99.02	.0053	1.30
	600	.602	99.08	.0061	1.41
	700	.669	99.11	.0068	1.48
	800	.727	99.13	.0073	1.53
	900	.778	99.15	.0078	1.55
	1,000	.824	99.16	.0083	1.57
200	300	.176	98.96	.0018	.48
	400	.301	99.11	.0030	.77
	500	.398	99.20	.0040	.95
	600	.477	99.25	.0048	1.06
	700	.544	99.29	.0055	1.13
	800	.602	99.31	.0061	1.18
	900	.653	99.32	.0066	1.20
	1,000	.699	99.34	.0070	1.22

Values for A are plotted against corresponding values for B in figure 11. An inspection of the figure shows that points corresponding to values of $r_2 = < 200$ feet fall approximately on a straight line through the origin, whereas points corresponding to values of $r_2 = > 200$ feet deviate to the right of a straight line. This is caused by the failure of the cone of depression to reach essential equilibrium in form much beyond 200 feet from the pumped well. Obviously, points to the right of the straight line should be disregarded in determining C. Values for A and B to be used in computing C may be

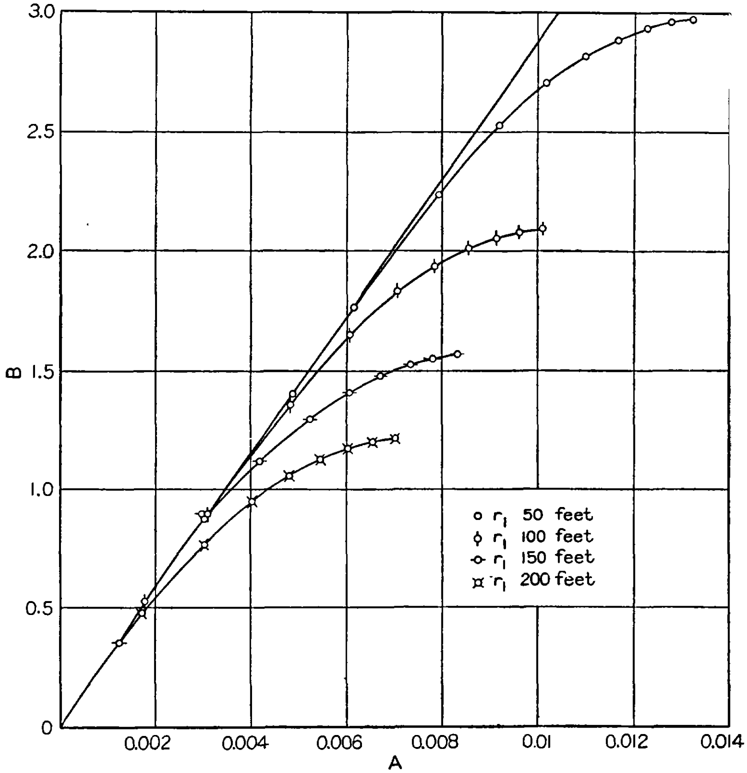

FIGURE 11.—Curves for the Grand Island test obtained by plotting A against B.

determined from any point on the straight line. For example, when $B=2.0$, $A=0.007$, and $C=\frac{A}{B}=0.0035$. Thus the coefficient of permeability computed by the limiting formula is

$$P_f = 284{,}958 \times 0.0035 = 997 \qquad (126)$$

GRADIENT FORMULA

The field coefficient of permeability may be computed also by the gradient formula

$$P_f = \frac{18{,}335q}{r(h_u + h_d)(f_{(r+10)u} + f_{(r+10)d} - f_{(r-10)u} - f_{(r-10)d})} \qquad (82)$$

in which the symbols are those defined on page 86. The altitude of the water table in the Grand Island test after 48 hours of pumping at 110, 120, and 130 feet upgradient and downgradient from the pumped well is given in the following table.

Altitude of water table in test near Grand Island after 48 hours of pumping

Distance upgradient from pumped well (feet)	Altitude of water table (feet)	Distance downgradient from pumped well (feet)	Altitude of water table (feet)
110	1,808.44	110	1,808.06
120	1,808.56	120	1,808.15
130	1,808.67	130	1,808.25

The thickness of the saturated water-bearing material 120 feet upgradient and 120 feet downgradient from the pumped well is 98.14 feet and 98.03 feet respectively. Substituting these data in the gradient formula

$$P_f=\frac{18{,}335\times540}{120(98.14+98.03)(1{,}808.67+1{,}808.25-1{,}808.44-1{,}808.06)}$$
$$=1{,}001 \qquad (127)$$

NON-EQUILIBRIUM FORMULA

The method of applying the non-equilibrium formula to the determination of permeability is outlined on pages 87–89. The field coefficient of permeability is computed by the formula

$$P_f=\frac{114.6q}{m}\left(\frac{W(u)}{s}\right) \qquad (91)$$

in which P_f is the field coefficient of permeability expressed in Meinzer's units, q is the discharge of the pumped well in gallons a minute, m is the thickness of water-bearing material in feet, $W(u)$ is the well function, and s is the draw-down in feet.

Average draw-downs at several distances from the pumped well and corresponding values of r^2/t for test near Grand Island, Nebr.

r (distance from pumped well in feet)	r^2/t	s (average of the draw-downs at distance r upgradient and downgradient, in feet)
50	1,250	3.04
100	5,000	2.16
150	11,250	1.63
200	20,000	1.28
300	45,000	.80
400	80,000	.51
500	125,000	.33
600	180,000	.22
700	245,000	.15
800	320,000	.10

First, the average of the draw-downs after 48 hours of pumping at equal distances on opposite sides of the pumped well are plotted against r^2/t on log log paper (pl. 2). Values for the average of the draw-downs at several distances from the pumped well and values of r^2/t for a pumping period of 48 hours are given in the preceding table. Second, using the values of the integral $W(u)$ and of u given in the table facing page 89, a type curve (pl. 1) is plotted to the same scale as that used in plate 2. Third, the curve on plate 2 is adjusted to the type curve so that the two curves coincide and a point of coincidence is selected. For the point $r^2/t=40{,}000$ ($r=200$ feet) and $s=1.28$ feet, the corresponding value on the type curve is $W(u)=1.95$ and $u=0.086$. Thus

$$P_f=\frac{114.6\times540\times1.95}{98.72\times1.28}=955 \qquad (128)$$

For the non-equilibrium formula the thickness of the water-bearing formation is assumed to be constant, thus the formula does not apply strictly to water-table conditions. However, this discrepancy can be partly eliminated by substituting $m-s$, the thickness of the saturated material at the point considered, for m, the thickness of the formation.

The specific yield of the water-bearing material is computed by equation (92).

$$S=\frac{uTt}{1.87r^2} \qquad (92)$$

By the graphical method, u was found to be 0.086. $r^2/t=20{,}000$ and $T=955\times98.72=94{,}278$. Thus the specific yield is

$$S=\frac{0.086\times94{,}278}{1.87\times20{,}000}=0.217=21.7 \text{ percent} \qquad (129)$$

which compares with an average value of 20.1 percent [16] computed by the formula

$$S=\frac{100(Y_1-Y)}{V} \qquad (130)$$

in which S is the specific yield, Y_1 is the quantity of ground water in cubic feet that percolates to the pumped well through a small cylindrical cross-sectional area around the pumped well, Y is the quantity of ground water in cubic feet that percolates through a larger cylindrical cross-sectional area, and V is the volume of water-bearing material in cubic feet that is unwatered between the cylinders.

RECOVERY FORMULA

In the Grand Island test the recovery of the water level after pumping stopped was observed in all of the observation wells and the pumped well. According to the Theis formula the coefficient of

[16] Wenzel, L. K., The Thiem method for determining permeability of water-bearing materials and its application to the determination of specific yield: U. S. Geol. Survey Water-Supply Paper 679, p. 55, 1937.

transmissibility and thus the field coefficient of permeability may be computed from the recovery of the water level in the pumped well.

$$T=\frac{264q}{s}\log_{10}\frac{t}{t'} \qquad (116)$$

in which T is the coefficient of transmissibility, q is the discharge of the pumped well in gallons a minute, s is the residual draw-down in

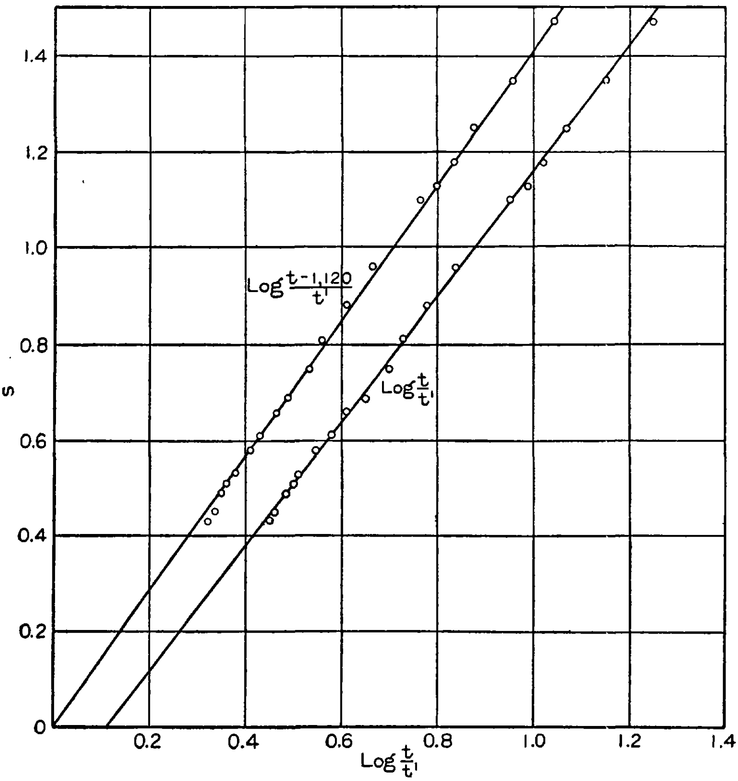

FIGURE 12.—Curves for Grand Island test obtained by plotting s against log $\frac{t}{t'}$.

feet, t is the time since pumping began, in any unit, and t' is the time since pumping stopped, expressed in the same unit.

The ratio $\dfrac{\log_{10}\frac{t}{t'}}{s}$ is determined graphically by plotting $\log_{10}\frac{t}{t'}$ against corresponding values of s and using for the ratio the slope of the straight line drawn through the plotted points (fig. 12). Values for $\log_{10}\frac{t}{t'}$ and for s for the Grand Island test are given in the following table.

The slope of the straight line constructed for values of $\log_{10}\frac{t}{t'}$ and s is $\frac{1.2-0.11}{1.42}=0.768$. Thus

$$T=264\times540\times0.768=109{,}486 \qquad (131)$$

and

$$P_f=\frac{109{,}486}{100}=1{,}095 \qquad (132)$$

The straight line does not pass through the origin, and it theoretically should. It can be made to do so approximately by applying an empirical correction to the formula as follows:

$$T=\frac{264q}{s}\log_{10}\frac{t\pm c}{t'} \qquad (117)$$

in which c is a correction factor. For the Grand Island test c is determined by trial and error to be $-1{,}120$. The slope of the straight line constructed from values of $\log_{10}\frac{t-1{,}120}{t'}$ and corresponding values of s is $\frac{1.06}{1.5}=0.707$.

Thus

$$T=264\times540\times0.707=100{,}790 \qquad (133)$$

and

$$P_f=\frac{100{,}790}{100}=1{,}008 \qquad (134)$$

Values of log $\frac{t}{t'}$ and s for test near Grand Island, Nebr.

t' (time after pumping stopped, in minutes)	t (time after pumping began, in minutes)	$\log\frac{t}{t'}$	s (residual draw-down in feet)
26	2,906	2,048	2.38
78	2,958	1,579	1.87
99	2,979	1,479	1.74
131	3,011	1,362	1.61
173	3,053	1,247	1.47
218	3,098	1,152	1.35
266	3,146	1,072	1.25
303	3,183	1,021	1.18
331	3,211	.987	1.13
364	3,244	.950	1.10
481	3,361	.844	.96
573	3,453	.780	.88
661	3,541	.729	.81
732	3,612	.693	.75
843	3,723	.645	.69
926	3,806	.614	.66
1,034	3,914	.579	.61
1,134	4,014	.549	.58
1,272	4,152	.514	.53
1,351	4,231	.496	.51
1,419	4,299	.481	.49
1,520	4,400	.461	.45
1,611	4,491	.446	.43

TEST NEAR KEARNEY

A pumping test to determine the permeability of the water-bearing sand and gravel in the Platte River Valley in the vicinity of Kearney, Nebr., was made in 1933 on the farm of J. Teed in the NW¼ sec. 27, T. 9 N., R. 14 W.[17] Five observation wells were constructed at distances of 50, 100, 150, 200, and 250 feet upgradient from the pumped well and five observation wells were constructed at the same distances downgradient from the pumped well. A test hole was drilled near the existing irrigation well, and the thickness of the saturated sand and gravel was found to be about 48 feet. The water in the formation was not confined under pressure. The irrigation well used for the test was 25 inches in diameter, and it penetrated the entire thickness of water-bearing material. It was equipped with an 8-inch electric turbine pump. The pumped well was operated continuously at a rate of 1,100 gallons a minute for about 24 hours, from 9:15 a. m., September 22, to 9:18 a. m., September 23, and measurements of the water level were made in the observation wells about every 2 hours. The draw-downs of the water level in the wells computed from these measurements appear at the end of this report. Records of the wells are given in a following table. The draw-down of the water table 16 and 24 hours after pumping began and the thickness of the saturated water-bearing material are given in an accompanying table. In this test no observations were made on the recovery of the water level after pumping stopped.

Draw-down of the water table and thickness of saturated water-bearing material, in feet, in the test near Kearney, Nebr., after 16 hours and 24 hours of pumping

Distance upgradient from pumped well (feet)	Draw-down		Thickness of saturated material		Distance downgradient from pumped well (feet)	Draw-down		Thickness of saturated material	
	16 hours	24 hours	16 hours	24 hours		16 hours	24 hours	16 hours	24 hours
50	3.82	3.97	44.18	44.03	50	3.72	3.88	44.28	44.12
100	2.81	2.99	45.19	45.01	100	2.74	2.91	45.26	45.09
150	2.31	2.47	45.69	45.53	150	2.22	2.38	45.78	45.62
200	1.96	2.12	46.04	45.88	200	1.80	1.97	46.20	46.03
250	1.64	1.78	46.36	46.22	250	1.53	1.70	46.47	46.30

Water levels, in feet below measuring points, in wells just before pumping started in pumping test near Kearney, Nebr.

Well	Water level	Well	Water level
Pumped well	14.24	X	13.56
Upgradient from pumped well:		Downgradient from pumped well:	
1	14.51	1	14.30
2	14.44	2	14.49
3	14.22	3	14.12
4	14.03	4	13.95
5	13.96	5	13.80

[17] Lugn, A. L., and Wenzel, L. K., Geology and ground-water resources of south-central Nebraska: U. S. Geol. Survey Water-Supply Paper 779, pp. 103–104, 1938.

Location, diameter, depth, and altitude of wells used in the test near Kearney, Nebr.

Well	Diameter (inches)	Depth below measuring point (feet)	Distance of measuring point above land surface (feet)	Altitude of measuring point above an assumed datum (feet)	Distance from axis of pumped well (feet)
Pumped well	25	59	0	27.87	0
X	1¼		.1	27.19	4.8
Upgradient from pumped well:					
1	1	24.2	1.2	28.20	49.66
2	1	22.9	1.2	28.19	99.57
3	1	21.0	1.3	28.04	149.63
4	1	23.2	1.2	27.91	199.58
5	1	18.3	1.4	27.91	249.60
Downgradient from pumped well:					
1	1	21.6	1.4	27.86	50.06
2	1	22.1	1.4	27.99	100.19
3	1¼	20.2	1.3	27.55	150.06
4	1¼	20.9	1.1	27.32	199.98
5	1¼	20.7	1.2	27.10	250.09

COMPUTATIONS OF PERMEABILITY

LIMITING FORMULA

The pumping rate for the Kearney test was 1,100 gallons a minute; hence by the limiting formula

$$P_f = 527.7 \times 1{,}100 \times C = 580{,}470C = 580{,}470\,\frac{A}{B} \qquad (135)$$

The following table gives values for A and B for 24 hours of pumping computed for r_1 (distance from the pumped well to nearest observation well) $=50$, 100, 150, and 200 feet, and for r_2 (distance from pumped well to a more distant observation well) $=100$, 150, 200, and 250 feet. Values of A are plotted against corresponding values of B in figure 13. Most of the points fall approximately on a straight line through the origin whose slope is $\frac{0.0141}{2.0}=0.00705$. Thus, by the limiting formula

$$P_f = 580{,}470 \times 0.00705 = 4{,}092 \qquad (136)$$

Values of A and B for test near Kearney, Nebr.

r_1	r_2	$\log \frac{r_2}{r_1}$	$0.25M$	A	B
50	100	0.301	44.56	0.0068	0.98
	150	.477	44.83	.0106	1.50
	200	.602	45.02	.0134	1.88
	250	.699	45.17	.0155	2.19
100	150	.176	45.31	.0039	.53
	200	.301	45.50	.0066	.91
	250	.398	45.66	.0087	1.21
150	200	.125	45.77	.0027	.38
	250	.222	45.92	.0048	.69
200	250	.097	46.11	.0021	.31

GRADIENT FORMULA

The altitudes of the water table after 24 hours of pumping in the Kearney test at 115, 125, and 135 feet upgradient and downgradient from the pumped well are given in the following table. The thickness of saturated water-bearing sand and gravel 125 feet upgradient and 125 feet downgradient from the pumped well is 45.31 feet and 45.38

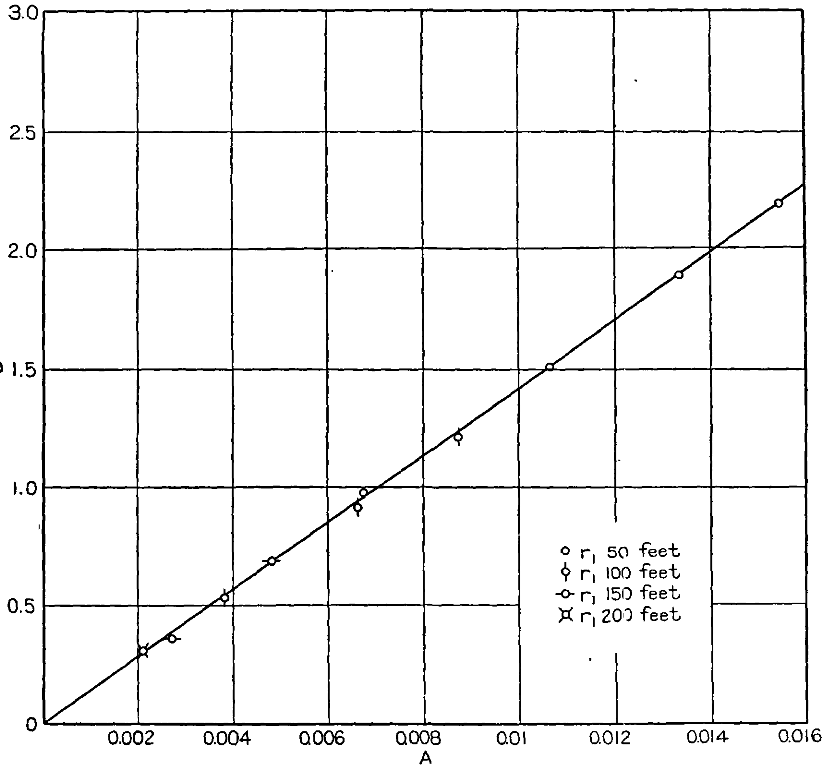

FIGURE 13.—Curve for Kearney test obtained by plotting A against B.

feet, respectively. Substituting these data in the gradient formula, equation (82), the field coefficient of permeability is

$$P_f=\frac{18{,}335\times 1{,}100}{125\ (45.31+45.38)(11.20+10.93-10.94-10.76)}=4{,}137 \quad (137)$$

Altitude of water table in test near Kearney after 24 hours of pumping

Distance upgradient from pumped well (feet)	Altitude of water table above assumed datum (feet)	Distance downgradient from pumped well (feet)	Altitude of water table above assumed datum (feet)
115	10.94	115	10.76
125	11.09	125	10.84
135	11.20	135	10.93

NON-EQUILIBRIUM FORMULA

Values of r, r^2/t, and s for a pumping period of 24 hours for the Kearney test are given in the following table, and values of s are plotted against corresponding values of r^2/t on plate 3.

Average draw-downs at several distances from the pumped well and corresponding values for r^2/t for test near Kearney, Nebr.

r (distance from pumped well, in feet)	r^2/t	s (average of the draw-downs at distance r upgradient and downgradient, in feet)
50	2, 500	3. 93
100	10, 000	2. 95
150	22, 500	2. 43
200	40, 000	2. 05
250	62, 500	1. 74

The curve on plate 3, when placed over the type curve, coincides in such a manner that for the point $r=200$, the corresponding values of $W(u)$ and u on the type curve are respectively 3.01 and 0.0282. Substituting for the field coefficient of permeability in formula (91),

$$P_f=\frac{114.6\times1,100\times3.01}{45.96\times2.05}=4,027 \qquad (138)$$

The specific yield of the water-bearing material is computed by substituting in formula (92). The coefficient of transmissibility is $4,027\times45.96=185,081$ and $r^2/t=40,000$. Thus

$$S=\frac{0.0282\times185,081}{1.87\times40,000}=0.07=7 \text{ percent} \qquad (139)$$

TEST NEAR GOTHENBURG

Later in 1933 a pumping test to determine the permeability of the water-bearing sand and gravel in the Platte River Valley was made about 2 miles east of Gothenburg on the farm of Albert Anderson in the SW¼NW¼ sec. 19, T. 11 N., R. 24 W. The irrigation well used for the test was 24 inches in diameter and 33 feet deep. It penetrated the entire thickness of sand and gravel. The well was equipped with a 6-inch horizontal centrifugal pump. Five observation wells were constructed upgradient from the pumped well at distances of 50, 100, 150, 190, and 250 feet, and five wells were constructed at the same distances downgradient. A test hole was drilled near the pumped well, and the thickness of the saturated sand and gravel was found to be 17 feet. The zone of saturation, however, extended up into loess for about 5 feet.

The pumped well was operated continuously at an average rate of about 532 gallons a minute for about 24 hours, from 8:42 a. m., October 1, to 8:20 a. m., October 2, and measurements of water level in the observation wells were made periodically. The draw-downs of the water level in the wells, computed from these measurements, appear at the end of this report. Records of the wells are given in the accompanying table. The draw-down of the water table in the observation wells after 16 hours and about 24 hours of pumping are given in a following table. Observations on the recovery of the water level were not made in this test.

Location, diameter, depth, and altitude of wells used in the pumping test near Gothenburg, Nebr.

Well	Diameter (inches)	Depth below measuring point (feet)	Distance of measuring point above land surface (feet)	Altitude of measuring point above an assumed datum (feet)	Distance from axis of pumped well (feet)
Pumped well	24	34.0	1.0	20.00	0
Upgradient from pumped well:					
1	1¼	20.3	1.3	20.07	49.91
2	1	22.7	1.4	20.11	99.95
3	1	23.6	1.4	19.99	149.99
4	1¼	20.7	1.0	19.78	190.16
5	1	21.9	3.5	22.98	249.88
Downgradient from pumped well:					
1	1¼	20.6	1.2	20.10	49.94
2	1	20.5	1.1	19.29	99.85
3	1	23.0	1.2	18.63	149.98
4	1	24.5	1.3	18.31	189.90
5	1	21.9	1.5	18.23	250.00

Water levels, in feet below measuring points, in wells just before pumping started in pumping test near Gothenburg, Nebr.

Well	Water level	Well	Water level
Pumped well	12.83		
Upgradient from pumped well:		Downgradient from pumped well:	
1	12.85	1	12.99
2	12.83	2	12.24
3	12.65	3	11.64
4	12.40	4	11.36
5	15.53	5	11.35

Draw-down of the water table in the test near Gothenburg, Nebr., after 16 hours and 24 hours of pumping

Distance upgradient from pumped well (feet)	Draw-drown (feet)		Distance downgradient from pumped well (feet)	Draw-down (feet))	
	16 hours	24 hours		16 hours	24 hours
50	4.97	5.16	50	4.93	5.13
100	3.66	3.88	100	3.63	3.85
150	2.79	3.01	150	3.05	3.25
190	2.32	2.53	190	2.62	2.82
250	1.82	2.04	250	2.08	2.28

The ground water in the Gothenburg area is not confined under pressure, hence artesian conditions do not exist. However, the permeability of the sand and gravel is so much greater than the permeability of the loess—in about the ratio of 4,000 to 2—that comparatively little water moves laterally through the loess. With such a condition it is necessary in computing permeability to use the artesian formulas—in which the thickness of saturated water-bearing material is unchanged during pumping by the draw-down of the water level. Thus, for the Gothenburg test, the thickness of the water-bearing material is considered to be 17 feet irrespective of the drawdown of the water table.

