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Pumping Tests on Wells in Iowa[1 2]

By RUSSELL M. JEFFORDS

INTRODUCTION

A systematic investigation of geology and ground-water resources of Iowa has been carried on for many years by the State Geological Survey, more recently in cooperation with the Geological Survey, United States Department of the Interior. The purpose of the current study is to collect and analyze data on the geology and on the occurrence, quantity, quality, and development of ground water throughout Iowa; to assist individuals and municipal, State, and Federal groups in the solution of problems relating to water supply from wells and springs; and to prepare for publication or other distribution such information as is of value to the citizens of Iowa and to the national economy. An important basis for most of this work comprises the study of drill cuttings and related information furnished by well drillers. This informal cooperation by drillers has expanded importantly the knowledge of the geologic and the ground-water conditions in Iowa, and increasingly accurate forecasts are possible as to the rocks that will be encountered in wells and the occurrence and mineral quality of the waters.

There are many types of pumping tests, some that are long and complex involving many observation wells and extended mathematical treatment, and many that are brief production tests. Commonly, however, tests conducted by drillers are intended to demonstrate the yield of the well for the customer and to give some idea as to the correct capacity and setting for the pump. The Geological Survey is requested frequently by drillers, supervising engineers, and municipal officials to assist in pumping tests at the completion of wells in order that data useful to general ground-water studies may be obtained or to plan and conduct areal ground-water studies that involve pumping tests. Although the Geological Survey has neither the funds nor personnel now to send representatives to tests following the completion of all wells in the State, these data, as reported by drillers, are exceedingly useful. When requested, however, representatives are present insofar as practicable for tests where the procedure and features of the installation are such that

[1]Published by permission of H. Garland Hershey, State Geologist and Director, Iowa Geological Survey, and of the Director of the U. S. Geological Survey.

[2]This paper was read at the 1950 session of the Iowa Academy of Science.

general information on the water-bearing formation may be obtained in addition to data on the specific well. The Geological Survey cooperates, moreover, in conducting tests at well installations where estimates of the long-term safe yield are desired. Besides obtaining the yield and drawdown data that are of immediate concern to the driller and owner, geologists attempt to use pumping-test information to determine the hydrologic properties of the water-bearing material or aquifer. These additional data are obtained simultaneously by a more intensive collection and analysis of information on the yield and water levels during a properly planned test. This knowledge, then, may be used at other wells or in the solution of different problems.

Drillers doubtlessly will find that application of the more technical suggestions may not be practical for testing most wells, but certainly the municipal, industrial, and other major wells should be tested carefully for the protection of both the driller and the owner. Essentially all well contractors have developed, through years of practical experience, reliable judgment or more or less empirical methods that permit estimation of the capacities of wells. Such careful evaluation on the basis of observation and experience generally is quite accurate insofar as the experienced driller encounters relatively similar geologic and hydrologic conditions. Major errors may occur, however, when long-term yields are predicted in this way for wells in unfamiliar areas or where conditions differ only slightly. For example, two identically constructed wells that penetrate gravel beds having a similar appearance and thickness may have the same initial yield and drawdown. After several months of similar pumping, however, one well may yield appreciably less water because of differences in the areal extent of the gravels, proximity to recharge areas, or other factors. The methods used by the Geological Survey, on the other hand, may be applied reliably in any area when they are adapted to the many varying conditions. For many well contractors, particularly those guaranteeing specific rates of production after pumping test wells, a moderate amount of study on these techniques should yield important returns.

Inasmuch as most adequately planned and conducted pumping tests cannot give reasonably reliable information on the yield of the well and the most desirable capacity and setting of the pump without also furnishing the fundamental data on the hydrologic nature of the material, the following comments have been prepared to serve as an introductory review of some factors relating to practically all pumping tests and also to explain the use, value, and applicability of the more intensive studies made by representatives of the Geological Survey during some pumping tests. This discussion of technique, however, does not comprise a thorough description of the available methods nor does it provide the necessary background to use and interpret the quantitative methods reliably.

The general principles governing the collection and interpretation of pumping-test data to be reviewed here are based on numerous studies by ground-water hydrologists, principally members of the U. S. Geological Survey. Test data used in the diagrams have been selected from the records of several hundred tests collected by many members of the Geological Survey in cooperation with numerous well drillers in Iowa. Acknowledgment is made to these individuals and to colleagues on the State and Federal Geological Surveys for use of data and for counsel in preparation of this summary.

Occurrence of Ground Water

Below a depth that varies with the climate, topography, and character of the material, many rocks have their pores and other openings completely filled with water, and thereby outline a zone defined by hydrologists as the zone of saturation. This water in the zone of saturation is termed ground water and it supplies the water to wells and springs.

Where the zone of saturation is overlain by permeable materials, the openings are filled with water up to a variable level, and the water level in wells indicates the position of the water table. Where the saturated water-bearing material is overlain by impermeable rocks, as are most aquifers in Iowa, there is no water table and the aquifer is considered to be under artesian rather than water-table conditions. Thus, the water level in a water-table well stands at the depth where it was first encountered, that is at the upper surface of the zone of saturation, whereas under artesian conditions the water level rises, after the water-bearing formation is encountered, to a level above the upper surface of the zone of saturation. The level to which artesian water will rise in a tightly cased well having no discharge is called the artesian-pressure or piezometric surface and to some extent this surface responds to pumpage much as the water table in shallower materials.