COMPUTATIONS OF PERMEABILITY

LIMITING FORMULA

The pumping rate for the Gothenburg test was 532 gallons a minute; hence by the limiting formula

$$P_f = 527.7 \times 532 \times C = 280{,}736C = 280{,}736\frac{A}{B} \qquad (140)$$

The following table gives values for A and B for 24 hours of pumping computed when r_1 (distance from the pumped well to nearest

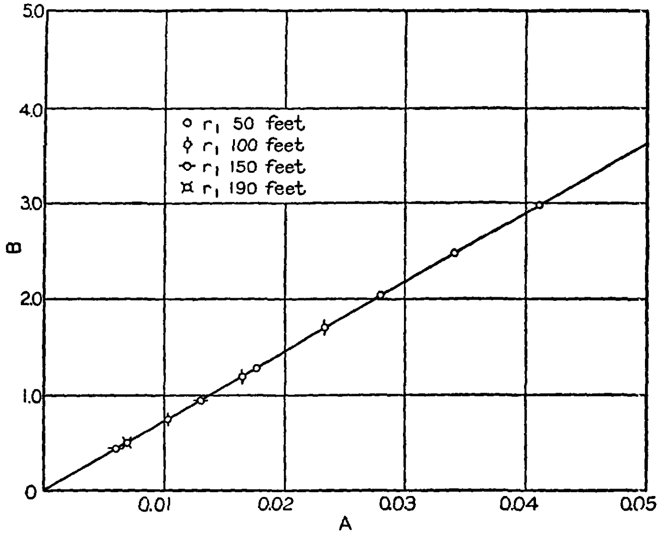

FIGURE 14.—Curve for Gothenburg test obtained by plotting A against B.

observation well) = 50, 100, 150, and 190 feet and r_2 (distance from pumped well to a more distant observation well) = 100, 150, 190, and 250 feet. Values of A are plotted against corresponding values of B in figure 14. Most of the points fall approximately on a straight line through the origin whose slope is $\frac{0.05}{3.63} = 0.0138$. Thus by the limiting formula

$$P_f = 280{,}736 \times 0.0138 = 3{,}874 \qquad (141)$$

Values of A and B for test near Gothenburg, Nebr.

r_1	r_2	$\log \frac{r_2}{r_1}$	0.25*M*	*A*	*B*
50	100	0.301	17	0.0177	1.28
	150	.477	17	.0281	2.02
	190	.580	17	.0341	2.47
	250	.699	17	.0411	2.99
100	150	.176	17	.0104	.74
	190	.279	17	.0164	1.19
	250	.398	17	.0234	1.71
150	190	.103	17	.0061	.45
	250	.222	17	.0131	.97
	250	.119	17	.0070	.52

GRADIENT FORMULA

The altitude of the water table after 24 hours of pumping in the Gothenburg test at 115, 125, and 135 feet upgradient from the pumped well and the same distances downgradient is given in the following table. The thickness of the saturated water-bearing material is 17 feet. Substituting these data in the gradient formula pertaining to artesian conditions (equation 83) the field coefficient of permeability is

$$P_f = \frac{9{,}168 \times 532}{125 \times 17(4.09 + 3.60 - 3.72 - 3.38)} = 3{,}890 \quad \text{---} \quad (142)$$

Altitude of water table in test near Gothenburg, Nebr., after 24 hours of pumping

Distance upgradient from pumped well (feet)	Altitude of water table above assumed datum (feet)	Distance downgradient from pumped well (feet)	Altitude of water table above assumed datum (feet)
115	3.72	115	3.38
125	3.91	125	3.50
135	4.09	135	3.60

NON-EQUILIBRIUM FORMULA

Values of r, r^2/t, and s, for a pumping period of 24 hours for the Gothenburg test are given in the following table, and values of s are plotted against corresponding values of r^2/t on plate 4. The curve on plate 4, when placed on the type curve, coincides in such a manner that for the point $r=150$ feet the corresponding values of $W(u)$ and u on the type curve are respectively 3.3 and 0.0212. Substituting for the field coefficient of permeability in formula (91)

$$P_f = \frac{114.6 \times 532 \times 3.3}{17 \times 3.13} = 3{,}781 \quad \text{---} \quad (143)$$

The specific yield of the water-bearing material is computed by equation (92). The coefficient of transmissibility is $3{,}781 \times 17 = 64{,}277$ and $r^2/t = 22{,}500$. Thus

$$S = \frac{0.0212 \times 64{,}277}{1.87 \times 22{,}500} = 0.0324 = 3.24 \text{ percent} \quad \text{---} \quad (144)$$

Average draw-downs at several distances from the pumped well and corresponding values for r^2/t for test near Gothenberg, Nebr.

r (distance from pumped well, in feet)	r^2/t	s (average of the draw-downs at distance r upgradient and downgradient, in feet)
50	2, 500	5. 15
100	10, 000	3. 87
150	22, 500	3. 13
190	36, 100	2. 68
250	62, 500	2. 16

The average specific yield of four samples of loess from the Platte Valley, Nebraska, was determined in the hydrologic laboratory of the Geological Survey to be about 20.[18] If the value determined by the non-equilibrium method is regarded as correct for a 24-hour period of draining and if it is assumed that the loess in this area possesses the same ultimate specific yield as that of the samples analyzed in the hydrologic laboratory, the amount of water drained from the loess around the pumped well in 24 hours represents only about 16 percent of the water that it would eventually yield in a longer period of draining.

TEST NEAR SCOTTSBLUFF

A pumping test to determine the permeability of the sand and gravel in the North Platte Valley near Scottsbluff, Nebr., was made in 1937 in connection with an investigation of the geology and ground-water resources of Scotts Bluff County. The test was made in the NW¼SE¼ sec. 11, T. 22 N., R. 56 W., with an irrigation well 24 inches in diameter and 46 feet deep, which is owned by Harry Pieper. Observation wells were constructed on a line through the pumped well about parallel to the slope of the water table at distances of about 50, 100, 150, 200, 300, 400, 500, and 600 feet both upgradient and downgradient from the pumped well. One observation well was constructed on the line about 11 feet downgradient from the pumped well. A test hole was drilled near the existing well and the thickness of the saturated water-bearing material was found to be about 123 feet. About 9 feet of the upper part of this material consisted of fine sand and silt, and hence very little water that was discharged by the well percolated to the well through this fine material. Consequently the artesian formulas for determining permeability must be used for this test, as they were for the test near Gothenburg.

The irrigation well was pumped continuously at a rate of about 1,270 gallons a minute from 11:53 a. m., November 2, to 3:32 a. m., November 3, during which time periodic measurements were made of the water

[18] Lugn, A. L., and Wenzel, L. K., Geology and ground-water resources of south-central Nebraska; U. S. Geol. Survey Water-Supply Paper 779, p. 90, 1938.

level in the observation wells. Regular measurements of the water levels in the observation wells were continued after pumping of the irrigation well stopped until about noon of November 4 in order to observe the recovery of the water table. The observed draw-downs of the water table in the observation wells during the pumping and after pumping stopped are given in a table at the end of this report. Records of the wells appear in the following table, and draw-downs in the wells 10 hours and 15 hours after pumping began are given in another table.

Location, diameter, depth, and altitude of wells used in the pumping test near Scottsbluff, Nebr.

Well	Diameter (inches)	Depth below measuring point (feet)	Distance of measuring point above land surface (feet)	Altitude of measuring point above an assumed datum (feet)	Distance from axis of pumped well (feet)
Pumped well	24	46.4	0	50.23	0
Upgradient from pumped well:					
1	1¼	28.4	.8	49.98	49.84
2	1¼	23.4	1.2	50.20	99.69
3	1¼	23.0	1.2	50.18	149.50
4	1¼	23.5	1.4	50.28	199.88
5	1¼	23.6	1.1	50.07	299.55
6	1¼	23.1	1.1	50.21	399.44
7	1¼	23.4	1.4	50.68	498.41
8	1¼	23.6	1.4	51.28	598.60
X	1¼	28.3	.4	49.92	11.23
Downgradient from pumped well:					
1	1¼	28.9	1.4	50.62	49.67
2	1¼	23.3	1.4	50.55	99.90
3	1¼	23.5	1.2	50.33	149.75
4	1¼	23.5	1.5	50.73	199.93
5	1¼	23.1	1.7	50.93	299.81
6	1¼	23.1	1.7	50.96	399.79
7	1¼	23.3	1.4	50.79	499.91
8	1¼	23.2	1.4	51.00	599.73

Water levels, in feet below measuring points, in wells just before pumping started in pumping test near Scottsbluff, Nebr.

Well	Water level	Well	Water level
Pumped well	13.38	X	13.08
Upgradient from pumped well:		Downgradient from pumped well:	
1	13.05	1	13.85
2	13.19	2	13.85
3	13.09	3	13.71
4	13.11	4	14.19
5	12.75	5	14.54
6	12.73	6	14.73
7	13.04	7	14.71
8	13.49	8	15.08

Draw-down of the water table in the test near Scottsbluff, Nebr., after 10 hours and 15 hours of pumping

Distance upgradient from pumped well (feet)	Draw-down (feet)		Distance downgradient from pumped well (feet)	Draw-down (feet)	
	10 hours	15 hours		10 hours	15 hours
50	6.56	6.69	50	6.81	6.93
100	4.73	4.87	100	4.57	4.73
150	3.90	4.03	150	3.77	3.95
200	3.42	3.55	200	3.22	3.40
300	2.71	2.86	300	2.44	2.61
400	2.21	2.36	400	1.88	2.06
500	1.85	1.99	500	1.44	1.62
600	1.54	1.67	600	1.20	1.36

COMPUTATIONS OF PERMEABILITY

LIMITING FORMULA

The pumping rate for the Scottsbluff test was 1,270 gallons a minute; hence by the limiting formula

$$P_f = 527.7 \times 1{,}270 \times C = 670{,}179C = 670{,}179 \frac{A}{B} \quad (145)$$

The following table gives values for A and B for 15 hours of pumping computed when r_1 (distance from the pumped well to nearest observation well) =50, 100, 150, 200, 300, 400, and 500 feet and r_2 (distance

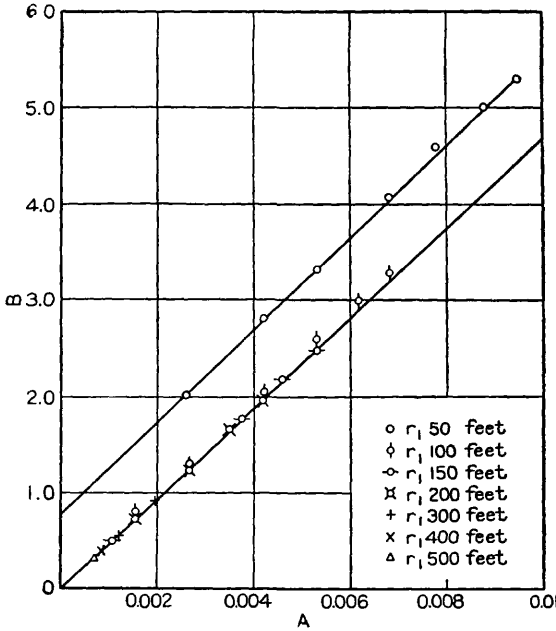

FIGURE 15.—Curves for Scottsbluff test obtained by plotting A against B.

from pumped well to a more distant observation well) =100, 150, 200, 300, 400, 500, and 600 feet. Values of A are plotted against corresponding values of B in figure 15. An inspection of the figure indicates that points corresponding to $r_1 = 50$ feet fall approximately on a straight line but the line passes above the origin. In like manner the points corresponding to $r_1 = 100$ feet fall on a straight line that passes just above the origin. The other points fall about on a straight line through the origin. The failure of points corresponding to $r_1 = 50$ and $r_1 = 100$ to fall on a straight line through the origin is probably caused chiefly by the increase in draw-down of the water level within a radius of 100 feet or more from the pumped well; the increase in draw-down is due to the failure of the well to completely penetrate the water-bearing material. These points, therefore, should be disregarded in the permeability computations. The slope of the straight line through the origin is $\frac{0.010}{4.7}=0.00213$. Thus by the limiting formula

$$P_f=670{,}179\times0.00213=1{,}427 \qquad (146)$$

Values of A and B for test near Scottsbluff, Nebr.

r_1	r_2	$\log\frac{r_2}{r_1}$	0.25M	A	B	r_1	r_2	$\log\frac{r_2}{r_1}$	0.25M	A	B
50	100	0.301	114	0.00264	2.01	150	200	0.125	114	0.00110	0.52
	150	.477	114	.00418	2.82		300	.301	114	.00264	1.26
	200	.602	114	.00528	3.34		400	.426	114	.00374	1.78
	300	.778	114	.00682	4.08		500	.523	114	.00459	2.19
	400	.903	114	.00792	4.60		600	.602	114	.00528	2.48
	500	1.000	114	.00877	5.01	200	300	.176	114	.00154	.74
	600	1.079	114	.00946	5.30		400	.301	114	.00264	1.27
100	150	.176	114	.00154	.81		500	.398	114	.00349	1.67
	200	.301	114	.00264	1.33		600	.477	114	.00418	1.96
	300	.477	114	.00418	2.07	300	400	.125	114	.00110	.53
	400	.602	114	.00528	2.59		500	.222	114	.00195	.93
	500	.699	114	.00613	3.00		600	.301	114	.00264	1.22
	600	.778	114	.00682	3.29	400	500	.097	114	.00085	.41
							600	.176	114	.00154	.70
						500	600	.079	114	.00069	.29

GRADIENT FORMULA

The altitude of the water table after 15 hours of pumping in the Scottsbluff test at 165, 175, and 185 feet both upgradient and downgradient from the pumped well is given in the following table. Substituting these data in the gradient formula (equation 83) the field coefficient of permeability is

$$P_f=\frac{9{,}168\times1{,}270}{175\times114(33.47+33.02-33.25-32.83)}=1{,}423 \qquad (147)$$

Altitude of water table in test near Scottsbluff, Nebr., after 15 hours of pumping

Distance upgradient from pumped well (feet)	Altitude of water table above assumed datum (feet)	Distance downgradient from pumped well (feet)	Altitude of water table above assumed datum (feet)
165	33.25	165	32.83
175	33.36	175	32.92
185	33.47	185	33.02

NON-EQUILIBRIUM FORMULA

Values of r, r^2/t, and s, for the Scottsbluff test for three periods of pumping are given in the following table. Values of s are plotted against corresponding values of r^2/t for 4, 8, and 15 hours of pumping on plate 5. A separate computation for permeability and for specific yield can be made from each curve. The curves when placed over the type curve coincide to give the following values for $W(u)$ and u corresponding to points selected for computations.

Values of W(u) and u for several periods of pumping corresponding to points selected for computations

Point selected for computations	r^2/t	Period of pumping (days)	s (feet)	$W(u)$	u
r=200 feet	240,000	0.167	2.90	2.99	0.029
r=300 feet	270,000	.333	2.49	2.64	.046
	144,000	.625	2.74	2.94	.031

Average draw-downs for three periods of pumping and corresponding values of r^2/t for test near Scottsbluff, Nebr.

r (distance from pumped well, in feet)	t (length of pumping period, in days)	r^2/t	s (average of the draw-downs at distance r upgradient and down-gradient, in feet)	r (distance from pumped well, in feet)	t (length of pumping period, in days)	r^2/t	s (average of the draw-downs at distance r upgradient and down-gradient, in feet)
50	0.167	15,000	6.29	300	0.167	540,000	2.17
	.333	7,500	6.59		.333	270,000	2.49
	.625	4,000	6.81		.625	144,000	2.74
100	.167	60,000	4.24	400	.167	960,000	1.65
	.333	30,000	4.56		.333	480,000	1.96
	.625	16,000	4.80		.625	256,000	2.21
150	.167	135,000	3.43	500	.167	1,500,000	1.27
	.333	67,500	3.75		.333	750,000	1.56
	.625	36,000	3.99		.625	400,000	1.81
200	.167	240,000	2.90	600	.167	2,160,000	1.02
	.333	120,000	3.23		.333	1,080,000	1.29
	.625	64,000	3.48		.625	576,000	1.52

The field coefficient of permeability computed from values of s and $W(u)$ for the 4-hour pumping period is

$$P_f=\frac{114.6\times 1{,}270\times 2.99}{114\times 2.90}=1{,}316 \qquad (148)$$

The field coefficient of permeability computed from values of s and $W(u)$ for the 8-hour pumping period is

$$P_f=\frac{114.6\times 1{,}270\times 2.64}{114\times 2.49}=1{,}354 \qquad (149)$$

The field coefficient of permeability computed from values of s and $W(u)$ for the 15-hour pumping period is

$$P_f=\frac{114.6\times 1{,}270\times 2.94}{114\times 2.74}=1{,}370 \qquad (150)$$

The specific yield computed from values of s and u for the 4-hour pumping period is

$$S=\frac{0.029\times (114\times 1{,}316)}{1.87\times 240{,}000}=0.0097=0.97 \text{ percent} \qquad (151)$$

The specific yield computed from values of s and u for the 8-hour pumping period is

$$S=\frac{0.046\times (114\times 1{,}354)}{1.87\times 270{,}000}=0.014=1.4 \text{ percent} \qquad (152)$$

The specific yield computed from values of s and u for the 15-hour pumping period is

$$S=\frac{0.031\times(114\times1{,}370)}{1.87\times144{,}000}=0.018=1.8 \text{ percent} \qquad (153)$$

The computed values for both permeability and specific yield increased with the period of pumping owing to the slow draining of the unwatered material. However, the computed specific yield increased

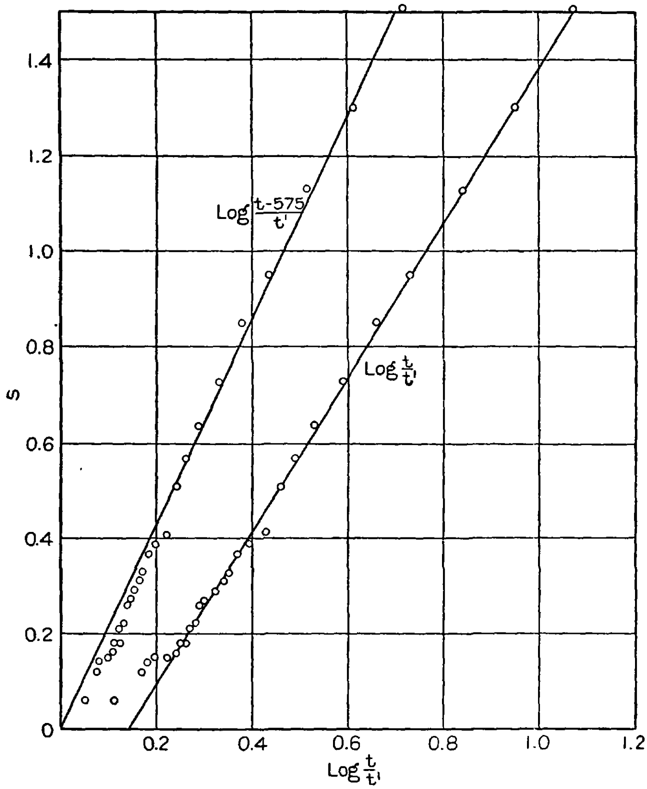

FIGURE 16.—Curves for Scottsbluff test obtained by plotting s against $\log \frac{t}{t'}$.

about 85 percent and the computed field coefficient of permeability increased only about 4 percent in the 11-hour period. As the water level during the pumping period did not decline below the fine sand and silt, the computed specific yield is that, of course, of this material and is not that of the sand and gravel through which most of the lateral percolation occurred.

If a smooth curve is constructed through the points corresponding to one value of r on plate 5 the field coefficient of permeability and the specific yield may be computed by adjusting the curve so constructed to the type curve. The permeability and specific yield are thus computed from the draw-down of the water level at the distance r from the pumped well. It is obvious, however, that these curves will be much flatter than those on plate 5 and thus the computed values for permeability will be high and those for specific yield will be low. This apparently is due to the slow draining of the material.

RECOVERY FORMULA

The recovery of the water level in the Scottsbluff area after pumping stopped was observed in the pumped well and in all the observation wells. Values of $\log_{10}\frac{t}{t'}$ and s (residual draw-down in the pumped well) for the Theis formula are given in the following table, and values of s are plotted against corresponding values of $\log_{10}\frac{t}{t'}$ in figure 16.

The slope of the straight line passing through most of the plotted points is $\frac{1.0-0.14}{1.38}=0.623$. Thus

$$T=264\times1{,}270\times0.623=208{,}879 \qquad (154)$$

and

$$P_f=\frac{208{,}879}{114}=1{,}832 \qquad (155)$$

The straight line does not pass through the origin as it theoretically should. It can be made to do so approximately by applying the empirical correction factor (see Grand Island test, p. 127). For the Scottsbluff test, c is determined by trial and error to be -550. The slope of the straight line constructed from values of $\log_{10}\frac{t-550}{t'}$ and corresponding values of s is $\frac{0.7}{1.5}=0.467$. Thus

$$T=264\times1{,}270\times0.467=156{,}576 \qquad (156)$$

and

$$P_f=\frac{156{,}576}{114}=1{,}373 \qquad (157)$$

Values of $\log\frac{t}{t'}$ and s for test near Scottsbluff, Nebr.

t' (time after pumping stopped, in minutes)	t (time after pumping began, in minutes)	$\log\frac{t}{t'}$	s (residual drawdown, in feet)	t' (time after pumping stopped, in minutes)	t (time after pumping began, in minutes)	$\log\frac{t}{t'}$	s (residual drawdown, in feet)
46	985	1.331	2.15	801	1,740	0.337	0.31
61	1,000	1.215	1.85	863	1,802	.320	.29
88	1,027	1.067	1.51	926	1,865	.304	.27
119	1,058	.949	1.30	982	1,921	.291	.26
160	1,099	.837	1.13	1,046	1,985	.278	.22
216	1,155	.728	.95	1,106	2,045	.267	.21
264	1,203	.659	.85	1,162	2,101	.257	.18
320	1,259	.595	.73	1,228	2,167	.247	.18
388	1,327	.534	.64	1,285	2,224	.233	.16
443	1,382	.494	.57	1,467	2,406	.215	.15
496	1,435	.461	.51	1,651	2,590	.196	.15
560	1,499	.428	.41	1,861	2,800	.178	.14
633	1,572	.395	.39	1,962	2,901	.170	.12
688	1,627	.374	.37	3,200	4,139	.112	.06
749	1,688	.353	.33				

TEST NEAR WICHITA, KANSAS

A pumping test to determine the permeability of the water-bearing sand and gravel in the Arkansas River Valley near Wichita, Kans., was made in 1937 under the direction of S. W. Lohman, of the Federal Geological Survey, in cooperation with the Kansas Geological Survey on the property of the Kansas Gas & Electric Co., in the NE¼NW¼ sec. 29, T. 26 S., R. 1 E., about 3 miles north of Wichita, Sedgwick County. Three observation wells were constructed at distances of about 50, 100, and 190 feet approximately upgradient from the pumped well and three observation wells were constructed on the same line at the same distances on the opposite side of the pumped well. Several observation wells were also constructed on a line at right angles to the other line of wells. The thickness of the saturated water-bearing material, as obtained from the log of the pumped well was 26.8 feet. The water in the formation was not confined under pressure. The well used for the test was 26 inches in diameter, and it penetrated the entire thickness of the water-bearing material. The well, which was equipped with an electric turbine pump, was operated continuously at a rate of 1,000±7 gallons a minute for about 19 days, from 10:37 a. m., November 8, to the afternoon of November 27, at which time the pump was unavoidably stopped. Pumping was resumed on November 28, but from a higher water level; hence permeability computations necessarily must be based on the draw-down of the water level prior to the first stopping of the pump. Measurements of water level were made periodically in all observation wells and in the pumped well throughout the period of pumping.

The log of the pumped well is given in the following table. The physical properties of samples of the material from the well were determined in the hydrologic laboratory of the Geological Survey and are given in an accompanying table. The average coefficient of permeability, P_m, of the samples taken below the nonpumping water table, weighted according to the thickness of the material represented in the section, is about 2,470.

Log of field well No. 303 of Kansas Gas & Electric Co. in NE¼NW¼ sec. 29, T. 26 S., R. 1 E.

[By S. W. Lohman, from examination of cuttings]

	Feet
Soil and clay	0–6
Fine sand, some medium sand	6–15
No sample; fine sand from driller's log	15–18
Static water level	17.3
Fine gravel and coarse sand, with clay balls	18–19
Fine gravel and coarse sand, with pebbles up to ¼ inch	19–20
Coarse brown sand, fine gravel, some pebbles	20–22
Coarse sand, fine gravel, some pebbles	22–25
Gravel, fine to coarse, with some coarse sand, pebbles up to ½ inch	25–34
Fine sand	34–36
Sand, coarse to medium, some fine gravel	36–38
Coarse sand, some fine gravel, and pebbles	38–46.5
Shale	46.5

Physical properties of water-bearing materials collected by S. W. Lohman from field well No. 303 of the Kansas Gas & Electric Co., 3 miles north of Wichita, Kans., in the NE¼NW¼ sec. 29, T. 26 S., R. 1 E.

[V. C. Fishel, Analyst]

Laboratory No.	Depth (feet)	Mechanical analysis (size in millimeters)							Apparent specific gravity	Porosity	Moisture equivalent by volume[1]	Coefficient of permeability P_m
		Medium and coarse gravel (larger than 2.0)	Fine gravel (2.0–1.0)	Coarse sand (1.0–0.50)	Medium sand (0.50–0.25)	Fine sand (0.25–0.125)	Very fine sand (0.125–0.062)	Silt and clay (less than 0.062)				
2285	6–15	1.2	1.0	2.1	13.1	63.6	14.1	3.5	1.45	43.1	3.6	200
2286	[2]18–19	19.6	24.2	17.4	25.9	8.8	1.3	1.5	1.54	37.0	9.7	30
2287	19–20	25.9	33.3	27.1	11.0	1.0	.1	.4	1.77	30.0	2.3	2,400
2288	20–22	19.1	22.2	26.9	18.6	7.1	2.9	1.4	1.81	28.2	1.1	1,250
2289	22–25	21.2	24.2	30.2	18.1	3.6	.6	.5	1.80	28.8	1.6	1,400
2290	25–34	53.8	16.5	14.1	11.9	2.3	.1	.1	1.91	24.1	1.7	4,500
2291	34–36	5.6	5.2	4.2	28.9	51.4	2.4	.2	1.67	34.4	2.4	490
2292	36–38	21.1	17.7	25.8	23.5	9.7	.7	.2	1.85	28.9	1.4	1,000
2293	38–41	20.7	28.3	28.9	16.3	3.5	.2	.1	1.83	30.0	2.8	1,800
2294	41–46.5	16.5	20.0	25.1	31.3	4.6	.3	.1	1.81	31.1	1.8	1,800

[1] Weight of the moisture retained after centrifuging at 1,000 times the force of gravity, divided by the weight of the dry material, multiplied by the apparent specific gravity.
[2] No sample between depths of 15 and 18 feet; drillers's log indicates fine sand.

The location, depth, and altitude of wells in the pumping test near Wichita are given in an accompanying table, and figures for the draw-down of the water level in the observation wells are given in another table.

Data on wells used in test near Wichita, Kans.

Well	Depth below measuring point (feet)	Distance of measuring point above land surface (feet)	Altitude of static water level (feet)	Distance from pumped well (feet)
Pumped well [1]	47.7	2.4	1,309.59	0
Up-gradient from pumped well:				
1N	41.5	1.8	1,309.65	49.2
2N	42.5	2.5	1,309.73	100.7
3N	42.4	2.0	1,309.91	189.4
Down-gradient from pumped well:				
1S	43.8	.7	1,309.55	49.0
2S	42.2	1.5	1,309.54	100.4
3S	42.6	.8	1,309.51	190.0

[1] Diameter, 26 inches.

Draw-down of the water level, in feet, in observation wells during pumping test near Wichita, Kans.

Time (days)	Well: North of pumped well 1	2	3	South of pumped well 1	2	3	Time (days)	Well: North of pumped well 1	2	3	South of pumped well 1	2	3
1	4.45	3.29	1.73	3.97	2.88	1.83	10	5.66	4.34	3.16	5.21	4.04	2.94
2	4.88	3.68	2.28	4.40	3.29	2.19	11	5.70	4.38	3.20	5.25	4.08	2.98
3	5.09	3.88	2.56	4.65	3.52	2.41	12	5.74	4.41	3.24	5.29	4.12	3.02
4	5.26	3.99	2.76	4.81	3.66	2.56	13	5.78	4.45	3.27	5.33	4.16	3.05
5	5.36	4.09	2.87	4.91	3.76	2.66	14	5.81	4.48	3.31	5.37	4.19	3.08
6	5.44	4.15	2.94	4.99	3.84	2.74	15	5.84	4.51	3.34	5.40	4.22	3.11
7	5.50	4.21	3.01	5.06	3.91	2.80	16	5.86	4.53	3.37	5.43	4.25	3.14
8	5.56	4.26	3.06	5.11	3.96	2.85	17	5.89	5.56	3.40	5.46	4.28	3.17
9	5.61	4.30	3.11	5.16	4.00	2.90	18	5.91	4.58	3.42	5.48	4.31	3.19

COMPUTATIONS OF PERMEABILITY

LIMITING FORMULA

The pumping rate for the Wichita test was 1,000 gallons a minute; hence by the limiting formula

$$P_f = 527.7 \times 1{,}000 \times C = 527{,}700C = 527{,}700\frac{A}{B} \qquad (158)$$

The following table gives values of A and B for 18 days of pumping computed for r_1 (distance from pumped well to nearest observation well) = 50, 70, 90, and 110 feet and r_2 (distance from pumped well to a more distant observation well) = 70, 90, 110, 130, 150, 170, and 190 feet. The draw-downs at these distances were obtained from a profile of the cone of depression. Values of A are plotted against values of B in figure 17. The points fall approximately on a straight line through the orgin whose slope is $\frac{0.025}{2.27} = 0.011$. Thus by the limiting formula

$$P_f = 527{,}700 \times 0.011 = 5{,}805 \qquad (159)$$

Values of A and B for test near Wichita, Kans.

r_1	r_2	$\log \frac{r_2}{r_1}$	0.25*M*	*A*	*B*	r_1	r_2	$\log \frac{r_2}{r_1}$	0.25*M*	*A*	*B*
50	70	0.146	21.4	0.0068	0.65	70	170	0.358	22.5	0.0171	1.50
	90	.255	21.6	.0118	1.07		190	.434	22.6	.0192	1.73
	110	.342	21.8	.0157	1.41	90	110	.087	22.3	.0039	.34
	130	.415	21.9	.0189	1.69		130	.160	22.5	.0071	.62
	150	.477	22.1	.0216	1.94		150	.222	22.6	.0098	.87
	170	.531	22.2	.239	2.15		170	.276	22.7	.0122	1.08
	190	.580	22.3	.0260	2.38		190	.325	22.8	.0143	1.31
70	90	.109	22.0	.0050	.42	110	130	.073	22.6	.0032	.28
	110	.196	22.1	.0089	.76		150	.135	22.8	.0059	.53
	130	.269	22.3	.0121	1.04		170	.189	22.9	.0083	.74
	150	.331	22.4	.0148	1.29		190	.237	23.0	.0103	.97

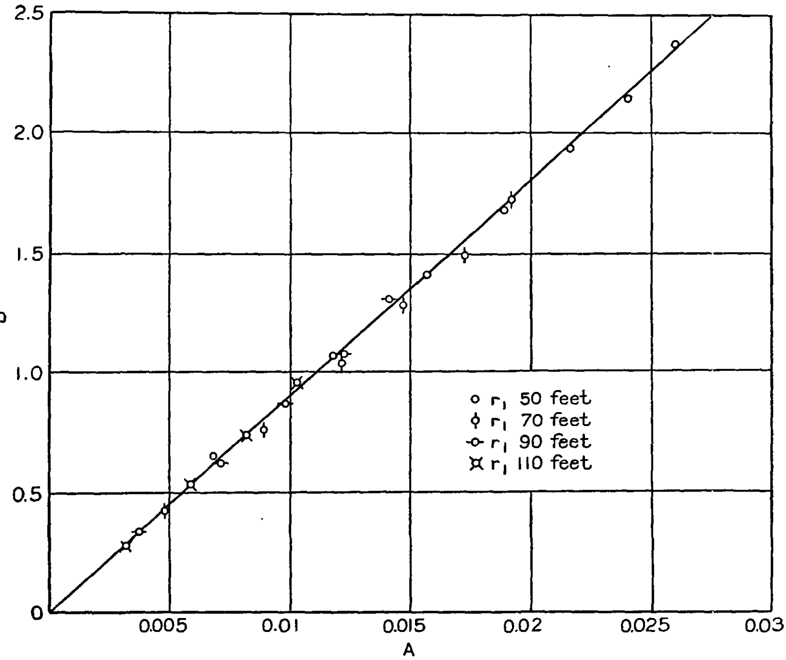

FIGURE 17.—Curve for Wichita test obtained by plotting *A* against *B*.

GRADIENT FORMULA

The altitudes of the water level after 18 days of pumping in the Wichita test at 140, 150, and 160 feet upgradient and downgradient from the pumped well are given in the following table. The thickness of the saturated water-bearing sand and gravel 150 feet upgradient from the pumped well is 22.9 feet and 150 feet downgradient from the well it is 23.2 feet. Substituting these data in the gradient formula (equation 82) the field coefficient of permeability is

$$P_f = \frac{18{,}335 \times 1{,}000}{150(22.9+23.2)(1{,}306.07+1{,}305.99-1{,}305.80-1{,}305.79)} = 5{,}641 \quad (160)$$

Altitude of water table in test near Wichita, Kans., after 18 days of pumping

Distance upgradient from pumped well (feet)	Altitude of water table above assumed datum (feet)	Distance downgradient from pumped well (feet)	Altitude of water table above assumed datum (feet)
140	1,305.80	140	1,305.79
150	1,305.94	150	1,305.89
160	1,306.07	160	1,305.99

NON-EQUILIBRIUM FORMULA

Values of r, r^2/t, and s for a pumping period of 18 days for the Wichita test are given in the following table and values of s are plotted against corresponding values of r^2/t on plate 6. The curve on plate 6, when placed over the type curve, coincides in such a manner that for the point $r=90$ feet the corresponding values of $W(u)$ and u on the type curve are respectively 5.19 and 0.00306. Substituting for the field coefficient of permeability in equation (91)

$$P_f=\frac{114.6\times 1{,}000\times 5.19}{22.2\times 4.63}=5{,}787 \quad \text{------} \quad (161)$$

The specific yield of the water-bearing material is computed by substituting in equation (92). The coefficient of transmissibility is $5{,}787\times 22.2=128{,}471$ and $r^2/t=450$. Thus

$$S=\frac{0.00306\times 128{,}471}{1.87\times 450}=0.467=47 \text{ percent} \quad \text{-----} \quad (162)$$

Average draw-downs at several distances from the pumped well and corresponding values of r^2/t for test near Wichita, Kans.

r (distance from pumped well, in feet)	r^2/t	s (average of the draw-downs at distance r upgradient and downgradient, in feet)
50	139	5.70
70	272	5.05
90	450	4.63
110	672	4.29
130	939	4.01
150	1,250	3.76
170	1,606	3.55
190	2,006	3.32

COMPARISON OF FIELD COEFFICIENTS OF PERMEABILITY DETERMINED BY DIFFERENT METHODS FROM DATA COLLECTED IN PUMPING TESTS IN NEBRASKA AND KANSAS

For the purpose of comparison, the field coefficients of permeability for the water-bearing materials near Grand Island, Kearney, Gothenburg, and Scottsbluff, Nebr., and near Wichita, Kans., as determined by several methods are given in the following table. The coefficients determined for any one test agree in general very closely.

Comparison of field coefficients of permeability determined by different methods

Method	Locality				
	Grand Island	Kearney	Gothen-burg	Scotts-bluff	Wichita
Limiting formula	997	4,092	3,874	1,427	5,805
Gradient formula	1,001	4,137	3,890	1,423	5,641
Non-equilibrium formula	955	4,027	3,781	1,370	5,787
Recovery formula (without empirical correction)	1,095			1,832	
Recovery formula (with empirical correction)	1,008			1,373	
Average coefficient, P_m, from laboratory determinations	1,200				2,470

METHOD FOR DETERMINING THE EFFECTIVENESS OF WELLS

The draw-down discharge relation of discharging wells is sometimes taken as an indication of the relative permeability of water-bearing formations that the wells tap. The discharge is assumed to be directly proportional to the draw-down. However, it has been found experimentally that for many wells this relation holds for only the first few feet of draw-down, after which the draw-down increases more rapidly than the discharge. Hence, it is not often possible to determine an accurate figure for the draw-down-discharge relation—usually expressed as the number of gallons per minute per foot of draw-down.

The straight-line draw-down-discharge relation should not be expected to hold precisely for water-table conditions where the casing of the pumped well is perforated throughout its length, because the area of casing through which the water enters the well becomes smaller with increased draw-down. The draw-down must occur more rapidly than the relative increase in discharge. In like manner the relation fails for artesian conditions when the water-bearing material around the well is unwatered.

The use of the draw-down-discharge relation for an indication of relative permeability often fails because of the difference in construction and development of wells. When wells are efficiently constructed there is a comparatively small loss of head at the casing due to entrance friction and the discharge per foot of draw-down is usually larger than in wells that are constructed less efficiently and in which there is a comparatively large loss of head due to the entrance of the water into the well. The areal permeability of the water-bearing material penetrated by two such wells may be the same, but the inference from the draw-down-discharge relations of the wells will be that the material around the efficient well is more permeable than the material around the less efficient well.

The loss of head due to entrance is mainly caused by inadequate spaces in the well casing through which the water must percolate. According to Darcy's law the discharge through a water-bearing material is equal to *PIA*. For a given casing, the area of the spaces and the permeability of the screen are fixed. Therefore, the flow into the casing depends upon the hydraulic gradient, which in turn depends principally upon the slope of the water level beyond the casing. The discharge of a well, then, is definitely limited by the size, area, and arrangement of the openings in the casing, and the discharge can be increased very little by lowering the water level in the well below a certain point where the hydraulic gradient outside the well has reached a maximum figure corresponding to the permeability and area of the openings of the casing of the well. When the water level in the well is lowered, the casing openings that are above the water level in the well and below the water level on the outside of the well function as orifices, and water spurts through them into the well.

There probably is no definite point below which the draw-down may be described as excessive. The deviation from the direct draw-down-discharge relation probably begins when the draw-down is small and then gradually increases as the draw-down increases but because the deviation is small at first it is not readily apparent. The discharge per unit of draw-down gives a relative estimate of the effectiveness of a well providing the wells compared are of the same diameter and penetrate materials of the same permeability. Another method for determining the efficiency of wells has been used to some extent recently. The water level in a small well put down just outside the casing of the pumped well is compared with the water level in the pumped well during its operation. The difference between the water levels in the two wells is inversely proportional to the effectiveness of the pumped well. This method, however, does not take into account the rearrangement of the material and hence the change in permeability near the well during the development of the well nor does this method make allowances for the diameter of the well.

The effectiveness of a well can be more satisfactorily ascertained by an application of the equilibrium or non-equilibrium formulas for determining permeability. The theoretical draw-down at the casing of the well may be computed by these formulas, from which the effectiveness of a well may be determined by the equation

$$E_w=\frac{100s_c}{s_1} \quad \text{-------------------} \quad (163)$$

in which E_w is the effectiveness of the discharging well, in percent; s_c is the theoretical draw-down of the water level at the casing of the well, computed by the equilibrium or non-equilibrium formulas, in feet; and s_1 is the observed draw-down in the well, in feet.

The theoretical draw-down of the water level in the pumped well may be computed by the following equilibrium formula pertaining to water-table conditions

$$s_c=H-\sqrt{h_2^2-\frac{1{,}055.4q\log_{10}\frac{r_2}{r_1}}{P_f}} \qquad (164)$$

in which s_c is the theoretical draw-down in the pumped well, in feet; H is the thickness of the saturated water-bearing material before pumping began, in feet; h_2 is the thickness of the saturated water-bearing material while pumping at a point at distance r_2 from the pumped well, where the cone of depression has reached essential equilibrium form, in feet; q is the discharge of the pumped well, in gallons a minute; P_f is the field coefficient of permeability; and r_1 is the radius of the pumped well, in feet.

For artesian conditions the corresponding formula is

$$s_c=\frac{527.7q}{HP_f}\log_{10}\frac{r_2}{r_1}+s_2 \qquad (165)$$

in which s_2 is the draw-down of the water level at distance r_2 from the pumped well and the other symbols are those previously defined. It is obvious that in the above formulas, as in all equilibrium formulas, only draw-downs obtained from the part of the cone of depression that has reached essential equilibrium in form can be used.

This method may be used to determine the effectiveness of the wells pumped for the five permeability tests described in this report. The following table gives the necessary data for computing the theoretical draw-down of the water level in the pumped wells by the above formulas.

Data for computing the theoretical draw-down of the water level in wells pumped for permeability tests

Locality	H	q	[1] P_f	r_2	s_2	h_2	r_1
Grand Island	100	540	997	100	2.16	97.84	1.0
Kearney	48	1,100	4,092	100	2.95	45.05	1.08
Gothenburg	17	532	3,874	100	3.87	17	1.0
Scottsbluff	114	1,270	1,427	150	3.99	114	1.0
Wichita	26.8	1,000	5,805	100	4.45	22.35	1.17

[1] Computed by the limiting formula.

The measured draw-down s_1, the computed theoretical draw-down s_c, and the effectiveness of the well E_w are given in the following table. The computations are based on the observed draw-downs in the pumped and observation wells at the end of the pumping periods.

Observed draw-down, computed draw-down, and effectiveness of wells pumped for permeability tests

Locality	s_1 (observed draw-down in feet)	s_c (computed theoretical draw-down in feet)	E_w (effectiveness of pumped well, in percent)
Grand Island	20.0	8.2	41
Kearney	11.0	9.6	87
Gothenburg	10.3	12.4	120
Scottsbluff	23.0	13.0	57
Wichita	15.0	14.6	97

The effectiveness of the wells pumped for the permeability tests range from 41 percent for the Grand Island well to 120 percent for the Gothenburg well. The Grand Island well was obviously ineffective because the water level just outside the well casing while pumping was in progress was observed to stand about 10 feet higher than the water level in the well and water spurted into the well through the casing perforations. The Gothenburg well, which penetrated only 17 feet of saturated sand and gravel, apparently had been developed to a high degree, inasmuch as it is more than 100 percent effective. An effectiveness of 100 percent indicates that the well casing and material around the well function as if there were no loss of head caused by the entrance of the water into the well. Where the well has been considerably developed the effective radius of the well is increased and the apparent effectiveness of the well under such conditions may be much greater than for perfect conditions with a smaller effective radius. By well development the permeability of the water-bearing material around the well may be considerably increased over that of the rest of the formation, and while the well is being pumped the slope of the water level through the material with the increased permeability may be considerably less than the slope that would have prevailed had the well been undeveloped. The draw-down in the pumped well will be decreased proportionally by the well development. It is thus possible to construct a well that for the diameter of its casing is more than 100 percent effective. The well may, of course, be developed in many ways, such as by surging, or by pumping it very strongly to withdraw from the material around the well as much of the fine sediments as possible. The same effect may be had by packing gravel around the casing during the drilling of the well.

The two wells with the lowest effectiveness—the Grand Island and Scottsbluff wells—did not penetrate the entire thickness of water-bearing material, and doubtless a large part of their relative ineffectiveness is due to this fact. The other three wells completely penetrated the water-bearing materials. The Grand Island, Gothenburg, and Scottsbluff wells were constructed with galvanized iron casing and the Kearney and Wichita wells with concrete casing.

The specific capacities of the wells (discharge per foot of drawdown) range from about 27 gallons a minute for the Grand Island well to 100 gallons a minute for the Kearney well. The specific capacity of the Gothenburg well is 51.7, the Scottsbluff well 55.2, and the Wichita well 66.7. It is apparent that the specific capacities of the wells have only a general relation to their effectiveness and to the permeability of the formations they tap.

RECORDS OF DRAW-DOWN FOR PUMPING TESTS IN NEBRASKA

GRAND ISLAND

Pumping for the test in the Grand Island area began at 6:05 a. m., July 29, 1931, and stopped at 6:04 a. m., July 31, 1931. Records of wells appear in the table on pages 120–121, and the location of the wells is shown in figure 10.

Draw-down of the water table in observation wells and pumped well near Grand Island

Well 1, line A

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:15 a. m.	0.00	7:04 a. m.	3.69	10:34 a. m.	1.26
6:11	.96	8:19	3.72	11:11	1.19
6:15	1.40	9:44	3.75	11:39	1.14
6:28	1.86	10:53	3.77	12:12 p. m.	1.11
6:50	2.11	11:41	3.79	2:10	.97
7:17	2.27	1:00 p. m.	3.80	3:41	.88
7:36	2.38	2:12	3.84	5:11	.81
8:09	2.54	4:13	3.85	6:22	.76
8:30	2.62	5:12	3.88	8:11	.69
8:40	2.66	6:28	3.89	9:37	.65
9:08	2.75	7:27	3.90	11:23	.60
9:36	2.84	10:20	3.93		
10:19	2.94	11:41	3.95	*Aug. 1, 1931*	
11:51	3.13				
1:24 p. m.	3.27	*July 31, 1931*		1:03 a. m.	.58
3:15	3.41			3:19	.52
5:06	3.51	1:33 a. m.	3.97	4:21	.51
6:12	3.55	3:52	4.01	5:47	.49
8:10	3.62	5:38	4.01	7:29	.44
9:44	3.65	6:09	2.88	8:59	.42
11:29	3.70	6:36	2.34		
		6:56	2.10		
July 30, 1931		7:27	1.86		
		7:50	1.73		
1:38 a. m.	3.68	8:21	1.61		
3:24	3.68	9:04	1.47		
5:06	3.67	9:49	1.36		

Draw-down of the water table in observation wells and pumped well near Grand Island—Continued

Well 2, line A

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:17 a. m.	0.00	5:18 a. m.	2.48	7:29 a. m.	1.85
6:17	.63	7:05	2.50	7:52	1.75
6:29	.77	8:22	2.51	8:22	1.62
6:51	.90	9:45	2.54	9:06	1.48
7:18	1.06	10:55	2.56	9:51	1.36
7:38	1.16	11:42	2.57	10:36	1.26
8:10	1.30	1:02 p. m.	2.59	11:12	1.21
8:42	1.41	2:14	2.61	11:43	1.15
9:11	1.51	3:47	2.59	12:13 p. m.	1.12
9:37	1.58	4:15	2.63	2:12	.98
10:20	1.69	5:14	2.65	3:42	.89
11:53	1.85	6:29	2.67	5:13	.81
1:26 p. m.	1.99	7:28	2.68	6:23	.76
3:17	2.13	10:22	2.70	8:12	.70
5:09	2.23	11:44	2.73	9:39	.65
6:17	2.29			11:25	.61
8:11	2.35	*July 31, 1931*			
9:47	2.40			*Aug. 1, 1931*	
11:32	2.45	1:36 a. m.	2.76	1:04 a. m.	.58
July 30, 1931		3:54	2.78	3:23	.53
		5:40	2.79	4:43	.50
		6:10	2.52	5:48	.49
1:42 a. m.	2.45	6:38	2.20	7:31	.44
3:26	2.46	6:59	2.04	9:00	.43

Well 3, line A

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:19 a. m.	0.00	5:20 a. m.	1.73	7:31 a. m.	1.59
6:19	.24	7:08	1.76	7:50	1.52
6:30	.32	8:25	1.77	8:24	1.44
6:53	.43	9:47	1.80	9:09	1.34
7:19	.52	10:57	1.81	9:54	1.26
7:39	.59	11:45	1.82	10:37	1.19
8:12	.69	1:05 p. m.	1.84	11:13	1.14
8:44	.76	2:15	1.86	11:45	1.09
9:12	.83	3:48	1.86	12:15 p. m.	1.05
9:39	.88	4:17	1.87	2:13	.94
10:21	.98	5:15	1.89	3:44	.86
11:55	1.12	6:31	1.91	5:14	.80
1:29 p. m.	1.24	7:30	1.92	6:25	.75
3:19	1.37	10:24	1.94	8:14	.69
5:11	1.46	11:46	1.96	9:41	.65
6:19	1.51			11:27	.60
8:13	1.58	*July 31, 1931*			
9:49	1.64			*Aug. 1, 1931*	
11:34	1.67	1:39 a. m.	1.98	1:08 a. m.	.56
July 30, 1931		3:56	2.01	3:25	.54
		5:41	2.03	4:45	.49
		6:11	1.92	5:49	.48
1:45 a. m.	1.70	6:40	1.78	7:32	.45
3:28	1.71	7:00	1.70	9:01	.43

Well 4, line A

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 29, 1931*—Con.		*July 30, 1931*—Con.	
5:22 a. m.	0.00	1:32 p. m.	0.88	5:23 a. m.	1.33
6:20	.12	3:22	.98	7:10	1.36
6:32	.17	5:12	1.06	8:26	1.37
6:54	.24	6:20	1.11	9:48	1.39
7:21	.31	8:15	1.17	10:58	1.41
7:40	.36	9:52	1.21	11:46	1.41
8:13	.42	11:36	1.25	1:07 p. m.	1.43
8:45	.48			2:17	1.44
9:14	.53	*July 30, 1931*		3:50	1.46
9:40	.58			5:17	1.49
10:23	.66	1:49 a. m.	1.29	6:33	1.49
11:56	.78	3:30	1.31	7:31	1.51

Draw-down of the water table in observation wells and pumped well near Grand Island—Continued

Well 4, line A—Continued

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 30, 1931—Con.		*July 31, 1931*—Con.		*July 31, 1931*—Con.	
10:27 p. m.	1.53	7:57 a. m.	1.32	8:15 p. m.	0.66
11:47	1.54	8:25	1.27	9:43	.63
		9:10	1.20	11:29	.58
July 31, 1931		9:56	1.13		
		10:39	1.08	*Aug. 1, 1931*	
1:43 a. m.	1.58	11:15	1.04		
4:00	1.60	11:46	1.01	1:35 a. m.	.55
5:43	1.61	12:16 p. m.	.98	3:26	.52
6:13	1.57	2:15	.88	4:49	.49
6:47	1.48	3:46	.82	5.50	.48
7:01	1.44	5:16	.76	7:34	.44
7:33	1.37	6:26	.72	9:03	.42

Well 5, line A

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:25 a. m.	0.00	5:24 a. m.	0.89	7:35 a. m.	1.04
6:21	.04	7:11	.90	7:59	1.01
6:33	.06	8:28	.92	8:26	.99
6:57	.11	9:50	.94	9:11	.95
7:22	.15	10:59	.95	9:57	.91
7:42	.18	11:48	.96	10:40	.88
8:15	.22	1:08 p. m.	.97	11:16	.86
8:47	.26	1:19	.99	11:48	.84
9:19	.29	3:52	1.00	12:19 p. m.	.82
9:42	.31	5:19	1.02	2:16	.75
10:25	.35	6:34	1.03	3:47	.71
11:57	.45	7:35	1.04	5:18	.66
1:35 p. m.	.53	10:30	1.06	6:28	.63
3:24	.60	11:49	1.08	8:16	.59
5:14	.67			9:45	.57
6:22	.71	*July 31, 1931*		11:31	.52
8:17	.75				
9:50	.78	1:47 a. m.	1.10	*Aug. 1, 1931*	
11:38	.81	4:02	1.13		
		5:45	1.14	1:37 a. m.	.45
July 30, 1931		6:14	1.13	4:50	.45
1:52 a. m.	.84	6:43	1.10	7:35	.41
3:34	.86	7:03	1.07	9:05	.40