When water is pumped from a well, the water level declines so that a gradient is developed toward the well and the depressed water table or artesian-pressure surface, known as the cone of depression, somewhat resembles in form an inverted cone having the apex at the well. The surface area affected thereby is known as the area of influence. As pumping continues, the area of influence increases

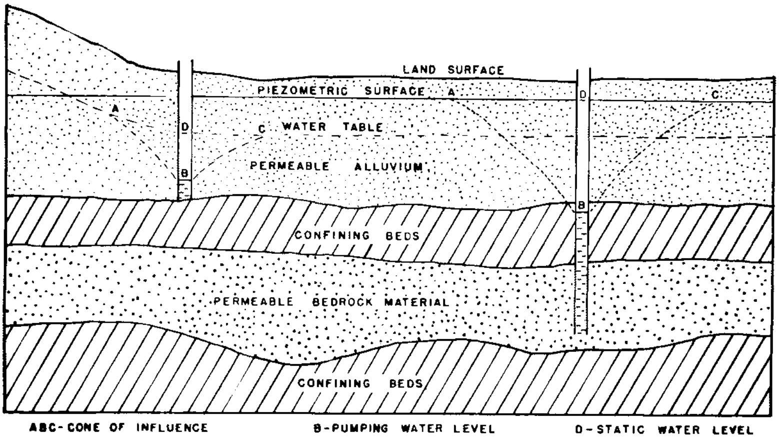

Figure 1. Diagrammatic geologic section showing the occurrence of ground water under water-table and artesian conditions, the water table and artesian-pressure or piezometric surface, and the effect of pumping on these surfaces.

in size and the cone of depression deepens until sufficient recharge is intercepted to balance the withdrawal. The particular condition under which water occurs at a well, however, has an important effect on the area of influence and the cone of depression (fig. 1).

Requirements of Pumping Tests

Inasmuch as the interpretation of a pumping test can be no more reliable or precise than the data obtained and used subsequently in the calculations, a sufficient amount of accurate basic information is necessary.

A carefully recorded log and reliable samples of the material drilled are desirable for the interpretation of the geology at the wells. Also, accurate records of the casing, amount and type of screen, if any, and pump setting are needed. The well should be developed adequately and should be bailed out thoroughly to remove loose cuttings and caved material.

In preparing for a pumping test, provision should be made for measuring the discharge accurately, for maintaining the pump at any desired steady discharge rate, and for determining the water level in the pumped well. Furthermore, the pump and power equipment should be tested briefly one or more days prior to the main test to insure their adequacy and to provide a general idea of the rate of pumping that can be maintained for the test. A sufficient period of time is necessary for the water level to return to static after any preliminary pumping. Careful preparation is very important inasmuch as any variation in the pumping rate or stoppage of the pump will seriously impair the value of the test and may make the data obtained entirely unreliable. Increasing the pumping rate during the last few minutes of a test is particularly injurious inasmuch as it reduces the accuracy of the very useful recovery data.

In addition, all pumpage from nearby wells should either be halted or maintained at a uniform rate, if possible, so that the ground-water levels in the vicinity of the tested well can become stabilized. Wherever practicable, provision should be made to measure the water level in nearby wells during the test. For shallow aquifers, small-diameter drive-point wells are useful as observation wells.

Pumping-test Procedures

Prior to the test, the depth to water in the pumped well and any observation wells is measured accurately at several times to determine the water level or the trend if water-level changes are occurring. After outlining the procedure to be followed during the test and defining the duties of each person participating in the test, the pump is turned on at a recorded time. Periodic measurements are made of the rate of discharge and the water level in the wells starting immediately after pumping begins (fig. 2). Measurements are made frequently with the time interval progressively increased from about one minute or less during the first 10 minutes of pumping when water levels are declining rapidly to 15 or 30 minutes after pumping 4 to 6 hours. Analysis of these data during the test permits intelligent modification of the interval between measurements and also gives indication as to possible defects in the operation of the test or special hydrologic conditions that must be considered.

Determinations of the temperature of the water, collection of samples for mineral analysis, and notes on any solid matter are made whenever time is available.

At the end of the agreed period of pumping or when the collected data are adequate, the pump is shut off at a recorded time, and water levels are measured with the same frequency during recovery as while the well was being pumped. If possible, the recovery measurements should be continued over a period of time equal to the pumping period or until the recovery is complete.

The water-level measurements during pumping tests should be made with an accuracy of 0.1 foot and preferably within 0.01 foot. The time at which measurements are made should be recorded precisely; the uniform spacing of measurements is, within reason, of less importance than the exact time when a measurement is made.