Well 6, line A

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:27 a. m.	0.00	5:27 a. m.	0.45	8:00 a. m.	0.63
6:23	.00	7:13	.46	8:28	.63
6:35	.00	8:30	.47	9:13	.62
6:58	.01	9:52	.48	9:59	.60
7:24	.02	11:01	.50	10:42	.59
7:44	.03	11:49	.51	11:18	.58
8:16	.06	1:10 p. m.	.51	11:50	.57
8:49	.09	2:21	.53	12:20 p. m.	.56
9:20	.10	3:55	.54	2:18	.54
9:44	.11	5:20	.56	3:49	.53
10:26	.14	6:36	.56	5:20	.50
11:58	.19	7:38	.57	6:30	.47
1:37 p. m.	.22	10:33	.59	8:18	.45
3:27	.28	11:50	.60	9:48	.44
5:15	.31			11:33	.41
6:24	.32	*July 31, 1931*			
8:19	.34			*Aug. 1, 1931*	
9:59	.36	1:50 a. m.	.62		
11:41	.38	4:04	.64	1:45 a. m.	.39
		5:47	.65	3:30	.38
July 30, 1931		6:16	.65	4:53	.37
		6:45	.65	5:54	.35
1:55 a. m.	.41	7:05	.65	7:37	.34
3:37	.42	7:38	.64	9:06	.32

Draw-down of the water table in observation wells and pumped well near Grand Island—Continued

Well 7, line A

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:29 a. m.	0.00	8:32 a. m.	0.35	8:30 a. m.	0.50
6:59	.02	9:54	.36	9:15	.50
7:26	.02	11:03	.37	10:00	.50
7:45	.03	11:51	.38	10:43	.49
8:18	.04	1:12 p. m.	.38	11:20	.48
8:50	.05	2:23	.39	11:51	.48
9:22	.06	3:57	.40	12:22 p. m.	.48
9:45	.06	5:27	.42	2:19	.46
10:28	.10	6:38	.42	3:51	.46
12:00 noon	.13	7:42	.43	5:22	.43
1:40 p. m.	.16	10:35	.45	6:31	.41
3:30	.19	11:52	.46	8:19	.39
5:17	.22			9:49	.38
6:25	.23	*July 31, 1931*		11:35	.37
8:20	.24				
10:02	.26	1:53 a. m.	.49	*Aug. 1, 1931*	
11:43	.28	4:07	.51		
July 30, 1931		5:49	.52	1:47 a. m.	.37
		6:17	.51	3:32	.35
1:58 a. m.	.30	6:47	.51	4:55	.34
3:40	.31	7:07	.51	5:56	.34
5:30	.32	7:39	.51	7:39	.30
7:15	.34	8:02	.51	9:07	.29

Well 8, line A

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:31 a. m.	0.00	8:34 a. m.	0.29	9:17 a. m.	0.44
7:01	.01	9:55	.30	10:01	.44
7:47	.02	11:05	.30	10:45	.43
8:20	.03	11:52	.31	11:21	.43
8:52	.04	1:14 p. m.	.32	12:26 p. m.	.43
9:24	.05	2:25	.33	2:21	.41
10:30	.09	3:58	.34	3:52	.41
12:01 p. m.	.11	5:30	.36	5:25	.40
1:43	.14	6:39	.36	6:32	.38
3:32	.16	7:43	.37	8:21	.37
5:18	.17	10:37	.39	9:53	.36
6:27	.18	11:54	.40	11:37	.35
8:22	.20				
10:07	.21	*July 31, 1931*		*Aug. 1, 1931*	
11:46	.22				
		1:54 a. m.	.41	1:49 a. m.	.34
July 30, 1931		4:10	.43	3:34	.33
2:00 a. m.	.24	5:50	.44	4:57	.32
3:42	.26	6:19	.44	5:57	.31
5:34	.27	7:08	.44	7:41	.29
7:17	.28	8:31	.44	9:09	.28

Well 9, line A

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:33 a. m.	0.00	8:38 a. m.	0.15	9:20 a. m.	0.27
7:48	.01	9:57	.16	10:08	.28
8:22	.01	11:06	.16	10:46	.28
8:54	.01	11:54	.17	11:23	.28
9:26	.01	1:17 p. m.	.18	12:27 p. m.	.28
10:33	.03	2:27	.18	2:23	.28
12:03 p. m.	.05	4:00	.19	3:54	.28
1:45	.06	5:32	.20	5:27	.28
3:34	.07	6:41	.20	6:34	.27
5:20	.07	8:05	.20	8:24	.27
6:29	.07	10:40	.22	9:56	.26
8:23	.08	11:55	.23	11:39	.26
10:11	.10	*July 31, 1931*		*Aug. 1, 1931*	
11:48	.12				
		1:57 a. m.	.23	1:50 a. m.	.26
July 30, 1931		4:13	.26	3:36	.26
2:04 a. m.	.12	5:53	.26	4:58	.25
3:47	.13	6:20	.26	5:58	.25
5:36	.14	7:10	.26	7:42	.23
7:20	.15	8:33	.26	9:11	.22

Draw-down of the water table in observation wells and pumped well near Grand Island—Continued

Well 10, line A

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:35 a. m.	0.00	9:59 a. m.	0.08	10:48 a. m.	0.16
7:52	.00	11:56	.09	11:25	.16
8:57	.00	1:19 p. m.	.09	12:30 p. m.	.17
10:34	.01	2:29	.09	2:25	.17
12:05 p. m.	.01	4:03	.10	3:56	.17
1:47	.02	5:34	.11	5:29	.17
3:37	.02	8:08	.11	6:36	.17
5:22	.03	10:42	.13	8:24	.17
8:26	.03			9:58	.18
10:13	.04	*July 31, 1931*		11:41	.18
11:51	.05				
		2:00 a. m.	.13	*Aug. 1, 1931*	
July 30, 1931		4:16	.13		
		5:55	.16	1:52 a. m.	.18
2:08 a. m.	.05	6:23	.16	3:38	.18
3:50	.06	7:11	.15	5:00	.18
5:38	.07	8:34	.15	6:00	.18
7:22	.07	9:22	.15	7:44	.17
8:40	.07	10:09	.16	9:13	.17

Well 11, line A

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:37 a. m.	0.00	2:31 p. m.	0.06	12:34 p. m.	0.11
8:58	.01	4:05	.07	2:27	.12
10:36	.02	5:35	.08	3:59	.13
1:51 p. m.	.01	8:10	.07	5:30	.13
3:40	.02	10:43	.09	6:37	.12
5:25	.03			8:26	.12
10:18	.04	*July 31, 1931*		10:01	.12
11:55	.04			11:45	.13
		2:04 a. m.	.10		
July 30, 1931		4:20	.11	*Aug. 1, 1931*	
		5:57	.11		
2:10 a. m.	.04	6:25	.11	1:55 a. m.	.15
3:52	.05	7:14	.10	3:40	.15
5:40	.05	8:35	.10	5:02	.15
8:42	.05	9:23	.11	6:02	.15
10:02	.06	10:11	.11	7:46	.14
11:57	.06	10:50	.11	9:15	.14
1:21 p. m.	.06	11:26	.11		

Well 13, line B

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1930*—Con.		*July 31, 1931*—Con.	
5:08 a. m.	0.00	5:22 a. m.	3.56	9:22 a. m.	1.38
6:11	1.87	7:11	3.58	10:20	1.25
6:54	2.13	8:34	3.60	10:58	1.18
7:13	2.25	9:41	3.63	11:32	1.12
7:35	2.33	11:08	3.67	12:10 p. m.	1.07
8:04	2.47	12:54 p. m.	3.69	1:02	1.00
8:39	2.58	2:12	3.72	1:57	.94
9:06	2.68	3:58	3.72	2:39	.90
9:27	2.74	5:17	3.76	3:36	.84
9:59	2.81	6:23	3.77	4:20	.80
11:24	2.98	7:27	3.79	5:20	.77
12:42 p. m.	3.11	8:52	3.78	6:22	.74
1:53	3.20	11:05	3.83	8:09	.69
3:23	3.31			10:06	.63
4:33	3.37	*July 31, 1931*			
5:48	3.43			*Aug. 1, 1931*	
6:51	3.46	1:19 a. m.	3.84		
9:34	3.54	3:50	3.87	12:38 a. m.	.56
11:23	3.59	5:30	3.87	2:44	.52
		6:11	2.72	3:53	.50
July 30, 1931		7:05	1.99	5:24	.47
1:35 a. m.	3.56	7:55	1.69	7:34	.43
3:11	3.56	8:34	1.52	9:04	.41

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Draw-down of the water table in observation wells and pumped well near Grand Island—Continued

Well 14, line B

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:15 a. m.	0.00	5:26 a. m.	2.31	9:25 a. m.	1.38
6:14	.49	7:14	2.33	10:23	1.24
6:56	.81	8:36	2.35	11:35	1.13
7:15	.91	9:43	2.37	12:14 p. m.	1.09
7:37	1.00	11:10	2.39	1:02	1.00
8:09	1.15	12:56 p. m.	2.42	2:00	.95
8:42	1.25	2:19	2.43	2:41	.91
9:08	1.34	4:01	2.45	3:38	.86
9:30	1.39	5:19	2.47	4:22	.83
10:03	1.47	6:25	2.48	5:23	.77
11:27	1.64	7:29	2.50	6:24	.75
12:44 p. m.	1.77	8:56	2.51	8:11	.69
1:54	1.86	11:11	2.52	10:32	.61
3:25	1.96				
4:35	2.03	*July 31, 1931*		*Aug. 1, 1931*	
5:50	2.09				
6:53	2.14	1:22 a. m.	2.54	12:40 a. m.	.56
9:39	2.22	3:51	2.59	2:46	.52
11:26	2.27	5:32	2.59	3:55	.51
July 30, 1931		6:16	2.31	5:25	.46
		7:09	1.90	7:37	.44
1:37 a. m.	2.29	7:58	1.66	9:06	.41
3:14	2.31	8:36	1.51		

Well 15, line B

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:20 a. m.	0.00	5:37 a. m.	1.59	9:29 a. m.	1.22
6:18	.19	7:17	1.61	10:25	1.12
6:59	.38	8:38	1.63	11:02	1.08
7:17	.43	10:46	1.65	11:37	1.04
7:41	.51	11:12	1.66	12:18 p. m.	.98
8:13	.59	1:00 p. m.	1.68	1:10	.93
8:44	.65	2:21	1.70	2:02	.88
9:10	.72	4:04	1.72	2:56	.83
9:33	.75	5:22	1.74	3:40	.81
10:21	.84	6:27	1.75	4:24	.77
11:30	.96	7:30	1.76	5:25	.74
12:46 p. m.	1.06	9:01	1.77	6:27	.71
1:57	1.14	11:14	1.79	8:18	.65
3:28	1.23			10:36	.58
4:38	1.30	*July 31, 1931*			
5:52	1.35			*Aug. 1, 1931*	
6:56	1.39	1:26 a. m.	1.81		
9:43	1.47	3:52	1.84	12:42 a. m.	.54
11:29	1.51	5:34	1.86	2:47	.51
July 30, 1931		6:18	1.73	3:56	.48
		7:11	1.54	5:26	.43
1:40 a. m.	1.55	8:00	1.41	7:40	.40
3:16	1.57	8:44	1.31	9:08	.39

Well 16, line B

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 29, 1931*—Con		*July 30, 1931*—Con.	
5:24 a. m.	0.00	1:59 p. m.	0.69	7:19 a. m.	1.09
6:20	.06	3:30	.76	8:40	1.10
7:01	.16	4:40	.81	9:48	1.12
7:19	.21	5:54	.85	11:25	1.13
7:45	.25	7:30	.90	1:02 p. m.	1.15
8:15	.30	9:45	.96	2:23	1.16
8:46	.34	11:32	.99	4:05	1.18
9:13	.38	*July 30, 1931*		5:23	1.19
9:35	.41			6:29	1.21
10:23	.47	1:43 a. m.	1.03	7:32	1.22
11:33	.55	2:19	1.04	9:04	1.23
12:48 p. m.	.63	5:39	1.08	11:19	1.25

Draw-down of the water table in observation wells and pumped well near Grand Island—Continued

Well 16, line B—Continued

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 31, 1931		*July 31, 1931*—Con.		*July 31, 1931*—Con.	
1:30 a. m.	1.27	11:40 a. m.	0.87	8:21 p. m.	0.59
3:54	1.29	12:23 p. m.	.84	10:38	.54
5:36	1.31	1:14	.80	*Aug. 1, 1931*	
6:22	1.27	2:05	.77	12:44 a. m.	.49
7:14	1.19	2:58	.74	2:50	.46
8:02	1.11	3:42	.72	3:58	.44
8:46	1.06	4:27	.68	5:27	.40
9:31	1.00	5:27	.65	7:42	.38
10:27	.93	6:29	.63	9:12	.37
11:04	.90				

Well 17, line B

July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:25 a. m.	0.00	5:41 a. m.	0.71	10:27 a. m.	0.74
6:23	.01	7:22	.73	11:05	.71
7:04	.08	8:42	.74	11:41	.69
7:21	.09	9:50	.75	12:27 p. m.	.67
7:48	.12	11:26	.76	1:17	.65
8:18	.14	1:05 p. m.	.78	2:07	.63
8:48	.18	2:25	.79	3:00	.60
9:15	.20	4:07	.81	3:43	.59
9:38	.22	5:25	.82	4:41	.57
			.82	5:28	.55
			.83	6:31	.54
			.85	8:23	.51
			.87	10:40	.47
				Aug. 1, 1931	
			.89	12:45 a. m.	.43
			.90	2:51	.40
			.92	4:00	.39
			.90	5:29	.37
			.86	7:44	.35
			.83	9:15	.32
			.80		
			.78		

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	July 31, 1931—Con.	
0.34	9:36 a. m.	0.48
.36	10:30	.47
.36	11:08	.46
.38	11:43	.46
.39	12:30 p. m.	.45
.41	1:19	.44
.41	2:09	.43
.42	3:01	.42
.43	3:45	.41
.44	4:44	.40
.44	5:31	.40
.46	6:34	.39
.47	8:28	.37
	10:43	.35
.48	*Aug. 1, 1931*	
.49	12:47 a. m.	.33
.51	2:53	.30
.50	4:02	.30
.50	5:30	.29
.49	7:46	.26
.49	9:17	.26

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Draw-down of the water table in observation wells and pumped well near Grand Island—Continued

Well 19, line B

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:32 a. m.	0.00	5:47 a. m.	0.26	9:38 a. m.	0.40
6:27	.00	7:28	.27	10:32	.39
7:09	.00	8:46	.28	11:09	.38
7:26	.00	9:55	.29	11:44	.38
7:53	.01	11:30	.29	12:33 p. m.	.37
8:27	.02	1:09 p. m.	.31	1:21	.37
8:52	.02	2:28	.31	2:11	.36
9:19	.03	4:10	.33	3:03	.36
9:43	.05	5:28	.33	3:47	.34
10:30	.07	6:34	.35	4:45	.33
11:40	.09	7:38	.35	5:33	.33
12:54 p. m.	.12	9:12	.35	6:40	.34
2:06	.13	11:30	.37	8:30	.32
3:36	.14			10:45	.30
4:46	.15	*July 31, 1931*			
6:01	.17			*Aug. 1, 1931*	
7:36	.18	1:37 a. m.	.38		
9:57	.20	4:03	.39	12:49 a. m.	.29
11:41	.22	5:42	.40	2:54	.28
July 30, 1931		6:33	.41	4:12	.26
		7:20	.41	5:31	.26
1:50 a. m.	.22	8:11	.41	7:48	.23
3:30	.25	8:52	.40	9:18	.22

Well 20, line B

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:35 a. m.	0.00	7:30 a. m.	0.17	10:35 a. m.	0.29
6:29	.00	8:48	.18	10:37	.29
7:56	.00	9:57	.19	11:46	.28
8:29	.01	11:32	.19	12:36 p. m.	.28
8:55	.01	1:11 p. m.	.21	1:24	.28
9:21	.02	2:30	.22	2:12	.27
9:50	.02	4:11	.23	3:04	.27
10:33	.03	5:30	.23	3:49	.27
11:43	.05	6:36	.23	4:47	.26
12:56 p. m.	.06	7:40	.23	5:35	.26
2:08	.07	9:15	.24	6:43	.26
3:38	.08	11:34	.25	8:33	.26
4:48	.08			10:47	.24
6:03	.10	*July 31, 1931*			
7:38	.11			*Aug. 1, 1931*	
10:02	.12	1:39 a. m.	.27		
11:46	.14	4:06	.28	12:50 a. m.	.23
		5:44	.29	2:55	.22
July 30, 1931		6:35	.29	4:14	.20
		7:22	.29	5:32	.20
1:53 a. m.	.15	8:17	.29	7:50	.18
3:32	.16	8:54	.29	9:20	.18
5:49	.17	9:40	.29		

Well 21, line B

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 29, 1931*—Con.		*July 30, 1931*—Con.	
5:38 a. m.	0.00	3:40 p. m.	0.04	5:51 a. m.	0.08
6:32	.01	4:50	.05	7:34	.10
7:58	.01	6:05	.05	8:50	.10
8:32	.01	7:40	.05	10:00	.10
8:57	.01	10:05	.07	11:34	.10
9:23	.01	11:51	.08	1:13 p. m.	.11
9:52	.01			2:32	.12
10:36	.02	*July 30, 1931*		4:13	.12
11:47	.03			5:31	.13
12:59 p. m.	.04	1:57 a. m.	.08	6:39	.13
2:12	.04	3:35	.08	7:41	.14

Draw-down of the water table in observation wells and pumped well near Grand Island—Continued

Well 21, line B—Continued

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 30, 1931—Con.		*July 31, 1931*—Con.		*July 31, 1931*—Con.	
9:19 p. m.	0.14	9:44 a. m.	0.17	6:45 p. m.	0.20
11:37	.15	10:36	.17	8:36	.19
July 31, 1931		11:13	.17	10:50	.18
		11:48	.18	*Aug. 1, 1931*	
1:42 a. m.	.16	12:39 p. m.	.18		
4:09	.17	1:26	.17	12:53 a. m.	.18
5:51	.16	2:14	.18	2:57	.17
6:38	.16	3:06	.18	4:16	.15
7:25	.16	3:51	.18	5:33	.16
8:14	.16	4:49	.18	7:52	.14
8:57	.17	5:37	.19	9:22	.14

Well 22, line B

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:40 a. m.	0.00	11:37 a. m.	0.06	11:16 a. m.	0.10
6:29	.00	1:15 p. m.	.06	11:50	.10
9:00	.00	2:34	.06	12:42 p. m.	.10
11:49	.01	4:15	.07	1:28	.10
1:01 p. m.	.01	5:32	.07	2:16	.10
2:15	.01	6:41	.07	3:07	.11
3:43	.01	7:43	.08	3:53	.11
4:52	.02	9:22	.08	4:51	.11
6:08	.02	11:40	.09	5:39	.11
7:41	.02			6:48	.12
10:09	.02	*July 31, 1931*		8:39	.12
11:54	.03			10:52	.12
		1:44 a. m.	.09		
July 30, 1931		4:13	.10	*Aug. 1, 1931*	
		5:53	.10		
2:02 a. m.	.04	6:40	.10	12:55 a. m.	.13
3:37	.04	7:27	.09	2:59	.12
5:53	.04	8:29	.09	4:18	.11
7:36	.04	9:00	.10	5:35	.10
8:53	.05	9:49	.10	7:55	.10
10:02	.05	10:39	.10	9:24	.10

Well 23, line B

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:43 a. m.	0.00	4:17 p. m.	0.03	12:45 p. m.	0.05
6:37	.00	5:34	.03	1:32	.05
11:54	.00	6:43	.03	2:19	.05
1:05 p. m.	.00	7:45	.04	3:09	.06
2:18	.00	9:28	.04	3:56	.06
4:54	.01	11:45	.05	4:54	.06
7:44	.01	*July 31, 1931*		5:41	.06
10:13	.01			6:51	.06
11:58	.01	1:47 a. m.	.05	8:43	.07
July 30, 1931		4:15	.05	10:56	.07
		5:55	.05		
2:05 a. m.	.00	6:43	.05	*Aug. 1, 1931*	
5:55	.01	7:31	.05		
7:39	.01	8:20	.05	12:59 a. m.	.08
8:56	.02	9:03	.05	3:01	.08
10:06	.02	9:53	.05	4:20	.08
11:41	.02	10:42	.05	5:37	.06
1:17 p. m.	.02	11:19	.05	7:58	.06
2:36	.03	11:52	.05	9:26	.06

Draw-down of the water table in observation wells and pumped well near Grand Island—Continued

Well 24, line B

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:45 a. m.	0.00	7:47 p. m.	0.04	1:35 p. m.	0.03
6:39	.00	9:31	.04	2:22	.03
11:56	.02	11:48	.05	3:11	.04
1:09 p. m.	.02	*July 31, 1931*		3 59	.04
2:21	.02	1:51 a. m.	.05	4:57	.04
4:56	.02	4:18	.05	5:44	.04
July 30, 1931		5:57	.05	6:52	.06
2:09 a. m.	.02	6:46	.04	9:46	.07
5:58	.02	7:33	.04	10:59	.07
7:41	.02	8:23	.04	*Aug. 1, 1931*	
8:58	.03	9:05	.04	1:01 a. m.	.07
10:08	.03	9:55	.04	3:04	.07
11:44	.03	10:45	.04	4:22	.06
1:20 p. m.	.03	11:22	.04	5:40	.06
2:39	.03	11:54	.04	8:00	.07
5:36	.04	12:44 p. m.	.04	9:28	.06
6:45	.04				

Well 25, line W

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:12 a. m.	0.00	7:13 a. m.	2.70	10:18 a. m.	1.29
5:34	.00	8:46	2.72	11:07	1.20
6:09	.64	10:22	2.75	11:42	1.14
6:10	.69	11:42	2.77	12:26 p. m.	1.07
6:21	.86	1:04 p. m.	2.79	1:14	1.02
6:48	1.06	2:12	2.82	2:14	.95
7:41	1.38	3:44	2.86	3:01	.90
8:26	1.57	5:24	2.87	3:33	.88
9:20	1.75	6:45	2.87	4:46	.82
11:08	1.98	7:47	2.88	5:16	.79
12:42 p. m.	2.15	*July 31, 1931*		7:07	.72
2:30	2.29	12:21 a. m.	2.94	9:12	.66
4:09	2.40	2:31	2.97	11:14	.60
5:35	2.47	4:55	2.98	*Aug. 1, 1931*	
7:24	2.53	6:02	2.98	1:35 a. m.	.55
9:45	2.60	6:05	2.92	3:17	.52
July 30, 1931		6:53	2.13	5:37	.47
1:50 a. m.	2.66	7:35	1.73	7:23	.43
3:06	2.69	8:22	1.60	8:55	.41
5:12	2.69	9:18	1.43		

Well 26, line W

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:14 a. m.	0.00	7:15 a. m.	1.22	10:19 a. m.	1.02
5:33	.00	8:48	1.23	11:08	.97
6:12	.05	10:23	1.26	11:44	.92
6:19	.09	11:44	1.28	12:28 p. m.	.89
6:50	.20	1:06 p. m.	1.29	1:15	.85
7:42	.31	2:14	1.29	2:15	.81
8:28	.41	3:45	1.32	3:02	.78
9:22	.49	5:26	1.35	3:45	.75
11:10	.63	6:47	1.35	4:47	.70
12:44 p. m.	.74	7:49	1.36	5:18	.69
2:33	.84	9:44	1.37	7:10	.63
4:15	.92	*July 31, 1931*		9:16	.58
5:37	.97	12:27 a. m.	1.41	11:18	.54
7:26	1.03	2:33	1.43	*Aug. 1, 1931*	
9:51	1.08	4:57	1.46	1:37 a. m.	.50
July 30, 1931		6:07	1.44	3:19	.46
1:52 a. m.	1.15	6:55	1.31	5:38	.44
3:08	1.18	7:37	1.24	7:24	.40
5:14	1.22	8:24	1.16	8:52	.38
		9:19	1.09		

Draw-down of the water table in observation wells and pumped well near Grand Island—Continued

Well 27, line W

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:18 a. m.	0.00	8:49 a. m.	0.66	10:20 a. m.	0.70
6:14	.01	10:25	.68	11:10	.68
6:17	.01	11:45	.69	11:46	.66
6:52	.04	1:07 p. m.	.71	12:27 p. m.	.65
7:44	.10	2:16	.72	1:16	.63
8:30	.15	3:47	.73	2:17	.60
9:24	.19	5:30	.75	3:05	.58
11:12	.26	6:48	.75	3:47	.57
12:46 p. m.	.34	7:50	.76	4:49	.56
2:35	.39	9:46	.78	5:20	.55
4:16	.44			7:12	.50
5:40	.47	*July 31, 1931*		9:18	.47
7:27	.50			11:20	.44
9:54	.54	12:29 a.m.	.80		
		2:36	.81	*Aug. 1, 1931*	
July 30, 1931		4:58	.85		
		6:09	.84	1:39 a. m.	.42
12:59 a. m.	.59	6:56	.82	3:20	.39
3:12	.63	7:39	.80	5:39	.37
5:16	.64	8:26	.77	7:26	.34
7:18	.65	9:21	.73	8:58	.33

Well 28, line W

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:20 a. m.	0.00	11:46 a. m.	0.33	11:11 a. m.	0.42
6:16	.00	1:10 p. m.	.35	11:48	.41
6:54	.01	2:18	.35	12:29 p. m.	.42
7:47	.02	3:49	.37	1:18	.41
8:32	.04	5:31	.37	2:18	.40
9:26	.06	6:50	.38	3:06	.39
11:14	.09	7:52	.38	3:48	.38
12:49 p. m.	.13	9:48	.40	4:50	.37
4:18	.19			5:22	.37
5:42	.20	*July 31, 1931*		7:15	.35
7:30	.21			9:21	.33
9:59	.22	12:31 a. m.	.43	11:22	.31
July 30, 1931		2:37	.42		
		5:02	.45	*Aug. 1, 1931*	
1:01 a. m.	.27	6:13	.45		
3:14	.28	6:59	.46	1:44 a. m.	.30
5:18	.29	7:41	.45	3:22	.29
7:19	.29	8:28	.44	5:40	.27
8:51	.30	9:23	.43	7:27	.26
10:26	.32	10:21	.42	9:01	.24

Well 29, line W

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:22 a. m.	0.00	11:48 a. m.	0.14	11:13 a. m.	0.22
6:56	.01	1:12 p. m.	.15	11:50	.22
7:49	.02	2:19	.15	12:31 p. m.	.23
8:34	.02	3:51	.16	1:19	.23
9:28	.02	5:34	.16	2:20	.23
11:17	.02	6:52	.17	3:07	.23
12:52 p. m.	.04	7:54	.17	3:49	.23
2:40	.05	9:50	.18	4:52	.23
4:21	.06			5:23	.22
6:44	.07	*July 31, 1931*		7:17	.22
7:32	.07			9:23	.22
10:04	.08	12:34 a. m.	.20	11:25	.20
July 30, 1931		2:40	.20		
		5:03	.21	*Aug. 1, 1931*	
1:05 a. m.	.11	6:15	.21		
3:16	.11	7:02	.22	1:44 a. m.	.20
5:20	.12	7:43	.22	3:15	.19
7:22	.12	8:30	.22	5:44	.19
8:53	.13	9:25	.22	7:29	.18
10:28	.14	10:22	.22	9:03	.18

Draw-down of the water table in observation wells and pumped well near Grand Island—Continued

Well 30, line W

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:24 a. m.	0.00	10:30 a. m.	0.06	11:14 a. m.	0.12
6:57	.00	11:50	.06	11:52	.12
7:52	.01	1:14 p. m.	.07	12:35 p. m.	.14
8:36	.01	2:21	.07	1:22	.14
9:30	.01	3:52	.07	2:21	.14
11:20	.01	5:36	.07	3:08	.14
12:55 p. m.	.01	6:53	.08	3:51	.14
2:42	.01	7:55	.09	4:53	.14
4:22	.01	9:52	.09	5:21	.15
5:46	.02			7:19	.14
7:34	.02	*July 31, 1931*		9:26	.14
10:07	.03			1:33	.14
		12:37 a. m.	.10		
July 30, 1931		2:41	.10	*Aug. 1, 1931*	
		6:16	.11		
1:07 a. m.	.05	7:04	.12	1:46 a. m.	.15
3:20	.06	7:45	.11	3:17	.15
5:24	.06	8:32	.11	5:45	.15
7:25	.05	9:27	.12	7:31	.13
8:55	.05	10:24	.12	9:05	.13

Well 31, line W

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:28 a. m.	0.00	10:32 a. m.	0.04	11:16 a. m.	0.09
7:00	.00	11:51	.05	11:54	.09
7:54	.00	1:16 p. m.	.05	12:27 p. m.	.10
8:39	.01	2:23	.05	1:24	.10
9:32	.01	3:54	.06	2:23	.10
11:23	.01	5:38	.06	3:11	.10
12:58 p. m.	.01	6:55	.07	3:51	.12
2:44	.01	7:57	.07	4:55	.11
4:25	.01			5:23	.12
5:50	.01	*July 31, 1931*		7:23	.11
7:36	.02			9:28	.12
10:10	.02	12:39 a. m.	.08	11:31	.12
		2:45	.09		
July 30, 1931		5:07	.09	*Aug. 1, 1931*	
		6:18	.08		
1:12 a. m.	.03	7:06	.09	1:48 a. m.	.12
3:25	.04	7:47	.09	3:25	.12
5:27	.04	8:33	.09	5:47	.12
7:27	.04	9:29	.09	7:33	.11
8:56	.04	10:25	.09	9:07	.12

Well 32, line D

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
4:58 a. m.	0.00	7:43 a. m.	2.87	9:06 a. m.	1.49
6:07	.75	8:57	2.89	9:46	1.37
6:19	1.06	10:23	2.92	10:28	1.28
6:36	1.24	11:13	2.93	11:12	1.21
7:18	1.49	12:12 p. m.	2.95	11:48	1.14
7:50	1.63	1:30	2.96	12:47 p. m.	1.06
8:26	1.76	3:02	3.00	1:03	1.05
9:22	1.94	4:35	3.01	2:36	.93
11:06	2.16	6:56	3.04	4:09	.86
12:22 p. m.	2.30	9:33	2.99	5:43	.79
2:15	2.45	9:35	2.99	7:08	.73
4:10	2.57	10:58	3.08	8:43	.67
5:30	2.63			10:33	.63
6:36	2.68	*July 31, 1931*			
8:43	2.76			*Aug. 1, 1931*	
10:38	2.81	12:05 a. m.	3.12		
		2:27	3.14	12:13 a. m.	.59
July 30, 1931		4:39	3.15	2:05	.55
		6:11	2.72	3:53	.51
12:16 a. m.	2.79	7:01	2.08	5:14	.49
2:29	2.83	7:36	1.85	6:39	.46
4:04	2.84	7:58	1.73	8:24	.42
6:10	2.85	8:23	1.63		

Draw-down of the water table in observation wells and pumped well near Grand Island—Continued

Well 33, line D

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:00 a. m.	0.00	6:22 a. m.	1.96	8:26 a. m.	1.53
6:09	.22	7:45	1.97	9:08	1.43
6:21	.37	9:00	2.01	9:49	1.31
6:38	.47	10:26	2.03	10:30	1.25
7:21	.69	11:16	2.02	11:14	1.19
7:52	.79	12:15 p. m.	2.04	11:51	1.14
8:28	.90	1:33	2.05	1:05 p. m.	1.05
9:25	1.03	3:04	2.07	4:11	.86
11:10	1.27	4:37	2.09	5:44	.80
12:24 p. m.	1.36	6:58	2.12	7:10	.75
2:18	1.51	9:39	2.11	8:46	.70
4:14	1.62	11:00	2.16	10:36	.64
5:31	1.68	*July 31, 1931*			
6:39	1.73			*Aug. 1, 1931*	
8:46	1.79	12:09 a. m.	2.20		
10:42	1.86	2:31	2.21	12:15 a. m.	.60
July 30, 1931		4:42	2.24	2:07	.56
		6:15	2.08	3:55	.53
12:21 a. m.	1.88	7:04	1.82	5:16	.50
2:32	1.92	7:38	1.69	6:41	.47
4:07	1.93	8:02	1.60	8:26	.45

Well 34, line D

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:05 a. m.	0.00	6:25 a. m.	1.46	8:28 a. m.	1.34
6:11	.09	7:47	1.48	9:10	1.28
6:23	.17	9:02	1.49	9:51	1.20
6:40	.26	10:30	1.52	10:31	1.14
7:24	.38	11:18	1.53	11:15	1.09
7:55	.46	12:17 p. m.	1.55	11:53	1.05
8:33	.55	1:35	1.56	2:59 p. m.	.88
9:26	.65	3:07	1.58	4:13	.82
11:12	.83	4:39	1.59	5:46	.76
12:27 p. m.	.91	7:00	1.62	7:11	.71
2:25	1.00	9:41	1.64	8:50	.67
4:17	1.14	11:02	1.66	10:38	.62
5:33	1.20				
6:44	1.24	*July 31, 1931*		*Aug. 1, 1931*	
8:49	1.31				
10:45	1.35	2:34 a. m.	1.71	12:18 a. m.	.57
July 30, 1931		4:46	1.71	2:10	.53
		6:20	1.65	3:57	.50
12:25 a. m.	1.38	7:06	1.53	5:18	.47
2:35	1.41	7:40	1.44	6:43	.46
4:11	1.44	8:04	1.40	8:27	.43

Well 35, line D

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:12 a. m.	0.00	6:30 a. m.	0.98	9:11 a. m.	1.03
6:13	.03	7:49	1.01	9:52	.99
6:27	.06	9:04	1.02	10:33	.94
6:42	.09	10:32	1.04	11:17	.91
7:26	.18	11:20	1.05	11:54	.89
7:58	.23	12:20 p. m.	1.07	1:11 p. m.	.83
8:36	.28	1:38	1.08	3:01	.77
9:29	.34	3:09	1.09	4:14	.72
11:15	.45	4:41	1.12	5:48	.68
12:30 p. m.	.54	7:02	1.14	7:14	.63
2:27	.63	9:44	1.16	8:53	.60
3:19	.70	11:04	1.18	10:41	.55
5:37	.76	*July 31, 1931*			
6:49	.79			*Aug. 1, 1931*	
8:53	.85	2:39 a. m.	1.21		
10:48	.88	4:48	1.24	12:21 a. m.	.52
July 30, 1931		6:27	1.17	2:12	.49
		7:08	1.15	4:00	.45
12:30 a. m.	.91	7:42	1.12	5:20	.45
2:38	.94	8:06	1.09	6:45	.41
4:14	.96	8:30	1.07	8:29	.40

Draw-down of the water table in observation wells and pumped well near Grand Island—Continued

Well 36, line D

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:16 a. m.	0.00	6:35 a. m.	0.55	9:13 a. m.	0.72
6:16	.00	7:52	.58	9:54	.71
6:30	.01	9:07	.59	10:35	.68
6:45	.01	10:34	.61	11:19	.65
7:29	.04	11:23	.61	11:56	.64
8:00	.07	12:23 p. m.	.63	1:13 p. m.	.63
8:40	.10	1:40	.64	3:04	.59
9:31	.13	3:11	.65	4:17	.56
11:17	.21	4:43	.67	5:51	.53
12:33 p. m.	.25	7:04	.69	7:16	.50
2:30	.31	9:46	.71	8:57	.47
4:23	.35	11:08	.72	10:44	.45
5:40	.38	*July 31, 1931*			
6:55	.40			*Aug. 1, 1931*	
8:56	.41	2:42 a. m.	.75		
10:54	.47	4:50	.77	12:23 a. m.	.42
July 30, 1931		6:29	.78	2:15	.41
		7:11	.77	4:02	.39
12:34 a. m.	.50	7:45	.76	5:22	.38
2:42	.52	8:09	.74	6:48	.36
4:18	.53	8:32	.74	8:31	.34

Well 37, line D

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:19 a. m.	0.00	6:40 a. m.	0.32	8:34 a. m.	0.50
6:32	.00	7:55	.34	9:15	.49
6:47	.00	9:10	.35	9:57	.49
7:32	.01	10:36	.36	10:37	.48
8:04	.02	11:24	.37	11:20	.47
8:43	.04	12:25 p. m.	.38	11:58	.47
9:34	.07	1:42	.39	1:16 p. m.	.45
11:19	.12	3:13	.40	4:19	.43
12:35 p. m.	.13	4:45	.42	5:53	.41
2:34	.16	7:07	.43	7:18	.38
4:25	.19	9:58	.45	8:59	.38
5:42	.20	11:10	.46	10:47	.35
7:06	.22				
9:00	.24	*July 31, 1931*		*Aug. 1, 1931*	
10:58	.25				
		2:49 a. m.	.49	12:26 a. m.	.34
July 30, 1931		4:52	.51	2:17	.33
		6:31	.50	4:04	.32
12:42 a. m.	.28	7:13	.50	5:24	.31
2:45	.30	7:47	.50	6:50	.30
4:21	.31	8:11	.50	8;33	.29

Well 38, line D

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:21 a. m.	0.00	7:56 a. m.	0.30	9:58 a. m.	0.44
6:50	.00	9:11	.32	10:39	.44
7:34	.02	10:38	.33	11:22	.43
8:10	.03	11:26	.34	11:59	.43
8:46	.04	12:27 p. m.	.35	1:18 p. m.	.42
9:36	.06	1:44	.35	3:09	.42
11:21	.10	3:15	.37	4:24	.40
2:36 p. m.	.14	4:47	.38	5:55	.39
4:28	.16	7:08	.39	7:20	.37
5:44	.18	9:50	.41	9:02	.36
7:14	.19	11:12	.42	10:50	.34
9:06	.20				
11:01	.22	*July 31, 1931*		*Aug. 1, 1931*	
July 30, 1931		4:59 a. m.	.46	12:28 a. m.	.34
		6:33	.47	2:20	.33
12:44 a. m.	.24	7:14	.47	4:06	.31
2:48	.26	7:52	.47	5:25	.31
4:24	.28	8:35	.46	6:53	.29
6:43	.29	9:16	.45	8:35	.28

Draw-down of the water table in observation wells and pumped well near Grand Island—Continued

Well 39, line D

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:25 a. m.	0.00	7:58 a. m.	0.16	9:59 a.m.	0.27
6:53	.00	9:14	.17	10:41	.27
7:37	.00	10:40	.18	11:24	.28
8:13	.00	11:30	.18	12:01 p. m.	.27
8:50	.00	12:30 p. m.	.19	1:20	.27
9:39	.02	1:47	.19	3:11	.27
11:24	.03	3:17	.20	4:26	.27
12:44 p. m.	.04	4:50	.21	5:56	.27
2:41	.06	7:10	.22	7:23	.26
4:31	.07	9:53	.23	9:07	.25
5:45	.08	11:15	.24	11:53	.25
7:21	.08	*July 31, 1931*		*Aug. 1, 1931*	
9:13	.10				
11:05	.11	12:38 a. m.	.25		
July 30, 1931		3:02	.26	12:31 a. m.	.25
		5:03	.28	2:23	.25
12:50 a. m.	.12	6:36	.27	4:09	.24
2:51	.13	7:16	.27	5:27	.23
4:27	.14	8:37	.28	6:56	.22
6:46	.15	9:18	.28	8:37	.22

Well 40, line D

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:28 a. m.	0.00	8:01 a. m.	0.07	10:44 a. m.	0.15
6:56	.00	9:17	.08	10:27	.15
8:53	.00	10:43	.08	12:04 p. m.	.15
9:44	.00	12:34 p. m.	.09	1:23	.16
11:26	.01	1:50	.09	3:14	.15
12:47 p. m.	.01	3:20	.10	4:45	.15
2:45	.02	4:52	.11	5:58	.15
4:34	.03	7:12	.11	7:25	.16
5:48	.04	9:59	.12	9:10	.16
7:28	.04	11:18	.13	10:57	.16
9:18	.04				
11:08	.05	*July 31, 1931*		*Aug. 1, 1931*	
July 30, 1931		5:06 a. m.	.15	12:35 a. m.	.17
		6:39	.14	2:26	.19
12:55 a. m.	.06	7:19	.14	4:11	.18
2:54	.07	8:40	.15	5:30	.17
4:31	.07	9:21	.15	6:58	.16
6:49	.07	10:03	.15	8:40	.15

Well 41, line D

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 30, 1931*—Con.	
5:32 a. m.	0.00	9:19 a. m.	0.05	10:06 a. m.	0.09
7:00	.00	12:36 p. m.	.07	10:45	.08
8:57	.01	1:54	.07	12:06 p. m.	.09
9:47	.00	3:22	.06	1:25	.07
11:29	.02	4:54	.07	3:17	.07
12:56 p. m.	.01	10:02	.07	4:47	.07
2:50	.02	11:21	.07	5:59	.08
4:38	.03			7:30	.11
5:51	.03	*July 31, 1931*		10:59	.12
7:35	.03			*Aug. 1, 1931*	
11:11	.04	12:50 a. m.	.07		
		3:09	.09	12:39 a. m.	.13
July 30, 1931		5:09	.10	2:28	.12
		6:42	.09	4:13	.12
1:00 a. m.	.04	7:21	.09	5:32	.13
2:58	.04	8:42	.09	7:01	.13
4:35	.05	9:23	.09	8:42	.12

Draw-down of the water table in observation wells and pumped well near Grand Island—Continued

Well 42, line D

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:36 a. m.	0.00	9:22 a. m.	0.03	12:07 p. m.	0.05
7:04	.00	12:40 p. m.	.03	1:29	.06
9:00	.00	4:57	.04	3:20	.07
9:53	.00	11:24	.04	4:51	.06
11:34	.01		.04	6:02	.08
1:00 p. m.	.01	*July 31, 1931*		7:33	.07
2:54	.02			11:03	.07
4:41	.02	12:55 a. m.	.05		
5:51	.02	3:13	.05	*Aug. 1, 1931*	
11:15	.02	5:13	.06		
		6:45	.05	12:41 a. m.	.08
July 30, 1931		7:24	.05	2:33	.09
		8:46	.05	4:19	.10
1:07 a. m.	.03	9:26	.05	5:33	.09
3:02	.03	10:48	.05	8:44	.09
4:40	.03	11:32	.05		

Well 43, line D

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:39 a. m.	0.00	9:25 a. m.	0.01	12:09 p. m.	0.05
7:06	.00	12:43 p. m.	.02	1:31	.05
9:03	.00	5:00	.03	3:22	.05
9:47	.00	11:27	.02	4:53	.05
11:39	.00			6:04	.06
1:03 p. m.	.01	*July 31, 1931*		7:37	.05
2:57	.00			11:06	.06
4:45	.00	12:59 a. m.	.03		
5:57	.00	3:17	.04	*Aug. 1, 1931*	
		5:16	.05		
July 30, 1931		6:49	.04	12:45 a. m.	.07
		8:50	.04	2:35	.07
1:12 a. m.	.01	9:30	.04	4:22	.08
3:06	.01	10:50	.04	5:35	.07
4:44	.01	11:34	.05	8:46	.07

Well 44, line C

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:45 a. m.	0.00	4:08 a. m.	2.93	9:22 a. m.	1.40
6:09	.93	6:12	2.94	9:59	1.30
6:27	1.28	7:51	2.96	10:38	1.21
6:47	1.43	9:07	2.99	11:19	1.14
7:09	1.57	10:25	3.00	12:10 p. m.	1.06
7:50	1.78	11:53	3.03	1:03	.99
8:29	1.93	1:30 p. m.	3.05	2:08	.92
9:10	2.05	3:16	3.07	2:40	.90
10:47	2.23	4:35	3.11	3:45	.84
12:09 p. m.	2.38	5:42	3.11	4:42	.78
1:19	2.48	6:52	3.13	5:13	.76
2:32	2.57	8:00	3.14	5:45	.75
3:54	2.64			7:09	.70
5:08	2.71	*July 31, 1931*		9:14	.63
6:16	2.76			11:13	.59
8:08	2.78	12:10 a. m.	3.19		
10:24	2.89	2:26	3.22	*Aug. 1, 1931*	
		4:40	3.23		
July 30, 1931		6:09	2.77	1:09 a. m.	.53
		6:57	2.09	3:14	.50
12:13 a. m.	2.88	7:51	1.72	6:40	.42
2:24	2.92	8:36	1.53	8:26	.40

Draw-down of the water table in observation wells and pumped well near Grand Island—Continued

Well 45, line C

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:08 a. m.	0.00	4:13 a. m.	2.09	9:24 a. m.	1.37
6:10	.32	6:21	2.10	10:02	1.28
6:30	.54	7:53	2.12	10:40	1.21
6:50	.67	9:10	2.14	11:21	1.14
7:11	.78	10:27	2.16	12:12 p. m.	1.06
7:52	.96	11:55	2.17	1:05	.99
8:31	1.09	1:32 p. m.	2.20	2:10	.91
9:12	1.21	4:37	2.24	2:55	.88
10:49	1.37	5:44	2.25	3:50	.84
12:11 p. m.	1.51	6:54	2.26	4:43	.78
1:21	1.59	8:02	2.27	5:16	.77
2:36	1.68	9:54	2.27	5:46	.74
3:58	1.76	*July 31, 1931*		7:12	.70
5:11	1.83	12:14 a. m.	2.33	9:17	.64
6:18	1.87	2:29	2.35	11:16	.58
8:15	1.93	4:44	2.37	*Aug. 1, 1931*	
10:33	2.01	6:12	2.20	1:11 a. m.	.55
July 30, 1931		7:02	1.88	3:16	.51
12:18 a. m.	2.04	7:54	1.63	4:55	.45
2:27	2.06	8:39	1.43	6:44	.41
				8:28	.40

Well 46, line C

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:11 a. m.	0.00	6:28 a. m.	1.47	10:04 a. m.	1.17
6:12	.10	7:55	1.49	10:43	1.12
6:32	.22	9:12	1.51	11:23	1.07
6:52	.29	10:29	1.52	12:14 p. m.	1.00
7:14	.37	11:58	1.53	1:07	.94
7:55	.48	1:34 p. m.	1.56	2:12	.88
8:33	.57	2:30	1.57	2:58	.84
9:14	.65	4:39	1.60	3:52	.80
10:51	.80	5:46	1.60	4:45	.75
12:13 p. m.	.92	6:57	1.62	5:18	.74
1:23	1.01	8:04	1.63	5:48	.72
2:39	1.07	9:57	1.64	7:14	.67
4:01	1.14	*July 31, 1931*		9:19	.61
5:13	1.19	12:18 a. m.	1.68	11:19	.56
6:20	1.24	2:34	1.70	*Aug. 1, 1931*	
8:25	1.32	4:47	1.72	1:13 a. m.	.52
10:36	1.36	6:15	1.67	3:17	.48
July 30, 1931		7:05	1.51	4:57	.44
12:26 a. m.	1.41	7:57	1.41	6:47	.41
2:30	1.43	8:42	1.31	8:30	.39
4:20	1.46	9:26	1.24		

Well 47, line C

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:14 a. m.	0.00	6:32 a. m.	1.00	10:07 a. m.	0.94
6:14	.05	7:58	1.01	10:45	.90
6:34	.10	9:15	1.03	11:25	.87
6:55	.14	10:31	1.04	12:17 p. m.	.83
7:16	.18	12:14 p. m.	1.07	1:09	.80
7:57	.26	1:36	1.08	2:13	.75
8:36	.29	3:32	1.10	3:00	.71
9:16	.35	4:41	1.11	3:54	.68
10:54	.46	5:48	1.11	4:46	.66
12:15 p. m.	.54	7:00	1.12	5:20	.64
1:26	.54	8:08	1.14	5:50	.62
2:42	.65	10:05	1.16	7:16	.59
4:04	.71	*July 31, 1931*		9:22	.54
5:15	.76	12:25 a. m.	1.17	11:21	.50
6:22	.79	2:42	1.20	*Aug. 1, 1931*	
8:29	.84	4:50	1.21	1:15 a. m.	.47
10:41	.89	6:18	1.19	3:20	.43
July 30, 1931		7:08	1.12	4:49	.39
12:33 a. m.	.93	7:59	1.06	6:49	.36
2:36	.96	8:45	1.01	8:32	.34
4:24	.98	9:29	.97		

Draw-down of the water table in observation wells and pumped well near Grand Island—Continued

Well 48, line C

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:16 a. m.	0.00	6:35 a. m.	0.60	10:10 a. m.	0.68
6:17	.01	8:00	.61	10:48	.66
6:36	.02	9:19	.63	11:28	.64
6:58	.04	10:34	.64	12:20 p. m.	.63
7:18	.06	12:20 p. m.	.66	1:13	.60
8:00	.10	1:38	.66	2:15	.58
8:41	.14	2:34	.68	3:02	.56
9:18	.16	4:43	.70	3:55	.54
10:57	.23	5:50	.70	4:48	.52
12:18 p. m.	.29	7:03	.70	5:21	.51
1:30	.32	8:11	.72	5:22	.51
2:44	.36	10:11	.73	7:18	.47
4:10	.40			9:25	.45
5:20	.43	*July 31, 1931*		11:25	.42
6:24	.45				
8:35	.48	12:30 a. m.	.75	*Aug. 1, 1931*	
10:45	.50	2:48	.77		
		4:53	.78		
July 30, 1931		6:22	.79	1:18 a. m.	.40
		7:17	.76	3:22	.37
12:40 a. m.	.55	8:02	.74	5:01	.34
2:39	.58	8:47	.71	6:52	.32
4:30	.60	9:33	.70	8:34	.30

Well 49, line C

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:18 a. m.	0.00	6:39 a. m.	0.28	10:12 a. m.	0.39
6:20	.00	8:03	.30	10:50	.38
6:40	.00	9:22	.30	11:31	.38
7:00	.00	10:38	.31	12:22 p. m.	.38
7:20	.01	12:27 p. m.	.33	1:16	.37
8:03	.03	1:40	.33	2:17	.36
8:43	.04	2:36	.34	3:05	.34
9:20	.05	4:45	.34	3:58	.34
11:01	.09	5:51	.35	4:51	.33
12:20 p. m.	.11	7:05	.36	5:24	.33
1:32	.14	8:14	.36	5:54	.32
2:50	.14	10:16	.37	7:21	.31
4:12	.16			9:30	.29
5:22	.17	*July 31, 1931*		11:28	.28
6:27	.18				
8:39	.20	12:36 a. m.	.38	*Aug. 1, 1931*	
10:50	.23	2:50	.40		
		4:57	.41		
July 30, 1931		6:25	.41	1:20 a. m.	.27
		7:21	.41	3:24	.25
12:55 a. m.	.24	8:05	.41	5:03	.22
2:43	.26	8:49	.40	7:01	.21
4:35	.27	9:35	.40	8:36	.20