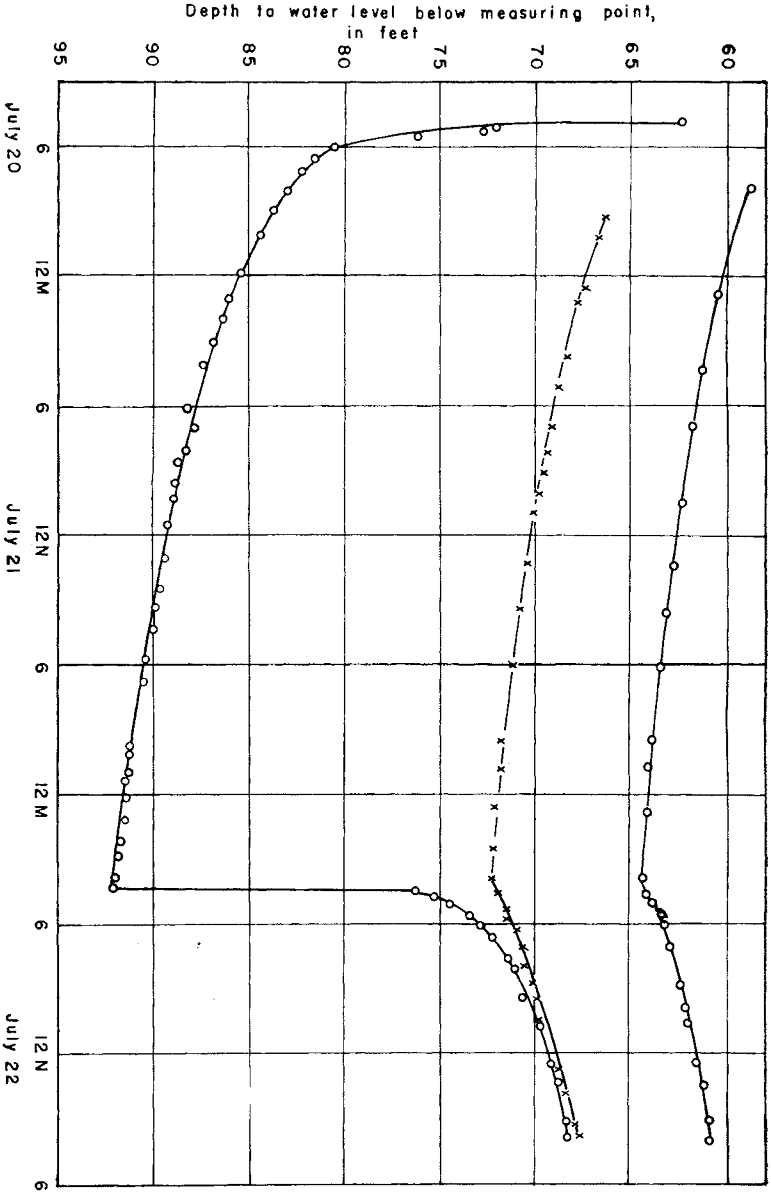

Figure 2. Hydrograph showing drawdown and recovery curves for the pumped well and two observation wells (950 and 1,800 feet from the pumped well) during a pumping test at Cinton, Iowa. Water is obtained from Cambrian sandstones and dolomites at a depth of about 1,950 feet.

METHODS OF WATER-LEVEL AND DISCHARGE MEASUREMENT

Water levels are determined readily for most purposes by using a weighted steel tape having the lower part coated by carpenter's blue chalk. The graduated tape is lowered into the well from a fixed measuring point at the top until the lower end is submerged in the water. The depth to water, then, is the difference between the reading at the measuring point and the length of tape that was wetted. Electrical instruments, which operate on the principle that an electric circuit is closed when an electrode reaches the water surface, may be used advantageously where the depth to water, splash, or other condition prevents reliable and rapid water-level determination by the wetted-tape method. These electric lines are particularly convenient for observing water levels while pumping at deeper wells in Iowa. Air lines and pressure gages are installed on many wells with the permanent pump. When water-level measurements are desired at these wells, air is pumped into the line until it escapes out the lower end and a reading is taken on the gage. This pressure, in feet of water required to force the water out of the air line, subtracted from the length of the air line gives the depth to the water level. Where the gage is calibrated in pounds per square inch, the pressure in feet of water is calculated by multiplying the reading in pounds by 2.31. Many of the gages, however, cannot be read accurately to less than 0.5 foot and few permit readings within 0.1 foot. Erroneous measurements are obtained, moreover, where leaks have developed in the air line or where the length of the line has been determined inaccurately. It is desirable, therefore, to have an opening in the base of the pump so that wetted-tape or electric-line measurements may be taken during pumping tests. The pressure head at flowing wells may be determined by closing the top of the well and observing the pressure by means of a calibrated gage or, if the water rises only a few feet above the surface, by connecting a hose to the well and observing the level at which the flow ceases.

Fluctuations in depth to water or in the pressure at flowing wells may be recorded by means of automatic water-stage recorders and recording pressure gages on the observation wells. These instruments comprise devices for determining the changes in water level or pressure and for recording this on a chart with the aid of a time mechanism. A continuous graph of the fluctuations for any desired period may be obtained in this way.

The discharge of the pumped well should be determined with particular care, inasmuch as this is important in any interpretation of the data. The yield of low-capacity wells may be measured by means of a stop watch and large container of known capacity, but numerous careful readings should be taken. Discharges in excess of about 100 gallons a minute, however, should be measured probably by orifice plate, weir, flume, flow gage, or other reliable technique. Especial attention to the psysical features of the installation are necessary to insure valid observations by any of the methods because seemingly minor deviations may introduce critical errors. The measurement of discharge by an orifice plate at the end of a freely discharging pipe is most common for the larger pumping tests in Iowa, and this seems a convenient and reliable means for testing with temporary pumping equipment. For this type of orifice measure, the discharge pipe must be smooth and kept full; the orifice plate must be sharp, clean, round, accurately milled, and precisely centered; the discharge pipe must be horizontal and extend 4 to 8 feet from any obstruction or bend; the discharge from the orifice must fall freely; and the piezometer tube should be located two feet back from the orifice plate, precisely centered in the horizontal plane, and exactly flush with the interior of the discharge pipe. Readings are taken by means of the piezometer tube, and the discharge value is determined by use of tables. Each of the other methods for measuring the discharge of pumped wells has specific conditions that must be satisfied to obtain reliable results.

Interpretation of Pumping Tests

Most pumping tests give rather obvious information on the yield and drawdown, or difference between the water level before pumping and at a particular time after pumping started and before the recovery is complete, for specific conditions. The significance of these data, however, often may not be as apparent as is assumed commonly, and the conditions at the time of the test may differ importantly from subsequent operating conditions. Accordingly, the Geological Survey attempts to codify the information so that wells may be judged more reliably and the pertinent features compared. Interpretations of pumping-test data can be made for relating the water level and yield during a short period of time to conditions that will result after a considerably longer period.

The many complexities suggest that any broad interpretation of test data should be based on considerable practical experience in wells and geology and with an adequate knowledge of ground-water hydraulics.

Specific capacity. The relation of the yield of a well to the drawdown comprises the specific capacity which is expressed commonly in gallons a minute per foot of drawdown occurring after a

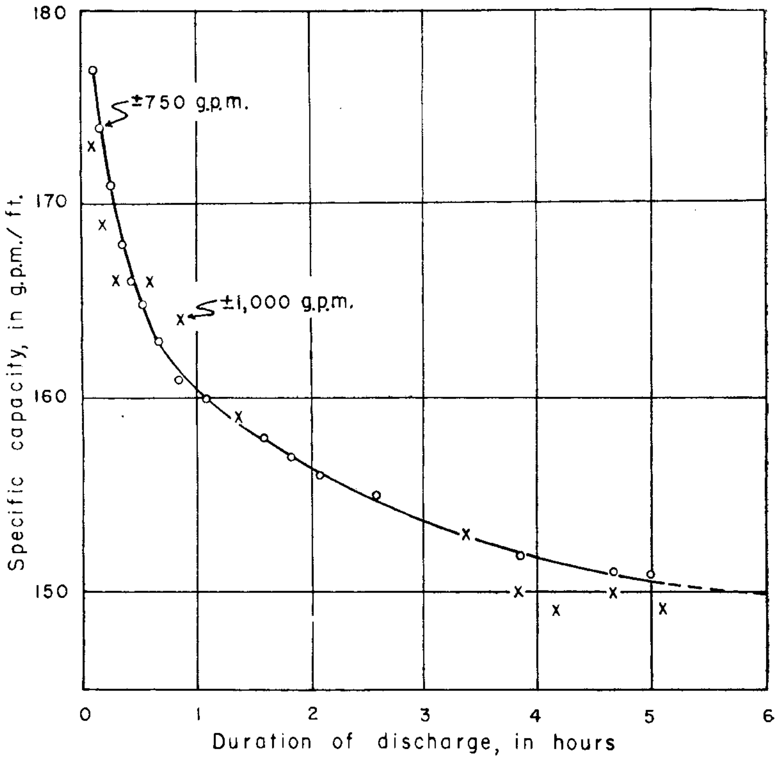

Figure 3. Graph showing relation of specific capacity to length of pumping during two 5-hour pumping tests at a screened well (artesian conditions) in Muscatine, Iowa. The speed of the pump fluctuated somewhat during the test at the higher rate.

given interval of continuous pumping. For example, if a well is pumped at the rate of 100 gallons a minute for 12 hours and the drawdown is 20 feet, the specific capacity is 5 gallons a minute per foot after 12 hours of pumping at 100 gallons a minute.

Inasmuch as water must move an increasing distance to reach the well as the area of lowered water levels or decreased artesian pressure expands, the initial specific capacity and those immediately after period of rest are materially higher than those to be obtained during prolonged pumpage (fig. 3). Accordingly, relatively useful values of the specific capacity can be determined only after pumping has continued at a steady rate for a long period and the drawdown is increasing very slowly. Moreover, the specific capacity of wells varies somewhat with both the duration and rate of discharge so that these data must be included in a statement of the specific yield and considered in an evaluation of the significance. As shown on figure 4, for example, the specific capacity of an artesian well, as calculated reliably on the basis of detailed pumping tests and including the well-loss factor, is about 57 gallons a minute per foot when pumping at 100 gallons a minute for 10 days, whereas the specific capacity after the same period of pumping at 1,000 gallons a minute would be only about 31 gallons a minute per foot.