Well 50, line C

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 29, 1931*—Con.		*July 30, 1931*—Con.	
5:21 a. m.	0.00	2:52 p. m.	0.13	6:41 a. m.	0.27
5:23	.00	4:14	.14	8:04	.28
6:22	.00	4:24	.17	9:24	.28
6:42	.00	6:30	.18	10:40	.29
7:03	.01	8:43	.20	12:30 p. m.	.30
7:22	.01	10:52	.21	1:42	.31
8:05	.02			2:38	.32
8:45	.03	*July 30, 1931*		4:46	.33
9:22	.04			5:53	.34
11:04	.08	12:57 a. m.	.23	7:07	.34
12:22 p. m.	.11	2:45	.24	8:15	.34
1:34	.13	4:38	.26	10:18	.36

Draw-down of the water table in observation wells and pumped well near Grand Island—Continued

Well 50, line C—Continued

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 31, 1931		*July 31, 1931*—Con.		*July 31, 1931*—Con.	
12:40 a. m.	0.37	11:33 a. m.	0.38	9:33 p. m.	0.29
2:58	.38	12:24 p. m.	.37	11:30	.28
4:59	.39	1:18	.36		
6:26	.40	2:18	.36	*Aug. 1, 1931*	
7:22	.40	3:06	.34		
8:06	.40	3:59	.33	1:22 a. m.	.26
8:51	.39	4:52	.33	3:27	.25
9:37	.39	5:25	.33	5:04	.23
10:14	.39	5:55	.32	7:03	.22
10:52	.38	7:22	.31	8:38	.21

Well 51, line C

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:24 a. m.	0.00	9:26 a. m.	0.16	10:54 a. m.	0.26
7:24	.01	10:42	.17	11:35	.25
8:08	.01	12:32 p. m.	.18	12:26 p. m.	.25
8:48	.01	1:44	.18	1:19	.25
9:25	.02	2:40	.18	1:20	.24
11:07	.03	4:48	.19	3:10	.24
12:24 p. m.	.05	5:55	.21	4:01	.24
1:37	.06	7:09	.21	4:54	.23
2:55	.07	8:16	.21	5:27	.23
4:17	.08	10:23	.22	5:56	.23
5:26	.09			7:25	.22
6:32	.09	*July 31, 1931*		9:36	.21
8:50	.11			11:34	.21
10:55	.11	12:43 a. m.	.23		
		3:06	.24	*Aug. 1, 1931*	
July 30, 1931		5:02	.24		
		6:29	.25		
1:04 a. m.	.13	7:25	.25	1:24 p. m.	.20
2:48	.14	8:09	.25	3:29	.19
4:43	.16	8:54	.25	5:07	.16
6:44	.16	9:39	.26	7:05	.15
8:07	.16	10:17	.25	8:40	.15

Well 52, line C

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:27 a. m.	0.00	8:09 a. m.	0.07	10:20 a. m.	0.14
5:29	.00	9:29	.07	10:57	.14
7:27	.00	10:45	.08	11:38	.14
8:11	.00	12:35 p. m.	.09	12:30 p. m.	.14
8:51	.01	1:46	.09	1:22	.14
9:27	.00	3:43	.09	2:22	.15
11:10	.01	4:50	.10	3:12	.15
12:27 p. m.	.02	5:57	.10	4:03	.15
1:40	.02	7:11	.10	4:55	.15
3:00	.03	8:22	.10	5:29	.15
4:19	.03	10:26	.10	5:58	.15
5:29	.04			7:27	.14
6:35	.04	*July 31, 1931*		9:39	.14
8:54	.04			11:37	.14
10:59	.05	12:48 a. m.	.11		
		3:10	.13	*Aug. 1, 1931*	
July 30, 1931		5:05	.12		
		6:32	.12	1:26 a. m.	.14
1:08 a. m.	.06	7:27	.13	3:32	.13
2:52	.07	8:12	.13	5:10	.13
4:50	.07	8:57	.13	7:07	.11
6:47	.07	9:41	.14	8:43	.09

Draw-down of the water table in observation wells and pumped well near Grand Island—Continued

Well 53, line C

Time	Draw-down (feet)
July 29, 1931	
5:30 a. m.	0.00
5:32	.00
7:30	.01
8:14	.00
8:53	.00
9:29	.00
11:13	.00
12:30 p. m.	.01
1:43	.01
3:03	.02
4:22	.02
5:31	.02
6:37	.03
9:00	.02
11:03	.03
July 30, 1931	
1:14 a. m.	.04
2:53	.03
4:55	.04
6:51	.04
July 30, 1931—Con.	
8:12 a. m.	0.04
10:48	.05
12:37 p. m.	.05
1:48	.05
3:45	.05
4:52	.05
6:00	.05
7:14	.06
8:25	.07
10:30	.07
July 31, 1931	
12:51 a. m.	.07
3:19	.08
5:07	.08
6:35	.08
7:30	.08
8:14	.08
8:59	.08
9:44	.09
10:22	.09
July 31, 1931—Con.	
11:01 a. m.	0.09
11:40	.09
12:33 p. m.	.09
1:25	.09
2:25	.09
3:15	.10
4:06	.10
4:59	.10
5:32	.10
6:00	.10
7:29	.10
9:43	.11
11:40	.11
Aug. 1, 1931	
1:28 a. m.	.10
3:34	.10
5:12	.10
7:11	.09
8:45	.09

Well 54, line C

Time	Draw-down (feet)
July 29, 1931	
5:34 a. m.	0.00
7:34	.00
8:17	.00
8:56	.00
9:32	.00
12:32 p. m.	.00
3:06	.00
5:34	.01
6:41	.01
9:05	.00
11:08	.00
July 30, 1931	
1:17 a. m.	.01
3:00	.01
5:00	.01
6:56	.00
8:15	.00
10:51	.00
12:40 p. m.	.01
July 30, 1931—Con.	
1:51 p. m.	0.01
3:48	.01
4:55	.01
6:02	.01
7:16	.01
8:27	.01
10:33	.02
July 31, 1931	
12:56 a. m.	0.02
3:22	.02
5:11	.03
6:38	.02
7:33	.02
8:16	.02
9:02	.02
9:46	.03
10:24	.03
11:04	.04
July 31, 1931—Con.	
11:43 a. m.	0.03
12:35 p. m.	.04
1:27	.03
2:27	.03
3:17	.04
4:08	.04
5:01	.04
5:34	.05
6:02	.05
7:32	.04
9:47	.05
11:43	.05
Aug. 1, 1931	
1:31 a. m.	.05
3:37	.05
5:14	.04
7:14	.04
8:49	.04

Well 55, line C

Time	Draw-down (feet)
July 29, 1931	
5:36 a. m.	0.00
7:36	.00
8:19	.00
8:59	.00
9:35	.00
3:09 p. m.	.00
5:36	.00
6:43	.00
9:15	.00
July 30, 1931	
1:21 a. m.	.00
5:05	.00
7:00	.00
8:17	.00
10:53	.00
12:43 p. m.	.00
1:53	.00
July 30, 1931—Con.	
5:07 p. m.	0.00
6:05	.00
7:18	.00
8:30	.00
10:36	.01
July 31, 1931	
1:00 a. m.	.01
3:30	.01
5:15	.01
6:40	.01
7:36	.01
8:19	.01
9:05	.01
9:49	.01
10:27	.02
11:07	.03
11:46	.03
July 31, 1931—Con.	
12:38 p. m.	0.02
2:29	.02
3:21	.03
4:11	.03
5:04	.03
5:36	.02
6:04	.03
7:35	.03
9:50	.04
11:46	.04
Aug. 1, 1931	
12:35 a. m.	.04
3:40	.04
5:16	.03
7:17	.03
8:52	.03

Draw-down of the water table in observation wells and pumped well near Grand Island—Continued

Well 56, line SW

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:05 a. m	0.00	6:14 a. m	2.83	10:36 a. m	1.26
6:12	.88	8:05	2.85	11:17	1.17
6:29	1.10	9:34	2.87	12:15 p. m	1.09
6:45	1.19	11:07	2.90	1:07	1.02
7:19	1.33	12:25 p. m	2.92	1:59	.95
7:33	1.48	1:41	2.94	2:41	.92
8:07	1.65	3:14	2.97	3:37	.87
8:30	1.75	4:37	2.99	4:21	.83
8:55	1.82	6:13	3.01	5:24	.79
9:25	1.90	7:18	3.02	6:22	.74
9:46	1.99	8:51	3.03	8:10	.68
10:14	2.02	11:01	3.06	10:28	.61
12:11 p. m	2.25				
1:47	2.38	*July 31, 1931*		*Aug. 1, 1931*	
3:20	2.49				
4:58	2.58	1:35 a. m	3.10	12:38 a. m	.57
6:22	2.63	3:16	3.11	2:44	.52
8:36	2.72	5:30	3.12	5:10	.48
11:04	2.79	6:12	2.73	6:37	.44
July 30, 1931		7:12	2.01	8:22	.42
		7:58	1.73		
2:23 a. m	2.82	8:53	1.51		
4:25	2.83	9:46	1.36		

Well 57, line SW

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:07 a. m	0.00	6:18 a. m	2.29	9:58 a. m	1.32
6:15	.53	8:06	2.31	10:38	1.21
6:31	.69	9:35	2.34	11:19	1.14
6:45	.76	11:09	2.36	12:20 p. m	1.06
7:10	.92	12:28 p. m	2.39	1:10	.98
7:35	.99	1:42	2.40	2:01	.93
8:11	1.24	3:15	2.42	2:53	.89
8:33	1.21	5:40	2.44	3:39	.85
8:59	1.18	6:14	2.46	4:18	.81
9:28	1.37	7:19	2.47	5:26	.77
10:16	1.48	8:53	2.48	6:24	.72
12:13 p. m	1.69	11:03	2.50	8:17	.67
1:50	1.81			10:32	.61
3:23	1.92	*July 31, 1931*			
5:00	2.03			*Aug. 1, 1931*	
6:24	2.08	1:37 a. m	2.54		
8:39	2.17	3:17	2.56	12:40 a. m	.56
11:07	2.23	5:31	2.58	2:45	.52
July 30, 1931		6:15	2.30	5:12	.47
		7:14	1.85	6:45	.43
2:25 a. m	2.27	8:01	1.62	8:24	.41
4:26	2.30	8:55	1.44		

Well 58, line SW

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:12 a. m	0.00	6:21 a. m	1.90	9:50 a. m	1.27
6:16	.35	8:08	1.93	10:40	1.17
6:34	.45	9:36	1.94	11:20	1.15
6:50	.53	11:11	1.96	12:21 p. m	1.04
7:13	.62	12:29 p. m	2.00	1:15	.97
7:37	.71	1:44	2.01	2:02	.92
8:13	.83	3:17	2.03	2:55	.89
8:35	.89	4:45	2.05	3:40	.85
9:01	.96	6:16	2.06	4:25	.81
9:30	1.03	7:20	2.07	5:28	.76
10:19	1.12	8:55	2.09	6:26	.73
12:15 p. m	1.31	11:06	2.10	8:19	.67
1:53	1.44			10:33	.61
3:24	1.54	*July 31, 1931*			
5:02	1.63			*Aug. 1, 1931*	
6:26	1.68	1:39 a. m	2.15		
8:42	1.76	3:21	2.16	12:42 a. m	.56
11:10	1.83	5:32	2.18	2:46	.52
July 30, 1931		6:17	1.97	5:12	.47
		7:17	1.67	6:47	.44
2:27 a. m	1.87	8:03	1.52	8:25	.42
4:27	1.90	8:57	1.39		

Draw-down of the water table in observation wells and pumped well near Grand Island—Continued

Well 59, line SW

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:15 a. m.	0.00	6:23 a. m.	1.59	9:52 a. m.	1.19
6:18	.11	8:10	1.62	10:42	1.10
6:35	.30	9:38	1.64	11:22	1.05
6:51	.37	11:12	1.66	12:23 p. m.	.98
7:14	.45	12:32 p. m.	1.68	1:18	.94
7:40	.51	1:45	1.70	2:03	.88
8:15	.60	3:17	1.72	2:56	.84
8:37	.66	4:47	1.74	3:41	.80
9:04	.72	6:17	1.75	4:27	.77
9:33	.77	7:22	1.76	5:29	.73
10:21	.86	8:57	1.78	6:27	.70
12:16 p. m.	1.05	11:09	1.79	8:21	.64
1:55	1.12			10:35	.85
3:27	1.24	*July 31, 1931*			
5:03	1.32			*Aug. 1, 1931*	
6:28	1.38	1:41 a. m.	1.83		
8:45	1.46	3:22	1.85		
11:12	1.51	5:35	1.86	12:44 a. m.	.54
July 30, 1931		6:21	1.72	2:47	.49
		7:19	1.52	5:13	.45
2:29 a. m	1.57	8:05	1.40	6:48	.42
4:31	1.59	8:59	1.28	8:26	.40

Well 60, line SW

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:17 a. m.	0.00	6:26 a. m.	0.89	9:01 a. m.	0.93
6:21	.04	8:12	.90	9:55	.88
6:35	.08	9:39	.92	10:45	.83
6:53	.11	11:14	.94	11:24	.81
7:16	.14	12:34 p. m.	.97	12:26 p. m.	.76
7:44	.17	1:47	.98	1:20	.73
8:17	.22	3:19	1.00	2:05	.70
8:40	.25	4:48	.99	2:58	.68
9:05	.28	6:18	1.01	3:43	.66
9:36	.32	7:23	1.02	4:43	.63
10:23	.35	8:59	1.04	5:32	.61
3:29 p. m.	.60	11:11	1.05	6:30	.59
5:05	.66			8:22	.54
6:30	.70	*July 31, 1931*		10:37	.50
8:49	.76			*Aug. 1, 1931*	
11:16	.79	1:43 a. m.	1.08		
		3:25	1.10	12:46 a. m.	.46
July 30, 1931		5:26	1.11	2:48	.42
		6:26	1.09	5:16	.39
2:31 a. m.	.85	7:22	1.01	6:49	.37
4:33	.88	8:07	.97	8:27	.36

Well 61, line SW

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:18 a. m.	0.00	6:28 a. m.	0.48	9:57 a. m.	0.59
6:23	.00	8:13	.48	10:48	.58
6:38	.01	9:41	.50	11:26	.56
6:54	.02	11:15	.51	12:28 p. m.	.54
7:17	.03	12:37 p. m.	.53	1:22	.52
7:46	.04	1:49	.54	2:06	.51
8:20	.06	3:21	.55	3:00	.50
8:41	.08	4:49	.57	3:45	.48
9:07	.10	6:20	.57	4:45	.47
9:38	.12	7:25	.58	5:33	.46
10:25	.14	9:01	.60	6:31	.44
12:21 p. m.	.21	11:13	.61	8:24	.41
2:02	.25			10:39	.39
3:30	.28	*July 31, 1931*			
5:07	.32			*Aug. 1, 1931*	
6:32	.33	1:45 a. m.	.63		
8:49	.37	3:27	.64		
11:20	.39	5:37	.66	12:48 a. m.	.37
July 30, 1931		6:29	.66	2:52	.34
		7:24	.65	5:17	.32
2:34 a. m.	.45	8:14	.62	6:50	.30
4:35	.46	9:04	.61	8:28	.30

Draw-down of the water table in observation wells and pumped well near Grand Island—Continued

Well 62, line SW

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:21 a. m.	0.00	6:34 a. m.	0.27	9:59 a. m.	0.40
6:24	.00	8:15	.27	10:50	.39
6:40	.00	9:42	.28	11:27	.39
6:56	.00	11:17	.29	12:31 p. m.	.38
7:18	.00	12:38 p. m.	.31	1:24	.37
7:49	.01	1:50	.32	2:08	.36
8:22	.02	3:23	.32	3:02	.36
8:43	.03	4:50	.34	3:46	.35
9:09	.04	6:21	.34	4:48	.34
9:40	.05	7:27	.35	5:35	.34
10:27	.07	9:03	.36	6:33	.34
12:23 p. m.	.11	11:16	.37	8:26	.32
2:05	.13			10:41	.30
3:33	.15	*July 31, 1931*			
5:08	.16			*Aug. 1, 1931*	
6:34	.17	1:47 a. m.	.39		
8:59	.18	3:29	.40		
11:23	.21	5:38	.41	12:50 a. m.	.29
July 30, 1931		6:31	.40	2:54	.28
		7:26	.41	5:19	.27
2:35 a. m.	.25	8:12	.41	6:52	.24
4:37	.25	9:07	.41	8:30	.24

Well 63, line SW

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:24 a. m.	0.00	6:38 a. m.	0.18	9:11 a. m.	0.30
6:58	.01	8:17	.18	10:01	.30
7:21	.01	9:43	.18	10:52	.29
7:51	.01	11:18	.19	11:30	.30
8:24	.01	12:40 p. m.	.20	12:34 p. m.	.29
8:45	.01	1:52	.21	1:26	.29
9:12	.02	3:25	.22	2:11	.29
9:42	.02	4:52	.23	3:03	.27
10:29	.03	6:22	.23	3:49	.27
12:25 p. m.	.05	7:29	.23	4:50	.27
2:07	.06	9:06	.24	5:37	.27
3:34	.08	11:18	.25	6:35	.26
5:10	.09			8:29	.25
6:36	.10	*July 31, 1931*		10:43	.25
9:03	.11			*Aug. 1, 1931*	
11:27	.12	1:49 a. m.	.27		
		3:32	.28	12:52 a. m.	.24
July 30, 1931		5:40	.28	2:55	.23
		6:35	.29	5:20	.22
2:38 a. m.	.14	7:29	.30	6:54	.20
4:39	.16	8:14	.30	8:31	.20

Well 64, line SW

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:26 a. m.	0.00	8:19 a. m.	0.11	10:03 a. m.	0.21
7:00	.00	9:45	.11	10:55	.21
7:24	.00	11:20	.12	11:31	.22
7:54	.00	12:42 p. m.	.13	12:37 p. m.	.21
8:48	.00	1:54	.13	1:28	.21
9:14	.00	3:26	.14	2:13	.21
9:44	.00	4:55	.15	3:05	.21
10:32	.01	6:24	.16	3:56	.21
12:27 p. m.	.02	7:30	.16	4:53	.20
2:08	.04	9:10	.17	5:39	.20
3:37	.04	11:21	.17	6:36	.19
5:11	.04	*July 31, 1931*		8:31	.20
6:38	.04			10:46	.20
9:07	.06	1:51 a. m.	.18	*Aug. 1, 1931*	
11:31	.07	3:35	.19		
July 30, 1931		5:42	.20	12:54 a. m.	.20
		6:38	.21	2:59	.19
2:41 a. m.	.10	7:31	.20	5:21	.18
4:44	.11	8:17	.21	6:57	.17
6:40	.10	9:12	.21	8:33	.16

Draw-down of the water table in observation wells and pumped well near Grand Island—Continued

Well 65, line SW

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:27 a. m.	0.00	9:46 a. m.	0.06	10:05 a. m.	0.14
7:01	.00	11:22	.07	10:57	.14
7:56	.00	12:44 p. m.	.08	11:33	.15
8:50	.00	1:55	.08	12:39 p. m.	.15
9:16	.00	3:27	.10	1:30	.15
10:34	.00	4:57	.10	2:15	.15
12:30 p. m.	.00	6:26	.10	3:07	.14
2:10	.01	7:31	.10	3:52	.14
3:40	.01	9:17	.11	4:55	.14
5:13	.02	11:23	.12	5:41	.15
6:40	.02	*July 31, 1931*		6:38	.15
9:10	.03	1:53 a. m.	.13	8:34	.16
11:36	.04	3:36	.13	10:48	.16
July 30, 1931		5:44	.13	*Aug. 1, 1931*	
2:44 a. m.	.06	6:41	.13	12:57 a. m.	.16
4:46	.07	7:34	.13	3:00	.14
6:43	.06	8:19	.13	5:23	.14
8:21	.06	9:14	.14	7:00	.13
				8:34	.14

Well 66, line SW

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:30 a. m.	0.00	1:56 p. m.	0.06	11:35 a. m.	0.10
10:36	.00	3:29	.06	12:41 p. m.	.09
12:32 p. m.	.00	4:58	.06	1:33	.10
2:12	.00	6:27	.06	2:16	.10
3:41	.01	7:32	.07	3:07	.10
5:15	.01	9:20	.07	3:54	.10
6:42	.01	11:26	.08	4:56	.10
9:13	.01	*July 31, 1931*		5:44	.11
July 30, 1931		1:55 a. m.	.09	6:40	.11
12:17 a. m.	.02	3:39	.09	8:36	.12
2:46	.03	5:45	.09	10:50	.12
4:50	.04	7:36	.08	*Aug. 1, 1931*	
6:48	.04	8;21	.08	12:59 a. m.	.12
8:23	.03	9:47	.09	3:02	.11
9:48	.04	10:07	.09	5:25	.11
11:23	.04	10:59	.10	7:02	.11
12:46 p. m.	.05			8:31	.11

Well 67, line SW

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*Jnly 31, 1931*—Con.	
5:32 a. m.	0.00	1:58 p. m.	0.05	11:38 a. m.	0.08
10:39	.01	3:31	.05	12:43 p. m.	.08
12:35 p. m.	.01	5:01	.05	1:35	.08
2:16	.02	6:29	.05	2:18	.08
3:44	.02	7:34	.06	3:10	.09
5:16	.02	9:22	.06	3:56	.09
6:44	.02	11:29	.07	4:58	.09
9:17	.02	*July 31, 1931*		5:47	.09
July 30, 1931		1:57 a. m.	.08	6:41	.09
12:22 a. m.	.03	3:41	.08	8:38	.11
2:48	.03	3:47	.08	10:52	.11
4:53	.03	6:47	.08	*Aug. 1, 1931*	
6:51	.03	7:39	.07	1:00 a. m.	.11
8:25	.03	8:23	.08	3:05	.11
9:49	.03	9:19	.08	5:26	.11
11:25	.03	10:10	.08	7:03	.10
12:47 p. m.	0.04	11:01	.08	8:33	.10

Draw-down of the water table in observation wells and pumped well near Grand Island—Continued

Well 68, line SW

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:35 a. m.	0.00	3:33 p. m.	0.03	11:40 a. m.	0.08
10:42	.00	5:05	.04	12:46 p. m.	.08
2:17 p. m.	.01	6:31	.04	1:38	.07
3:47	.01	7:35	.04	2:20	.07
5:20	.01	9:23	.04	3:12	.07
6:46	.01	11:31	.05	3:58	.07
9:19	.01	*July 31, 1931*		5:00	.07
July 30, 1931		1:59 a. m.	.06	5:49	.07
12:25 a. m.	.03	3:44	.05	6:43	.07
2:52	.03	5:48	.07	8:40	.08
4:56	.03	6:50	.07	10:54	.08
6:54	.02	7:42	.07	*Aug. 1, 1931*	
8:27	.02	8:26	.07	1:01 a. m.	.08
9:51	.02	9:22	.07	3:07	.08
11:27	.02	10:12	.07	5:27	.08
12:52 p. m.	.03	11:04	.07	7:05	.08
2:00	.03			8:34	.08

Well 69, line SW

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:38 a. m.	0.00	2:01 p. m.	0.03	11:42 a. m.	0.06
10:43	.00	3:35	.03	12:49 p. m.	.06
2:20 p. m.	.00	5:11	.03	1:40	.06
3:49	.00	6:32	.03	2:20	.06
5:21	.00	7:36	.04	3:14	.06
6:48	.01	9:26	.04	4:01	.06
9:22	.02	11:34	.04	5:02	.06
July 30, 1931		*July 31, 1931*		5:51	.06
12:27 a. m.	.02	2:00 a. m.	.05	6:45	.05
2:56	.02	3:46	.05	8:43	.07
4:59	.02	6:56	.04	10:56	.07
6:57	.02	7:45	.04	*Aug. 1, 1931*	
8:28	.02	9:24	.04	1:04 a. m.	.07
9:53	.02	10:15	.05	3:09	.07
11:29	.02	11:06	.06	5:29	.08
12:54 p. m.	.02			7:06	.07

Well 70, line SW

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:40 a. m.	0.00	2:04 p. m.	0.02	11:44 a. m.	0.05
10:46	.00	3:37	.03	12:51 p. m.	.05
2:22 p. m.	.00	5:13	.03	1:42	.05
3:51	.01	6:34	.03	2:24	.05
5:25	.01	7:38	.03	3:16	.05
6:50	.01	9:28	.03	4:03	.05
9:24	.01	11:36	.03	5:05	.05
July 30, 1931		*July 31, 1931*		5:54	.06
12:30 a. m.	.01	2:03 a. m.	.03	6:47	.05
2:58	.02	3:50	.04	8:46	.06
5:01	.02	5:52	.04	10:58	.07
7:00	.01	7:00	.04	*Aug. 1, 1931*	
8:30	.01	7:48	.05	1:06 a.m.	.07
9:54	.01	8:31	.05	3:11	.07
11:31	.01	9:26	.04	5:30	.06
12:57 p. m.	.02	10:17	.05	7:07	.06
		11:08	.05	8:44	.07

Draw-down of the water table in observation wells and pumped well near Grand Island—Continued