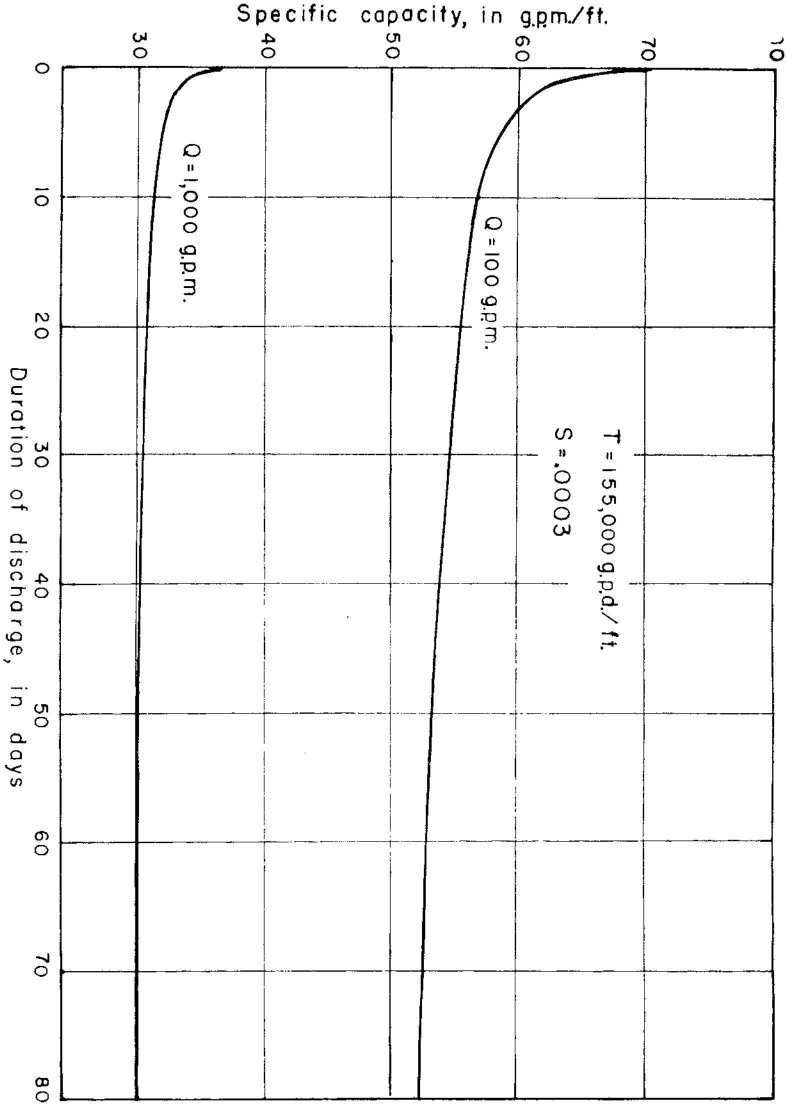

Figure 4. Graph showing relation of specific capacity to length and rate of pumping. Well-loss factor and coefficients of transmissibility and storage are taken from data obtained by Jacobs, 1946. The effective radius of the well is assumed to be 0.8 foot.

Time-drawdown relation. Under normal conditions where the basic assumptions of steady discharge and a completely penetrated extensive aquifer having uniform thickness and permeability are approximated, the drawdown at the pumped well and at other wells nearby increases for a relatively short time and then the rate of increase of drawdown progressively diminishes. For most wells in Iowa, excepting the shallow water-table wells, this gradually increasing drawdown subsequent to the initial period forms a straight line when the drawdowns are plotted against the logarithm of time

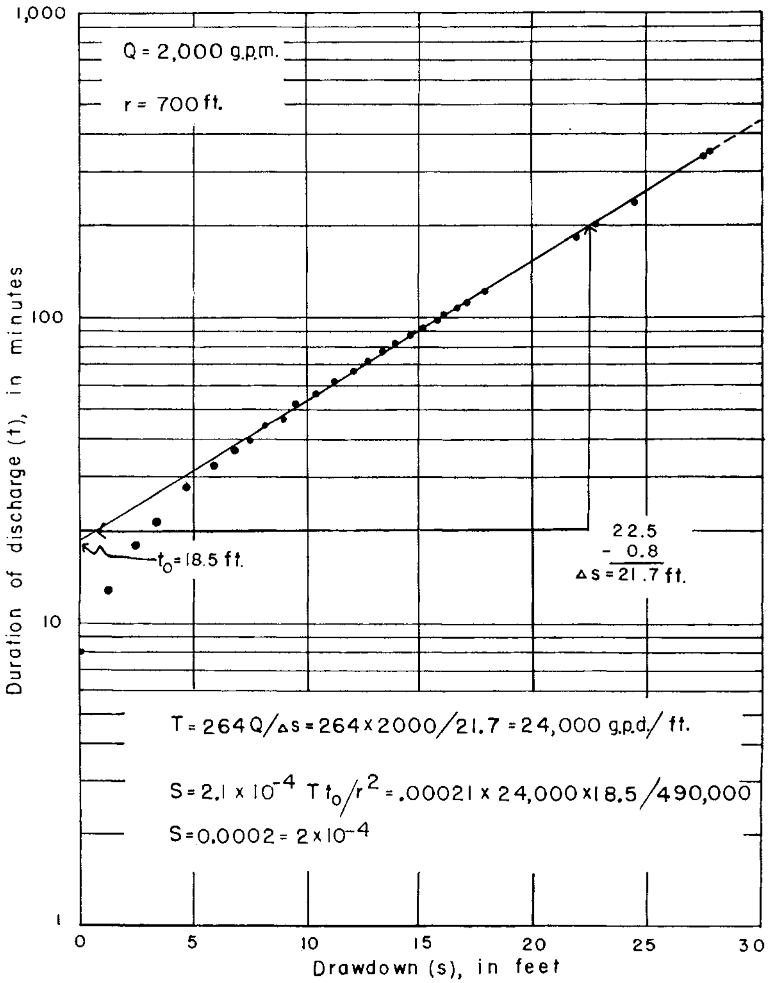

Figure 5. Time-drawdown relation at an observation well 700 feet from a pumped well in the city well field at Dubuque, Iowa. Water is obtained from Cambrian sandstones at a depth of about 1,780 feet. The diagram also illustrates the method for rapid calculation of the coefficients of transmissibility and storage.

since the start of pumping.[2] For example, where the water-bearing formation is relatively extensive and uniform, the plotted points commonly form a curve for a short period immediately following the start of pumping, and then this curve flattens to a straight line (fig. 5).

After several hours of pumping at many wells, the water level declines slowly and unless very accurate measurements are made, it may be concluded that the well has become stabilized and additional declines will not occur. As shown on figure 5, the drawdown is 26.4 feet after five hours of pumping and increases only 0.2 foot in ten minutes. If this trend is continued, however, extrapolation of the time-drawdown line indicates that the drawdown would be 41.2 feet after pumping at the same rate for one day, 56.6 feet at the end of five days, 73.5 feet at the end of one month, and 89.5 feet at the end of six months.

This type of graph showing the time-drawdown relation can be plotted as water levels are determined during a test, and has particular importance in judging the desirable duration of the test and also for other preliminary interpretations. Thus, where the basic geologic assumptions are approximated and the discharge rate is constant, the straight-line relationship between drawdown and time established at the particular discharge rate is persistent. Accordingly, unless marked changes in the nature of the water-bearing formation or the condition of recharge and natural discharge are plausible, a pumping test for the wells penetrating the deeper bedrock formations may be halted shortly after this straight-line relation is established clearly. The drawdown after any selected period of pumping at this rate then may be determined by extrapolation of the plotted points. Obviously, such tests should continue for several hours; but 2- to 4-day tests may not be necessary or desirable except in special cases.

Hydrologic properties of the aquifer. The capacity of the water-bearing formation to transmit water and to yield this water to wells is a critical factor in estimating the value of a well, future yields or drawdowns, well interference, and other problems. Also, these characteristics enter into the estimates of the drawdown should the subsequent discharge rate be different from that during the test. Two of the hydrologic characteristics are the coefficient of transmissibility, or the product of the permeability and the saturated thickness of the aquifer expressed in gallons a day per foot, and the coefficient of storage which is the volume of water in cubic

[2]The use of semi-logarithm graph paper eliminates calculation of the logarithms.

feet that is released from a vertical column of the aquifer having a base one foot square as the water or piezometric level falls one foot. Recent developments in quantitative studies of ground-water reservoirs furnish reliable and relatively rapid methods for determining the hydrologic properties of aquifers. These methods have been applied widely throughout the country during recent years, and the estimates based on them have been reasonably accurate and reliable insofar as the natural geologic conditions could be evaluated in the mathematical treatment. For example, predictions several years in advance of drawdown of more than 125 feet as a result of doubling the pumping rate at Lufkin, Texas, were less than 5 percent in error, and predictions a year in advance of a drawdown of 300 feet proved accurate within 3 percent at South Camp Hood, Texas.

Although the mathematical background and derivation of these hydrologic equations are relatively complex, simplifications that are valid for many wells are convenient to use. Where the drawdown (s) in feet is plotted against the logarithm of the time (t) in minutes since discharge began, and the discharge (Q) is in gallons a minute, the coefficient of transmissibility (T) in gallons a day per foot is calculated by the formula

$$T = 264Q/\Delta s$$

where Δs is the change in drawdown in feet over one logarithmic cycle on the graph. The coefficient of storage (S) is obtained then, when the water-level measurements in an observation well are available, from the equation

$$S = 0.00021\ Tt_0/r^2$$

where t_0 is the time in minutes at the intercept of the plotted straight line on the zero-drawdown line of the time-drawdown graph and r is the distance in feet from the observation well to the discharging well (fig. 5).

These values of the coefficients of transmissibility and storage are of particular importance in comparing the hydraulic properties of water-bearing formations. Moreover, conservative estimates of the extent and amount of drawdown as well as the probable degree of interference with other wells and the yield and drawdown after selected periods of pumping can be made by substituting appropriate values in other hydrologic equations.

The useful general equation[3] is as follows:

$$s = \frac{264Q}{T} (\log 0.3Tt/r^2S)$$

or solving for the yield

$$Q = \frac{sT}{264 \log 0.3Tt/r^2s}$$

where

s = drawdown in feet

Q = discharge in gallons a minute

T = coefficient of transmissibility in g. p. d./ft.

S = coefficient of storage

r = effective radius of the pumped well or the distance from the pumped well to the point where the drawdown is desired, measured in feet

t = time in days

At a well near Muscatine, Iowa, for example, the coefficient of transmissibility was calculated by these methods to be about 420,000 g.p.d./ft. and the coefficient of storage as 0.055. Using these hydrologic constants and assuming a pumping period of 5 hours at about 750 and 1,050 gallons a minute, the theoretical drawdowns at selected distances from the pumped well were calculated. Comparison of these calculated drawdowns with observed water levels in a number of rather closely spaced observation wells after 5 hours of pumping at these two rates (fig. 6) indicates relatively close accord. Similarly, by use of this formula, the drawdown in the vicinity of the pumped well may be calculated for any selected period. These determinations, also, may be used to calculate conditions in the vicinity of the well under different discharge rates than during the test. For example, if a well was tested at 500 gallons a minute and the hydrologic constants were determined, the drawdowns at a higher rate may be approximated (figs. 6-8).

Although these drawdowns are computed without the usual corrections for geologic or hydrologic boundaries, recharge, and local changes in the character of the aquifer, they indicate the general nature of the relations. As indicated on figure 7, the relative drawdowns at the pumped well may not be indicative of drawdowns in the surrounding area, and wells may be spaced more closely for some aquifers than for others, even though the pumpage is the same. Also, for wells pumped at a uniform rate, the drawdown may become essentially stabilized nearby after several days or not for

[3]The inclusion of factors for well loss and for partial penetration is necessary for some studies.