Well 71, line A

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:09 a. m.	0.00	3:18 a. m.	8.54	7:24 a. m.	1.79
6:13	8.68	4:57	8.45	7:46	1.66
6:25	8.80	5:00	8.46	8:18	1.54
6:37	8.24	6:58	8.50	9:00	1.42
6:41	7.45	8:13	8.56	9:45	1.30
6:42	7.45	9:39	8.65	10:32	1.21
7:08	7.58	10:50	8.69	11:08	1.15
7:32	7.58	11:37	8.75	11:36	1.10
8:06	7.75	12:54 p. m.	8.74	12:06 p. m.	1.06
8:26	7.76	2:08	8.88	2:06	.93
9:05	7.95	3:36	8.24	3:38	.85
9:31	8.03	4:10	8.95	6:19	.74
10:14	8.17	5:10	8.95	6:43	.71
11:48	8.29	6:24	8.93	8:09	.67
1:18 p. m.	8.62	7:20	8.92	9:38	.62
3:08	8.79	10:14	9.06	11:19	.59
4:55	8.87	11:38	9.07		
6:06	8.85			*Aug. 1, 1931*	
6:08	8.85	*July 31, 1931*			
8:05	8.89				
9:36	8.90	1:19 a. m.	9.05	1:00 a. m.	.55
11:24	9.02	3:38	9.03	3:17	.50
July 30, 1931		5:31	8.97	4:37	.48
		6:06	2.89	5:44	.47
1:28 a. m.	8.64	6:32	2.23	7:25	.43
3:15	8.56	6:53	2.01	8:56	.41

Well 72, line A

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:11 a. m.	0.00	5:03 a. m.	4.76	9:02 a. m.	1.45
6:09	3.26	7:02	4.76	9:47	1.34
6:15	3.37	8:16	4.80	10:33	1.24
6:27	3.50	9:42	4.85	11:09	1.18
6:45	3.38	10:51	4.86	11:38	1.13
6:46	3.40	11:39	4.88	12:10 p. m.	1.09
6:48	3.41	12:57 p. m.	4.88	2:09	.95
7:15	3.56	2:10	4.93	3:40	.86
7:34	3.64	3:39	4.75	5:08	.80
8:08	3.79	4:12	4.94	6:20	.74
8:28	3.86	5:11	4.97	8:10	.68
8:38	3.88	6:26	4.97	9:35	.63
9:07	3.97	7:26	4.99	11:21	.59
9:35	4.06	10:18	5.02		
10:17	4.13	11:41	5.05	*Aug. 1, 1931*	
11:50	4.30				
1:22 p. m.	4.45	*July 31, 1931*		1:01 a. m.	.55
3:13	4.59			3:19	.52
4:59	4.66	1:31 a. m.	5.06	4:40	.50
6:10	4.70	3:50	5.10	5:45	.46
8:07	4.75	5:35	5.08	7:27	.43
9:40	4.79	6:08	2.95	8:57	.40
11:27	4.86	6:34	2.36		
July 30, 1931		6:55	2.11		
		7:26	1.85		
1:33 a. m.	4.77	7:49	1.71		
3:21	4.77	8:19	1.59		

Draw-down of the water table in observation wells and pumped well near Grand Island—Continued

Well 73, line S

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:53 a. m.	0.00	10:36 a. m.	1.52	11:21 a. m.	1.03
6:37	.26	11:57	1.54	12:09 p. m.	.99
7:13	.36	1:20 p. m.	1.57	12:45	.95
8:02	.49	2:28	1.58	1:30	.91
8:47	.59	3:59	1.59	2:26	.86
9:40	.69	5:45	1.61	3:16	.81
11:30	.84	7:01	1.63	3:59	.78
1:04 p. m.	.97	8:02	1.64	5:04	.75
2:49	1.07	10:01	1.65	5:31	.73
4:31	1.17	*July 31, 1931*		7;29	.66
5:55	1.23			9:34	.61
7:40	1.29	12:17 a. m.	1.69	11:38	.55
10:23	1.36	2:50	1.71		
July 30, 1931		5:10	1.73	*Aug. 1, 1931*	
		6:24	1.62		
1:17 a. m.	1.42	7:14	1.48	1:55 a. m.	.53
3:30	1.45	7:54	1.37	3:35	.49
5:38	1.48	8:43	1.28	5:49	.45
7:42	1.49	9:34	1.19	7:38	.41
9:01	1.50	10:29	1.10	9:20	.39

Well 74, line S

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:55 a. m.	0.00	10:38 a. m.	0.84	11:24 a. m.	0.77
6:39	.06	11:59	.85	12:10 p. m.	.76
7:15	.12	1:23 p. m.	.87	12:46	.73
8:04	.18	2:30	.88	1:31	.71
8:49	.24	4:00	.90	2:27	.68
9:42	.28	6:47	.91	3:17	.67
11:32	.36	7:03	.91	4:00	.65
1:06 p. m.	.44	8:03	.93	5:05	.62
2:51	.50	10:03	.94	5:32	.60
4:34	.57	*July 31, 1931*		7:31	.55
5:56	.61			9:37	.51
7:42	.65	12:47 a. m.	.97	11:40	.48
10:26	.69	2:52	.99		
July 30, 1931		5:11	1.00	*Aug. 1, 1931*	
		6:25	.99		
1:19 a. m.	.75	7:15	.95	1:51 a. m.	.46
3:32	.78	7:57	.92	3:37	.44
5:41	.79	8:44	.88	5:50	.41
7:44	.81	9:35	.84	7:39	.37
9:03	.83	10:30	.81	9:22	.35

Well 75, line S

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:57 a. m.	0.00	10:40 a. m.	0.61	11:25 a. m.	0.63
6:41	.02	12:00 noon	.62	12:11 p. m.	.62
7:17	.06	1:24 p. m.	.63	12:48	.61
8:05	.10	2:32	.65	1:47	.58
8:51	.14	4:02	.66	2:30	.57
9:44	.18	6:49	.67	3:18	.56
11:34	.23	7:04	.68	4:01	.55
1:08 p. m.	.30	8:05	.68	5:06	.52
3:52	.34	10:05	.69	5:33	.51
4:38	.39	*July 31, 1931*		7:33	.48
6:00	.42			9:40	.45
7:45	.44	12:51 a. m.	.72	11:42	.42
10:28	.48	2:54	.75		
July 30, 1931		5:13	.76	*Aug. 1, 1931*	
		6:27	.75		
1:22 a. m.	.53	7:17	.73	1:52 a. m.	.40
3:35	.55	7:58	.72	3:39	.38
6:44	.57	8:46	.69	5:51	.35
7:46	.58	9:37	.68	7:41	.32
9:05	.59	10:31	.65	9:23	.31

Draw-down of the water table in observation wells and pumped well near Grand Island—Continued

Well 76, line S

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:59 a. m.	0.00	9:07 a. m.	0.41	9:38 a. m.	0.53
6:43	.01	10:41	.43	10:33	.52
7:19	.03	12:02 p. m.	.44	11:27	.50
8:07	.06	1:26	.46	12:12 p. m.	.50
8:53	.08	2:34	.47	12:49	.49
9:46	.11	4:04	.47	1:25	.47
11:36	.15	5:50	.48	3:19	.46
1:10 p. m.	.19	7:05	.49	4:02	.45
2:55	.23	8:06	.50	5:07	.43
4:40	.26	10:08	.51	5:35	.43
6:01	.28			7:34	.40
7:46	.29	*July 31, 1931*		9:42	.38
10:32	.32			11:44	.35
		12:54 a. m.	.53		
July 30, 1931		2:55	.54	*Aug. 1, 1931*	
		5:16	.55		
1:25 a. m.	.37	6:29	.56	1:54 a. m.	.35
3:37	.38	7:19	.56	5:52	.30
5:46	.39	8:00	.55	7:43	.28
7:48	.40	8:40	.54	9:24	.27

Well 77, line N

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:37 a. m.	0.00	9:10 a. m.	2.41	10:35 a. m.	1.27
6:24	.70	10:44	2.45	11:30	1.18
7:28	1.06	1:27 p. m.	2.50	1:02 p. m.	1.07
8:14	1.24	2:35	2.51	2:50	.94
8:58	1.38	4:05	2.52	3:24	.91
9:52	1.51	5:53	2.55	4:35	.86
11:40	1.72	7:07	2.56	5:08	.83
1:13 p. m.	1.86	8:09	2.57	5:39	.81
3:00	1.99	10:11	2.59	7:38	.73
4:48	2.10			9:50	.65
6:03	2.16	*July 31, 1931*		11:49	.60
8:02	2.23				
10:38	2.31	12:59 a. m.	2.63	*Aug. 1, 1931*	
		2:58	2.65		
July 30, 1931		5:18	2.67	2:00 a. m.	.56
		6:34	2.18	3:45	.53
1:29 a. m.	2.35	7:23	1.86	5:58	.49
3:40	2.36	8:03	1.68	7:45	.45
5:48	2.38	8:52	1.51	9:27	.42
7:50	2.40	9:42	1.38		

Well 78, line N

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:40 a. m.	0.00	10:46 a. m.	1.42	11:31 a. m.	1.03
6:26	.16	12:14 p. m.	1.46	12:17 p. m.	.99
7:31	.35	1:30	1.47	1:04	.94
8:16	.45	2:37	1.48	2:03	.90
9:01	.54	4:07	1.49	2:51	.87
9:54	.63	5:55	1.51	3:25	.83
11:43	.76	7:09	1.53	4:40	.80
1:15 p. m.	.88	8:11	1.54	5:09	.76
3:01	.99	10:13	1.56	5:42	.75
4:44	1.07			7:40	.69
6:10	1.12	*July 31, 1931*		9:43	.62
8:06	1.19			11:51	.57
10:41	1.25	1:03 a. m.	1.59		
		3:00	1.61	*Aug. 1, 1931*	
July 30, 1931		5:20	1.63		
		6:37	1.51	2:03 a. m.	.53
1:32 a. m.	1.31	7:25	1.39	3:48	.50
3:42	1.36	8:07	1.31	5:59	.47
5:50	1.37	8:55	1.23	7:47	.43
7:53	1.39	9:43	1.16	9:28	.41
9:11	1.40	10:37	1.10		

Draw-down of the water table in observation wells and pumped well near Grand Island—Continued

Well 79, line N

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:42 a. m.	0.00	10:48 a. m.	0.78	11:33 a. m.	0.77
6:29	.03	12:16 p. m.	.80	12:19 p. m.	.75
7:33	.11	1:32	.81	1:05	.73
8:19	.15	2:39	.82	2:05	.70
9:03	.20	4:09	.84	2:54	.68
9:57	.25	5:57	.86	3:26	.67
11:45	.32	7:11	.87	4:41	.64
1:17 p. m.	.39	8:12	.88	5:10	.63
3:08	.45	10:15	.90	5:44	.62
4:46	.51			7:42	.57
6:12	.54	*July 31, 1931*		9:55	.53
8:09	.58			11:53	.50
10:45	.63	3:04 a. m.	.94		
July 30, 1931		5:22	.96	*Aug. 1, 1931*	
		6:39	.94		
1:34 a. m.	.68	7:27	.92	2:04 a. m.	.47
3:45	.71	8:09	.89	3:49	.44
5:55	.73	8:56	.86	6:00	.42
7:55	.75	9:45	.83	7:49	.39
9:13	.76	10:38	.80	9:30	.37

Well 80, line N

July 29, 1931		*July, 30, 1931*—Con.		*July 31, 1931*—Con.	
5:44 a. m.	0.00	9:14 a. m.	0.48	10:40 a. m.	0.60
6:31	.00	10:50	.49	11:35	.59
7:35	.05	12:17 p. m.	.50	12:21 p. m.	.59
8:20	.07	1:34	.51	1:07	.57
9:05	.10	2:40	.52	2:06	.56
10:00	.13	4:11	.53	2:56	.54
11:48	.18	5:59	.55	3:27	.54
1:21 p. m.	.22	7:12	.57	4:43	.52
3:10	.26	8:14	.58	5:11	.51
3:48	.29	10:17	.59	5:45	.50
6:14	.31			7:43	.47
8:14	.33	*July 31, 1931*		9:58	.45
10:48	.37			11:56	.42
		1:08 a. m.	.62		
July 30, 1931		3:05	.64	*Aug. 1, 1931*	
		5:21	.65		
		6:41	.66	2:05 a. m.	.40
1:27 a. m.	.41	7:29	.66	3:51	.38
3:47	.44	8:11	.64	6:01	.36
5:58	.44	8:58	.63	7:50	.34
7:57	.47	9:47	.62	9:31	.33

Well 81, line N

July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:46 a. m.	0.00	9:16 a. m.	0.27	10:42 a. m.	0.42
6:32	.00	10:52	.29	11:37	.42
7:37	.01	12:30 p. m.	.30	12:23 p. m.	.42
8:22	.02	1:35	.32	1:09	.42
9:07	.04	2:41	.32	2:08	.42
10:04	.06	4:13	.34	2:58	.40
11:53	.08	6:01	.34	3:28	.40
1:24 p. m.	.11	7:14	.35	4:45	.39
3:12	.12	8:15	.36	5:13	.39
3:50	.14	10:19	.37	5:50	.38
6:16	.15			7:45	.37
8:18	.17	*July 31, 1931*		10:00	.34
10:52	.20			11:50	.34
		1:10 a. m.	.40		
July 30, 1931		3:07	.40	*Aug. 1, 1931*	
		5:25	.42		
		6:43	.43	2.07 a. m.	.32
1:43 a. m.	.23	7:31	.43	3:55	.32
3:50	.24	8:13	.43	6:02	.31
6:00	.25	9:00	.43	7:52	.28
7:59	.27	9:49	.43	9:32	.27

Draw-down of the water table in observation wells and pumped well near Grand Island—Continued

Well 83 (pumped well)

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 31, 1931*—Con.		*July 31, 1931*—Con.	
5:06 a. m.	0.00	10:30 a. m.	1.25	9:30 p. m.	0.66
July 31, 1931		11:07	1.18	11:18	.61
6:30 a. m.	2.38	11:35	1.13	*Aug. 1, 1931*	
7:22	1.87	12:08 p. m.	1.10	12:58 a. m.	.58
7:43	1.74	2:05	.96	4:16	.53
8:15	1.61	3:37	.88	3:35	.51
8:57	1.47	5:05	.81	5:43	.49
9:42	1.35	6:16	.75	7:24	.45
		8:07	.69	8:55	.43

Well 84, line SW

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
July 29, 1931		*July 30, 1931*—Con.		*July 31, 1931*—Con.	
5:50 a. m.	0.00	7:10 a. m.	3.36	9:43 a. m.	1.39
6:09	.06	8:37	3.38	10:33	1.30
6:27	.34	10:01	3.38	11:15	1.20
6:43	.57	11:40	3.41	12:11 p. m.	1.10
7:06	.84	12:24 p. m.	3.42	1:05	1.03
7:30	1.10	1:40	3.44	1:57	.96
8:04	1.40	3:13	3.46	2:39	.92
8:28	1.58	4:34	3.49	3:35	.86
8:53	1.74	6:40	3.60	4:19	.84
9:22	1.90	7:44	3.62	5:19	.79
9:50	2.04	11:50	3.71	7:04	.73
11:04	2.31			8:53	.68
12:07 p. m.	2.48	*July 31, 1931*		11:09	.61
1:45	2.59				
3:18	2.85	1:33 a. m.	3.75	*Aug. 1, 1931*	
4:55	2.97	3:15	3.76		
7:10	3.09	5:29	3.77	1:13 a. m.	.57
9:34	3.19	6:09	3.58	3:10	.52
July 30, 1931		7:07	2.16	5:35	.47
		7:50	1.79	7:13	.44
5:09 a. m.	3.34	8:38	1.60	8:51	.4[illegible]

KEARNEY

Pumping for the test in the Kearney area began at 9:15 a. m., September 22, 1933, and stopped at 9:18 a. m., September 23, 1933. Records of the wells appear in the table on page 129.

Draw-down of the water table in observation wells and pumped well near Kearney

Pumped well

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
Sept. 22, 1933		*Sept. 23, 1933*		*Sept. 25, 1933*	
8:25 a. m.	0.00	12:46 a. m.	10.82	1:05 p. m.	0.0[illegible]
10:10	9.59	3:08	10.92		
11:37	10.01	6:30	11.02		
2:04 p. m.	10.31	8:58	11.00		
3:16	10.36				
5:02	10.54				
7:54	10.72				

Draw-down of the water table in observation wells and pumped well near Kearney—Continued

Well X

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
Sept. 22, 1933		*Sept. 23, 1933*		*Sept. 25, 1933*	
8:28 a. m.	0.00	12:45 a. m.	7.90		0.04
9:31	6.30	3:11	7.99		
10:06	6.68	6:31	8.04		
11:10	6.99	8:59	8.02		
2:03 p. m.	7.36	9:17	8.04		
3:13	7.47				
5:03	7.56				
7:55	7.74				

Well 1, upgradient

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
Sept. 22, 1933		*Sept. 23, 1933*		*Sept. 25, 1933*	
8:33 a. m.	0.00	12:33 a.m.	3.79		0.06
9:50	2.44	3:14	3.87		
11:27	2.89	6:33	3.93		
2:00 p. m.	3.22	9:02	3.97		
3:21	3.35				
5:15	3.46				
8:12	3.63				

Well 2, upgradient

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
Sept. 22, 1933		*Sept. 23, 1933*		*Sept. 25, 1933*	
8:35 a. m.	0.00	12:35 a. m.	2.79		0.06
9:53	1.56	3:16	2.86		
11:28	1.91	6:35	2.93		
1:59 p. m.	2.25	9:03	2.97		
3:23	2.36				
5:16	2.49				
8:14	2.64				

Well 3, upgradient

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
Sept. 22, 1933		*Sept. 23, 1933*		*Sept. 25, 1933*	
8:39 a. m.	0.00	12:37 a. m.	2.28		0.06
9:51	1.17	3:18	2.36		
11:30	1.49	6:36	2.43		
1:58 p. m.	1.78	9:04	2.46		
3:24	1.89				
5:17	2.00				
8:15	2.14				

Well 4, upgradient

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
Sept. 22, 1933		*Sept. 23, 1933*		*Sept. 25, 1933*	
8:43 a. m.	0.00	12:40 a. m.	1.97		0.08
10:00	.96	3:21	2.01		
11:31	1.22	6:38	2.08		
1:56 p. m.	1.49	9:05	2.11		
3:26	1.58				
5:19	1.68				
8:18	1.81				

Well 5, upgradient

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
Sept. 22, 1933		*Sept. 23, 1933*		*Sept. 25, 1933*	
8:45 a. m.	0.00	12:41 a. m.	1.64		0.06
10:02	.73	3:23	1.69		
11:32	.95	6:40	1.74		
1:55 p. m.	1.17	9:06	1.78		
3:29	1.28				
5:22	1.38				
8:20	1.49				

Draw-down of the water table in observation wells and pumped well near Kearney—Continued

Well 1, downgradient

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
Sept. 22, 1933		*Sept. 23, 1933*		*Sept. 25, 1933*	
8:49 a. m.	0.00	12:48 a. m.	3.72		0.06
9:35	2.09	3:26	3.76		
11:39	2.76	6:43	3.83		
2:05 p. m.	3.11	9:09	3.87		
3:01	3.21				
5:04	3.30				
5:10	3.33				
7:58	3.52				

Well 2, downgradient

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
Sept. 22, 1933		*Sept. 23, 1933*		*Sept. 25, 1933*	
8:56 a. m.	0.00	12:50 a. m.	2.73		0.06
9:38	1.33	3:28	2.79		
11:41	1.88	6:45	2.88		
2:07 p. m.	2.17	9:11	2.89		
3:03	2.24				
5:05	2.39				
7:59	2.55				

Well 3, downgradient

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
Sept. 22, 1933		*Sept. 23, 1933*		*Sept. 25, 1933*	
9:01 a. m.	0.00	12:52 a. m.	2.21		0.06
9:40	.95	3:29	2.27		
11:42	1.40	6:46	2.34		
2:08 p. m.	1.67	9:12	2.38		
3:04	1.75				
5:07	1.88				
8:01	2.04				

Well 4, downgradient

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
Sept. 22, 1933		*Sept. 23, 1933*		*Sept. 25, 1933*	
9:04 a. m.	0.00	12:55 a. m.	1.79		0.06
9:42	.63	3:31	1.85		
11:43	1.02	6:47	1.93		
2:09 p. m.	1.27	9:13	1.96		
3:06	1.34				
5:08	1.47				
8:04	1.62				

Well 5, downgradient

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
Sept. 22, 1933		*Sept. 23, 1933*		*Sept. 25, 1933*	
9:06 a. m.	0.00	12:52 a. m.	1.52		0.06
9:44	.41	3:32	1.58		
11:44	.77	6:49	1.65		
2:10 p. m.	1.00	9:14	1.70		
3:08	1.08				
5:09	1.20				
8:07	1.35				

GOTHENBURG

Pumping for the test in the Gothenburg area began at 8:42 a. m., October 1, 1933, and stopped at 8:20 a. m., October 2, 1933. Records of the wells appear in the table on page 132.

Draw-down of the water table in observation wells and pumped well near Gothenburg

Pumped well

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
Oct. 1, 1933		*Oct. 1, 1933*—Con.		*Oct. 2, 1933*	
8:17 a. m.	0.0	2:41 p. m.	10.3	9:45 a. m.	1.90

Well 1, upgradient

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
Oct. 1, 1933		*Oct. 1, 1933*—Con.		*Oct. 2, 1933*	
8:19 a. m.	0.00	2:25 p. m.	4.38	12:29 a. m.	4.96
9:11	3.22	4:15	4.53	3:01	5.05
9:52	3.69	6:30	4.68	6:37	5.13
11:07	4.08	10:26	4.87	8:02	5.16
12:45 p. m.	4.22				

Well 2, upgradient

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
Oct. 1, 1933		*Oct. 1, 1933*—Con.		*Oct. 2, 1933*	
8:20 a. m.	0.00	2:26 p. m.	3.10	12:30 a. m.	3.66
9;13	2.03	4:16	3.24	3:03	3.75
9:53	2.42	6:30	3.39	6:38	3.83
11:08	2.77	10:27	3.57	8:03	3.87
12:46 p. m.	2.93				

Well 3, upgradient

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
Oct. 1, 1933		*Oct. 1, 1933*—Con.		*Oct. 2, 1933*	
8:22 a. m.	0.00	2:26 p. m.	2.25	12:32 a. m.	2.78
9:15	1.29	4:17	2.38	3:04	2.87
9:55	1.62	6:31	2.52	6:40	2.96
11:09	1.92	10:28	2.70	8:04	2.99
12:47 p. m.	2.09				

Well 4, upgradient

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
Oct. 1, 1933		*Oct. 1, 1933*—Con.		*Oct. 2, 1933*	
8:23 a. m.	0.00	2:27 p. m.	1.79	12:35 a. m.	2.32
9:16	.93	4:18	1.93	3:06	2.39
9:56	1.20	6:32	2.06	6:41	2.49
11:10	1.48	10:29	2.24	8:05	2.52
12:47 p. m.	1.65				

Well 5, upgradient

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
Oct. 1, 1933		*Oct. 1, 1933*—Con.		*Oct. 2, 1933*	
8:24 a. m.	0.00	2:28 p. m.	1.36	12:36 a. m.	1.82
9:17	.60	4:19	1.47	3:08	1.90
9:58	.87	6:33	1.59	6:44	2.00
11:11	1.05	10:31	1.75	8:07	2.03
12:51 p. m.	1.21				

Draw-down of the water table in observation wells and pumped well near Gothenburg—Continued

Well 1, downgradient

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
Oct. 1, 1933		*Oct. 1, 1933*—Con.		*Oct. 2, 1933*	
8:27 a. m.	0.00	2:31 p. m.	4.36	12:39 a. m.	4.93
9:20	3.39	4:21	4.51	3:12	5.01
10:00	3.76	6:35	4.66	6:47	5.09
11:21	4.10	10:33	4.84	8:09	5.12
12:53 p. m.	4.20				

Well 2, downgradient

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
Oct. 1, 1933		*Oct. 1, 1933*—Con.		*Oct. 2, 1933*	
8:28 a. m.	0.00	2:32 p. m.	3.09	12:41 a. m.	3.64
9:21	2.22	4:22	3.23	3:13	3.72
10:01	2.52	6:36	3.37	6:49	3.81
11:22	2.82	10:34	3.55	8:11	3.83
12:54 p. m.	2.92				

Well 3, downgradient

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
Oct. 1, 1933		*Oct. 1, 1933*—Con.		*Oct. 2, 1933*	
8:29 a. m.	0.00	2:33 p. m.	2.52	12:43 a. m.	3.05
9:22	1.72	4:23	2.65	3:14	3.12
10:02	1.98	6:37	2.78	6:50	3.21
11:23	2.26	10:35	2.96	8:13	3.24
12:55 p. m.	2.37				

Well 4, downgradient

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
Oct. 1, 1933		*Oct. 1, 1933*—Con.		*Oct. 2, 1933*	
8:30 a. m.	0.00	2:34 p. m.	2.12	12:45 a. m.	2.62
9:23	1.38	4:24	2.24	3:16	2.69
10:03	1.61	6:37	2.36	6:51	2.78
11:24	1.86	10:37	2.54	8:15	3.81
12:56 p. m.	1.98				

Well 5, downgradient

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
Oct. 1, 1933		*Oct. 1, 1933*—Con.		*Oct. 2, 1933*	
8:31 a. m.	0.00	2:34 p. m.	1.63	12:46 a. m.	2.08
9:24	1.00	4:25	1.74	3:18	2.15
10:04	1.18	6:39	1.86	6:52	2.24
11:25	1.33	10:38	2.01	8:16	2.27
12:57 p. m.	1.51				

SCOTTSBLUFF

Pumping for the test in the Scottsbluff area began at 11:53 a. m., November 2, 1937, and stopped at 3:32 a. m., November 3, 1937. Records of the wells appear in the table on page 136.