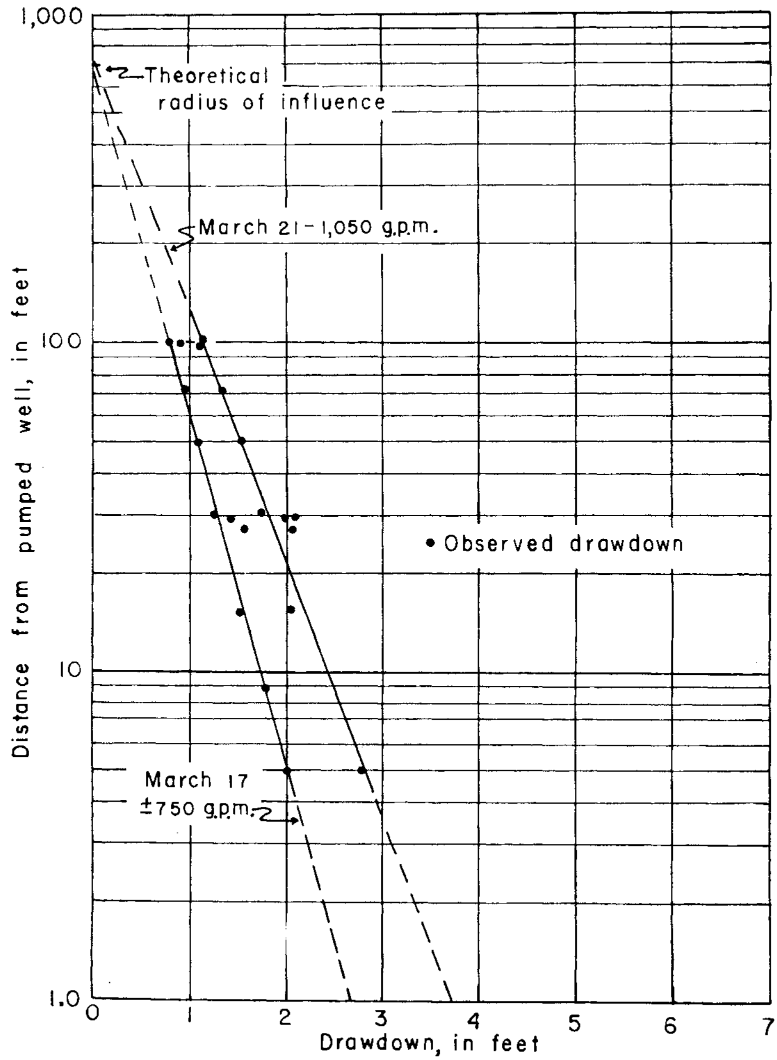

Figure 6. Graph showing comparison of observed and calculated drawdowns in closely spaced observation wells during two pumping tests at about 750 and 1,050 gallons a minute on a screened well (artesian conditions) in Muscatine, Iowa.

many months, depending on the hydrologic properties of the aquifer (fig. 8.). Similarly, as indicated on figure 9, the yield of identically constructed wells penetrating aquifers having different hydrologic properties and pumped at a uniform drawdown reach approximate stabilization at very different rates.

Special Studies and Complexities

Evaluation of drawdown and yield relations is affected markedly by more or less controllable factors such as discharge rates; measurements of the time, drawdown, and rate of discharge; and adequate disposal of the water pumped. Accordingly, changes in pumping rate, shutdowns, or other departures from a rigidly controlled test may induce factors that are extremely difficult or impossible to resolve and may even result in erroneous interpretations. Moreover, these types of studies are based on the assumption that wells completely penetrate the permeable water-bearing formation and that

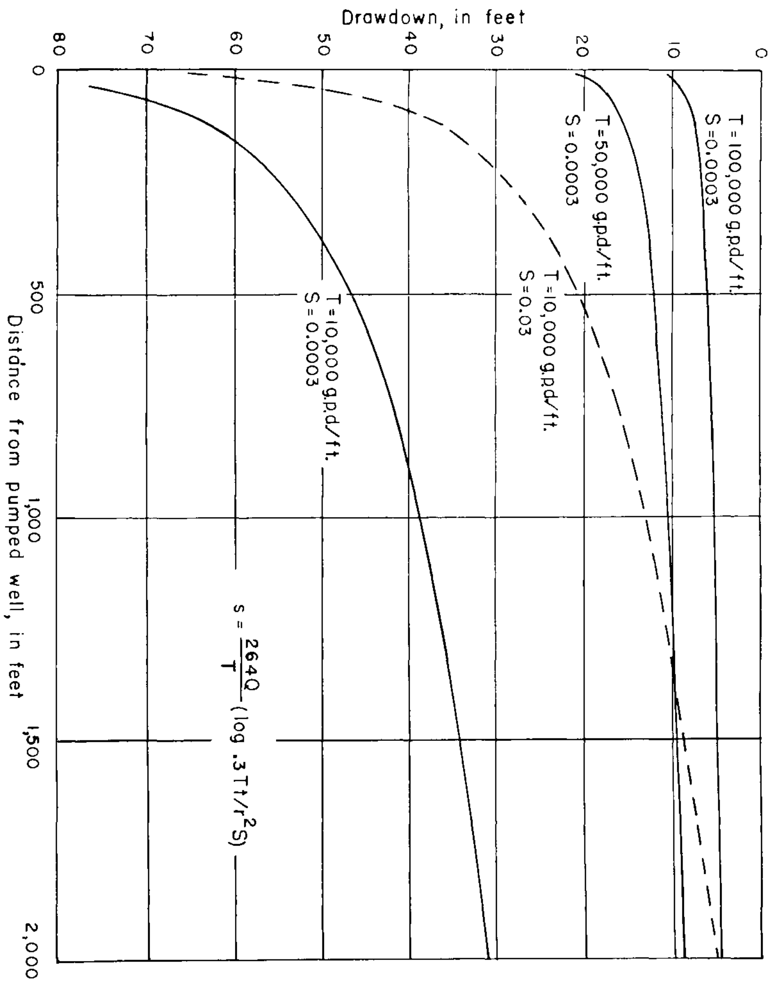

Figure 7. Theoretical drawdowns within 2,000 feet of a well pumped at 500 gallons a minute in an infinite homogeneous artesian aquifer having assumed hydrologic properties after 6 months of constant discharge. Calculations are not adjusted for the effects of recharge or well loss.