Draw-down of the water table in observation wells and pumped well near Scottsbluff

Pumped well

Time	Draw-down (feet)
Nov. 2, 1937	
11:14 a. m.	0.00
11:55	11.87
12:15 p. m.	21.06
12:34	21.52
12:50	21.72
1:08	21.89
1:25	22.27
1:31	21.98
1:52	22.05
2:20	22.42
2:31	22.57
2:53	22.32
3:13	22.69
3:30	22.20
3:49	22.32
4:07	22.42
4:31	22.49
4:50	22.57
5:28	22.76
6:20	22.47
7:10	22.59
8:02	22.02
9:03	22.49

Time	Draw-down (feet)
Nov. 2, 1937—Con.	
10:00 p. m.	21.96
11:05	22.69
Nov. 3, 1937	
12:05 a. m.	23.07
1:02	23.09
2:00	22.99
3:09	22.95
4:00	4.01
4:18	2.15
4:33	1.85
5:00	1.51
5:31	1.30
6:12	1.13
7:08	.95
7:56	.85
8:52	.73
10:00	.64
10:55	.57
11:48	.51
12:52 p. m.	.41
2:05	.39
3:00	.37

Time	Draw-down (feet)
Nov. 3, 1937—Con.	
4:01 p. m.	0.33
4:53	.31
5:55	.29
6:58	.27
7:54	.26
8:58	.22
9:58	.21
10:54	.18
Nov. 4, 1937	
12:00 m.	.18
12:57 a. m.	.16
2:00	.16
3:03	.14
3:59	.15
5:05	.14
5:58	.14
7:03	.15
8:00	.15
9:05	.14
10:33	.14
12:14 p. m.	.12
Nov. 5, 1937	
8:52 a. m.	.06

Well 1, upgradient

Time	Draw-down (feet)
Nov. 2, 1937	
11:16 a. m.	0.00
11:56	2.14
12:17 p. m.	4.87
12:36	5.20
12:52	5.39
1:09	5.54
1:26	5.65
1:56	5.72
2:37	5.96
3:15	6.05
3:50	6.13
4:33	6.18
5:30	6.30
6:23	6.35
7:12	6.41
8:03	6.45
9:05	6.49
10:03	6.56
11:06	6.64

Time	Draw-down (feet)
Nov. 3, 1937	
12:08 a. m.	6.61
1:03	6.62
2:11	6.66
3:12	6.64
3:42	3.66
4:03	2.53
4:19	2.12
4:35	1.89
5:01	1.59
5:33	1.38
6:15	1.16
7:10	.93
7:58	.85
8:54	.74
10:02	.63
10:57	.55
11:49	.50
12:54 p. m.	.45
2:08	.38
3:02	.35
4:03	.30
4:54	.30

Time	Draw-down (feet)
Nov. 3, 1937—Con.	
5:58 p. m.	0.29
7:00	.28
7:57	.25
9:04	.22
9:59	.21
10:55	.20
Nov. 4, 1937	
12:02 a. m.	.18
12:59	.17
2:02	.16
3:05	.14
4:01	.14
5:09	.16
6:01	.14
7:05	.15
8:02	.13
9:07	.12
10:35	.12
12:15 p. m.	.12
Nov. 5, 1937	
8:54 a. m.	.06

Well 2, upgradient

Time	Draw-down (feet)
Nov. 2, 1937	
11:18 a. m.	0.00
11:58	1.73
12:18 p. m.	3.04
12:37	3.37
12:53	3.59
1:11	3.78
1:27	3.85
1:57	3.98
2:39	4.15
3:16	4.22
3:52	4.31
4:35	4.35
5:31	4.47
6:25	4.51
7:13	4.59
8:05	4.64
9:06	4.64
10:05	4.73
11:08	4.74

Time	Draw-down (feet)
Nov. 3, 1937	
12:11 a. m.	4.79
1:05	4.80
2:12	4.86
3:16	4.84
3:45	4.99
4:04	2.37
4:20	2.06
4:35	1.86
5:02	1.60
5:34	1.33
6:20	1.12
7:11	.92
8:00	.81
8:55	.68
10:03	.60
11:00	.52
11:51	.49
12:55 p. m.	.43
2:11	.35
3:04	.34
4:05	.29
4:55	.28

Time	Draw-down (feet)
Nov. 31, 1937—Con.	
6:00 p. m.	0.27
7:02	.25
7:59	.23
9:06	.20
10:01	.20
10:57	.17
Nov. 4, 1937	
12:04 a. m.	.17
1:01	.14
2:04	.15
3:07	.13
4:02	.14
5:12	.13
6:03	.13
7:08	.13
8:04	.12
9:08	.11
10:37	.11
12:17 p. m.	.10
Nov. 5, 1937	
8:56 a. m.	.03

Draw-down of the water table in observation wells and pumped well near Scottsbluff—Continued

Well 3, upgradient

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
Nov. 2, 1937		*Nov. 3, 1937*—Con.		*Nov. 3, 1937*—Con.	
11:20 a. m.	0.00	1:06 a. m.	3.97	8:00 p. m.	0.24
12:00 noon	1.38	2:15	4.01	9:03	.23
12:20 p. m.	2.30	3:19	4.03	10:03	.21
12:39	2.51	3:48	2.79	10:59	.18
12:56	2.74	4:05	2.15		
1:13	2.91	4:37	1.65	*Nov. 4, 1937*	
1:28	3.01	5:04	1.43		
2:00	3.15	5:35	1.23	12:06 a. m.	.18
2:40	3.32	6:21	1.05	1:03	.15
3:17	3.40	7:12	.88	2:06	.16
3:53	3.48	8:02	.78	3:09	.15
4:36	3.54	8:57	.68	4:03	.15
5:34	3.65	10:05	.59	5:14	.15
6:27	3.66	11:01	.51	6:04	.16
7:15	3.76	11:53	.48	7:10	.14
8:06	3.81	12:58 p. m.	.43	8:05	.13
9:08	3.85	2:17	.37	9:10	.12
10:07	3.90	3:06	.34	10:38	.13
11:09	3.91	4:09	.29	12:18 p. m.	.11
Nov. 3, 1937		4:57	.30	*Nov. 5, 1937*	
		6:02	.27		
12:12 a. m.	3.97	7:03	.25	8:57 a. m.	.05

Well 4, upgradient

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
Nov. 2, 1937		*Nov. 3, 1937*—Con.		*Nov. 3, 1937*—Con.	
11:25 a. m.	0.00	1:08 a. m.	3.51	8:03 p. m.	0.24
12:03 p. m.	1.25	2:17	3.55	9:11	.21
12:22	1.87	3:22	3.54	10:04	.21
12:41	2.13	3:50	2.35	11:02	.18
12:57	2.29	4:07	1.98	*Nov. 4, 1937*	
1:15	2.43	4:39	1.54		
1:30	2.54	5:05	1.35	12:08 a. m.	.19
2:01	2.68	5:36	1.18	1:05	.18
2:42	2.83	6:24	1.01	2:08	.17
3:19	2.91	7:14	.85	3:12	.15
3:55	3.00	8:03	.76	4:05	.15
4:38	3.07	8:59	.64	5:17	.15
5:35	3.18	10:06	.58	6:06	.14
6:29	3.24	11:04	.48	7:11	.14
7:16	3.28	11:54	.47	8:07	.13
8:08	3.33	1:00 p. m.	.42	9:11	.13
9:10	3.36	2:20	.34	10:39	.13
10:09	3.43	3:08	.34	12:20 p. m.	.13
11:11	3.44	4:10	.29		
Nov. 3, 1937		4:58	.28	*Nov. 5, 1937*	
		6:05	.28		
12:14 a. m.	3.49	7:05	.27	8:58 a. m.	.07

Well 5, upgradient

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
Nov. 2, 1937		*Nov. 3, 1937*—Con.		*Nov. 3, 1937*—Con.	
11:27 a. m.	0.00	1:10 a. m.	2.79	7:08 p. m.	0.24
12:05 p. m.	.81	2:18	2.85	8:05	.23
12:24	1.30	3:25	2.83	9:15	.20
12:42	1.51	3:52	2.03	10:06	.20
12:58	1.65	4:08	1.77	11:04	.17
1:16	1.77	4:24	1.58	*Nov. 4, 1937*	
1:32	1.86	4:41	1.39		
2:03	1.99	5:06	1.25	12:10 a. m.	.17
2:43	2.13	5:37	1.08	1:07	.15
3:20	2.22	6:26	.93	2:10	.16
3:56	2.30	7:16	.77	4:07	.14
4:39	2.36	8:05	.70	5:19	.15
5:36	2.47	9:00	.60	6:09	.14
6:31	2.53	10:08	.54	7:13	.12
7:18	2.57	11:05	.46	8:08	.12
8:10	2.60	11:56	.43	9:12	.13
9:12	2.66	1:02 p. m.	.38	10:41	.11
10:11	2.72	2:23	.33	12:21 p. m.	.10
11:13	2.74	3:10	.32		
Nov. 3, 1937		4:12	.28	*Nov. 5, 1937*	
		5:00	.27		
12:16 a. m.	2.79	6:09	.27	9:00 a. m.	.04

Draw-down of the water table in observation wells and pumped well near Scottsbluff—Continued

Well 6, upgradient

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
Nov. 2, 1937		*Nov. 3, 1937*—Con.		*Nov. 3, 1937*—Con.	
11:29 a. m.	0.00	1:12 a. m.	2.30	9:17 p. m.	0.19
12:07 p. m.	.58	2:21	2.36	10:08	.19
12:26	.93	3:27	2.35	11:06	.18
12:44	1.10	3:53	1.77		
1:00	1.22	4:10	1.53	*Nov. 4, 1937*	
1:17	1.34	4:25	1.39		
1:33	1.40	4:43	1.27	12:12 a. m.	.17
2:05	1.52	5:08	1.13	2:12	.15
2:45	1.66	5:39	.99	4:09	.14
3:22	1.74	6:28	.86	5:23	.14
3:58	1.82	8:07	.66	6:12	.14
4:41	1.87	9:02	.57	7:15	.12
5:38	1.97	10:09	.51	8:10	.12
6:33	1.98	11:07	.42	9:13	.12
7:20	2.08	11:57	.41	10:43	.11
8:12	2.14	1:04 p. m.	.36	12:22 p. m.	.10
9:14	2.14	2:24	.32		
10:13	2.23	3:12	.30	*Nov. 5, 1937*	
10:15	2.24	4:14	.25		
Nov. 3, 1937		6:11	.24	9:01 a. m.	.03
		7:09	.23		
12:18 a. m.	2.30	8:08	.22		

Well 7, upgradient

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
Nov. 2, 1937		*Nov. 3, 1937*—Con.		*Nov. 3, 1937*—Con.	
11:30 a. m.	0.00	1:14 a. m.	1.93	7:12 p. m.	0.24
12:08 p. m.	.39	2:22	1.99	8:10	.22
12:28	.69	3:30	1.97	9:19	.19
12:46	.83	3:55	1.56	10:10	.19
1:02	.94	4:11	1.41	11:08	.17
1:19	1.03	4:27	1.26		
1:34	1.10	4:44	1.15	*Nov. 4, 1937*	
2:07	1.19	5:09	1.03		
2:46	1.32	5:40	.93	12:15 a. m.	.17
3:24	1.39	6:30	.81	1:10	.15
3:59	1.46	7:19	.69	4:11	.14
4:42	1.56	8:10	.62	5:25	.14
5:40	1.62	9:04	.54	7:17	.14
6:35	1.69	10:11	.52	8:12	.13
7:21	1.73	11:09	.41	9:15	.13
8:15	1.78	11:59	.40	10:44	.13
9:15	1.82	1:06 p. m.	.35	12:24 p. m.	.13
10:15	1.86	2:26	.31		
11:17	1.89	3:13	.29	*Nov. 5, 1937*	
Nov. 3, 1937		4:16	.26		
		5:03	.26	9:03 a. m.	.05
12:20 a. m.	1.93	6:14	.24		

Well 8, upgradient

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
Nov. 2, 1937		*Nov. 3, 1937*		*Nov. 3, 1937*—Con.	
11:32 a.m.	0.00	12:22 a.m.	1.63	6:18 p. m.	0.22
12:10 p.m.	.30	2:24	1.66	7:13	.20
12:30	.52	3:37	1.68	8:13	.19
12:47	.62	3:56	1.36	10:12	.16
1:04	.71	4:12	1.21	11:10	.14
1:20	.78	4:28	1.11		
1:34	.83	4:46	1.04	*Nov. 4, 1937*	
2:09	.93	5:11	.93	12:17 a.m.	.14
2:48	1.04	5:42	.85	1:12	.12
3:25	1.09	6:32	.73	2:16	.12
4:00	1.16	7:21	.62	4:13	.12
4:44	1.21	8:12	.57	5:27	.12
5:43	1.32	9:06	.49	6:16	.12
6:39	1.37	10:12	.44	7:18	.11
7:23	1.41	11:11	.36	8:13	.11
8:17	1.48	12:00 noon	.35	10:56	.10
9:17	1.50	1:08 p.m.	.32	12:25 p. m.	.09
10:17	1.55	3:15	.26		
11:18	1.57	4:17	.22	*Nov. 5, 1937*	
		5:05	.22	9:04 a. m.	.05

Draw-down of the water table in observation wells and pumped well near Scottsbluff—Continued

Well X, downgradient

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
Nov. 2, 1937		*Nov. 3, 1937*		*Nov. 3, 1937*—Con.	
10:47 a. m.	0.00	12:05 a. m.	12.62	7:00 p. m.	0.27
11:57	9.35	1:02	12.67	7:55	.25
12:07 p. m.	11.12	1:59	12.63	8:54	.23
12:18	11.62	3:06	12.66	9:59	.21
12:30	11.74	3:45	4.67	10:57	.20
12:44	11.84	4:12	2.39	*Nov. 4, 1937*	
12:59	11.86	4:36	1.92	12:02 a. m.	.18
1:15	12.05	5:00	1.52	12:56	.17
1:56	12.24	5:31	1.32	1:55	.16
2:38	12.31	6:15	1.09	3:01	.15
3:13	12.40	7:08	.98	4:00	.15
3:48	12.42	7:56	.82	5:00	.14
4:34	12.48	8:52	.74	6:01	.14
5:27	12.50	10:00	.62	7:03	.14
6:17	12.57	10:57	.57	8:02	.13
7:10	12.58	11:46	.49	9:20	.13
8:06	12.56	12:52 p. m.	.42	10:36	.13
9:00	12.62	2:00	.39	12:15 p. m.	.11
10:04	12.61	3:02	.37	*Nov. 5, 1937*	
11:00	12.64	3:59	.33	8:52 a. m.	.05
		4:54	.29		
		5:56	.28		

Well 1, downgradient

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
Nov. 2, 1937		*Nov. 3, 1937*		*Nov. 3, 1937*—Con.	
10:49 a. m.	0.00	12:07 a. m.	6.82	4:56 p. m.	0.30
11:59	3.43	1:04	6.89	5:56	.30
12:09 p. m.	4.71	2:02	6.87	7:03	.27
12:20	5.24	3:09	6.92	8:56	.24
12:31	5.42	3:47	3.45	10:02	.21
12:46	5.63	4:14	2.14	11:00	.20
1:00	5.75	4:33	1.81	*Nov. 4, 1937*	
1:17	5.89	5:01	1.51	12:04 a. m.	.18
1:58	6.12	5:33	1.31	12:58	.18
2:39	6.24	6:20	1.10	1:57	.17
3:15	6.34	7:10	.96	4:04	.16
3:50	6.40	7:58	.85	5:03	.15
4:35	6.49	8:53	.74	7:04	.15
5:31	6.56	10:02	.63	8:04	.15
6:20	6.60	10:58	.58	9:22	.14
7:12	6.67	11:47	.52	10:39	.14
8:07	6.69	12:54 p. m.	.44	12:17 p. m.	.11
9:02	6.75	2:02	.41	*Nov. 5, 1937*	
10:06	6.77	3:05	.37		
11:04	6.83	4:00	.33	8:54 a. m.	.06

Well 2, downgradient

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
Nov. 2, 1937		*Nov. 3, 1937*		*Nov. 3, 1937*—Con.	
10:51 a. m.	0.00	12:09 a. m.	4.61	5:57 p. m.	0.31
11:59	1.81	1:06	4.69	7:05	.27
12:10 p. m.	2.61	2:04	4.70	8:00	.25
12:20	2.98	3:10	4.74	9:01	.25
12:32	3.19	3:51	2.35	10:04	.22
12:47	3.38	4:17	1.98	11:01	.20
1:02	3.50	4:36	1.71		
1:19	3.63	5:03	1.48	*Nov. 4, 1937*	
2:00	3.50	5:34	1.30		
2:40	3.97	6:21	1.10	12:06 a. m.	.18
3:16	4.08	7:12	.96	1:00	.18
3:51	4.14	8:00	.85	3:06	.16
4:37	4.23	8:55	.75	5:06	.16
5:35	4.34	10:04	.65	6:06	.15
6:22	4.37	11:00	.59	8:05	.14
7:14	4.42	11:49	.51	9:24	.14
8:09	4.44	12:56 p. m.	.47	10:40	.14
9:04	4.53	2:04	.42	12:18 p. m.	.12
10:07	4.54	3:06	.37	*Nov. 5, 1937*	
11:07	4.63	4:03	.34		
		4:58	.33	8:55 a. m.	.06

Draw-down of the water table in observation wells and pumped well near Scottsbluff—Continued

Well 3, downgradient

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
Nov. 2, 1937		*Nov. 3, 1937*		*Nov. 3, 1937*—Con.	
10:55 a. m.	0.00	12:12 a. m.	3.81	5:59 p. m.	0.29
12:00 noon	1.23	1:07	3.81	7:07	.27
12:10 p. m.	1.88	2:06	3.86	8:03	.34
12:21	2.22	3:14	3.96	9:03	.23
12:27	2.40	3:57	2.25	10:06	.21
12:48	2.56	4:18	1.86	*Nov. 4, 1937*	
1:04	2.71	4:37	1.63	12:08 a. m.	.17
1:20	2.83	5:04	1.42	1:02	.17
2:02	3.04	5:34	1.26	2:01	.16
2:41	3.16	6:23	1.04	3:09	.15
3:18	3.26	7:14	.92	4:08	.14
3:53	3.31	8:01	.81	6:08	.14
4:39	3.41	8:56	.73	7:09	.14
5:37	3.49	10:05	.63	9:25	.14
6:24	3.51	11:01	.56	10:42	.14
7:16	3.59	11:51	.49	12:19 p. m.	.11
8:11	3.64	12:58 p. m.	.45	*Nov. 5, 1937*	
9:07	3.71	2:06	.40	8:56 a. m.	.05
10:09	3.73	3:09	.36		
11:10	3.79	4:04	.34		
		4:59	.30		

Well 4, downgradient

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
Nov. 2, 1937		*Nov. 3, 1937*		*Nov. 3, 1937*—Con.	
10:59 a. m.	0.00	12:14 a. m.	3.28	7:09 p. m.	0.26
12:01 p. m.	.99	1:09	3.31	8:05	.24
12:11	1.45	2:09	3.36	9:05	.22
12:23	1.74	3:15	3.36	10:08	.20
12:36	1.90	4:20	1.72	11:05	.19
12:49	2.05	4:38	1.52	*Nov. 4, 1937*	
1:05	2.18	5:06	1.34	12:10 a. m.	.18
1:22	2.30	5:36	1.19	1:04	.16
2:03	2.50	7:16	.88	2:03	.15
2:43	2.61	8:04	.74	3:11	.14
3:19	2.71	8:57	.70	4:11	.14
3:54	2.77	10:07	.60	5:10	.14
4:40	2.86	11:03	.55	7:11	.14
5:40	2.94	11:53	.48	8:09	.14
6:25	3.00	1:01 p. m.	.43	9:27	.13
7:18	3.03	2:08	.39	12:22 p. m.	.11
8:12	3.09	3:10	.35	*Nov. 5, 1937*	
9:09	3.14	4:05	.33	8:57 a. m.	.04
10:11	3.19	5:01	.29		
11:13	3.24	6:01	.29		

Well 5, downgradient

Time	Draw-down (feet)	Time	Draw-down (feet)	Time	Draw-down (feet)
Nov. 2, 1937		*Nov. 3, 1937*		*Nov. 3, 1937*—Con.	
11:02 a. m.	0.00	12:16 a. m.	2.47	7:11 p. m.	0.26
12:02 p. m.	.56	1:12	2.53	8:08	.24
12:12	.91	2:11	2.53	9:08	.22
12:24	1.10	3:18	2.58	10:10	.20
12:37	1.24	4:03	1.74	11:08	.19
12:50	1.36	4:22	1.53	*Nov. 4, 1937*	
1:06	1.47	4:40	1.36	12:12 a. m.	.18
1:24	1.59	5:07	1.21	1:05	.17
2:04	1.75	5:37	1.09	2:05	.15
2:45	1.84	7:18	.82	3:13	.15
3:20	1.94	8:05	.74	4:14	.15
3:55	1.98	8:59	.66	5:13	.14
4:41	2.09	10:08	.57	7:13	.14
5:43	2.16	11:05	.53	8:10	.14
6:28	2.23	11:56	.45	9:28	.13
8:14	2.23	1:04 p. m.	.42	10:45	.12
9:11	2.38	2:10	.38	12:23 p. m.	.11
10:12	2.40	3:12	.33	*Nov. 5, 1937*	
11:15	2.46	4:07	.32	8:58 a. m.	.03
		5:03	.28		
		6:03	.28		

Draw-down of the water table in observation wells and pumped well near Scottsbluff—Continued

Well 6, downgradient

Time	Draw-down (feet)	Time		Time	Draw-down (feet)
Nov. 2, 1937		*Nov. 3, 1937*		*Nov. 3, 1937*—Con.	
11:04 a. m.	0.00	12:18 a. m.	1.95	5:06 p. m.	0.28
12:03 p. m.	.35	1:14	2.01	7:14	.26
12:13	.59	2:14	2.03	8:10	.23
12:25	.75	3:21	2.06	9:10	.23
12:38	.85	4:05	1.43	10:12	.21
12:52	.94	4:24	1.34	11:10	.20
1:08	1.05	4:41	1.23		
1:27	1.12	5:08	1.13	*Nov. 4, 1937*	
2:05	1.27	5:39	.95		
2:46	1.36	6:29	.51	1:13 a. m.	.18
3:21	1.44	7:20	.78	3:15	.16
3:52	1.49	8:07	.71	4:16	.14
4:42	1.57	9:00	.63	6:22	.14
5:45	1.68	10:10	.53	8:11	.13
6:30	1.71	11:07	.50	9:30	.13
7:23	1.76	11:57	.42	12:24 p. m.	.11
8:16	1.78	1:06 p. m.	.42		
9:13	1.86	2:12	.38	*Nov. 5, 1937*	
10:14	1.87	3:16	.34		
11:17	1.94	4:09	.33	8:59 a. m.	.05

Well 7, downgradient

Nov. 2, 1937		*Nov. 3, 1937*		*Nov. 3, 1937*—Con.	
11:05 a. m.	0.00	12:20 a. m.	1.53	5:06 p. m.	0.25
12:04 p. m.	.17	1:15	1.58	7:16	.22
12:14	.35	2:17	1.59	8:12	.21
12:26	.46	3:23	1.63	9:12	.21
12:39	.51	4:07	1.30	11:11	.18
12:53	.64	4:26	1.18		
1:10	.72	4:43	1.09	*Nov. 4, 1937*	
1:29	.78	5:08	1.00		
2:08	.91	5:40	.91	12:17 a. m.	.15
2:47	.99	6:31	.78	1:10	.15
3:23	1.06	7:22	.72	3:17	.14
4:00	1.12	8:10	.64	5:17	.14
4:44	1.17	9:03	.59	7:17	.13
5:47	1.22	10:12	.49	9:31	.13
6:31	1.30	11:08	.48	12:26 p. m.	.11
7:25	1.31	11:59	.39		
8:19	1.36	1:08 p. m.	.36	*Nov. 5, 1937*	
9:15	1.44	2:14	.35		
10:16	1.44	3:20	.29	9:00 a. m.	.04
11:20	1.51	4:11	.29		

Well 8, downgradient

Nov. 2, 1937		*Nov. 3, 1937*		*Nov. 3, 1937*—Con.	
11:07 a. m.	0.00	12:22 a. m.	1.26	8:14 p. m.	0.18
12:05 p. m.	.13	1:18	1.32	10:19	.17
12:15	.26	2:21	1.33	11:13	.16
12:27	.35	3:26	1.37		
12:41	.42	4:10	1.11	*Nov. 4, 1937*	
12:54	.49	4:28	1.00		
1:12	.56	4:45	.94	1:12 a. m.	.14
1:30	.62	5:10	.87	3:20	.12
2:09	.72	5:42	.80	4:21	.12
2:49	.79	6:33	.68	5:19	.12
3:25	.85	7:25	.63	7:19	.12
4:01	.90	8:12	.55	8:15	.11
4:45	.96	9:05	.52	10:51	.11
5:49	1.00	11:10	.42	12:27 p. m.	.10
6:34	1.06	12:01 p. m.	.33		
7:27	1.09	1:11	.32	*Nov. 5, 1937*	
8:21	1.13	2:16	.26		
9:17	1.19	3:22	.26	9:01 a. m.	.04
10:17	1.20	5:09	.23		
11:22	1.25	7:18	.20		

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