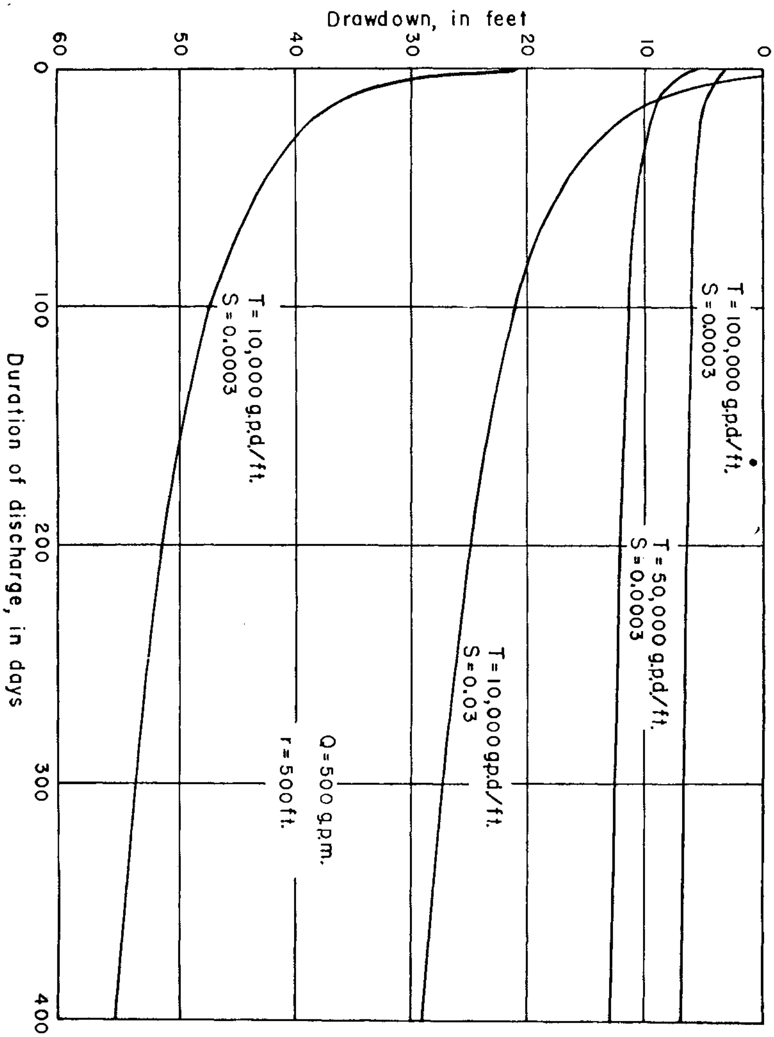

Figure 8. Theoretical drawdowns in a well 500 feet from a well pumped at 500 gallons a minute. Hydrologic properties assumed for an infinite homogeneous artesian aquifer but no adjustments made for effect of recharge or well loss.

this formation is essentially homogeneous and uniform in thickness over a relatively wide area. Although these geologic assumptions are approximated satisfactorily for most important aquifers in the bedrock formations of Iowa, many of the relatively shallow sand and gravel aquifers are small in extent or receive recharge nearby. Accordingly, pumping tests in the unconsolidated materials should be planned especially carefully and measurements should be made very frequently over a long period to permit recognition of the significant local conditions. The rapid inflow of water, as from a stream or pond, results in a marked decrease in the rate of decline of drawdown so that the semi-logarithmic plotting of drawdown against time deviates from the straight-line relation and bends upward (fig. 10). Conversely, a channel-fill of sand and gravel limited on one or more sides by less permeable clay or rock is indicated by an apparent marked increase in the rate of drawdown and a downward bend of the plotted points on the semi-logarithmic graph (fig. 11). Failure to recognize these boundary-type conditions or failure to recognize that the deviations from a straight-line plot are caused simply by changes in pumping rates may result in important inaccuracies in the interpretation of the pumping test (fig. 12).

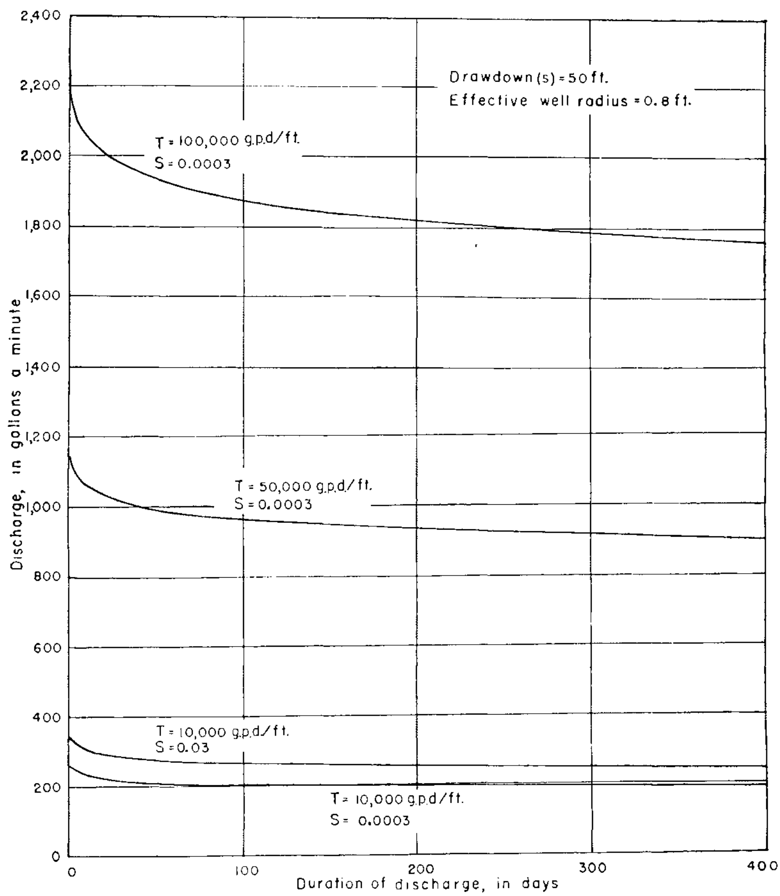

Figure 9. Theoretical relation between yield and length of pumping for wells in infinite homogeneous artesian aquifers having assumed hydrologic properties. The amount of drawdown is assumed to be 50 feet and the well radius to be 0.8 foot. Effects of recharge and well loss are not included.

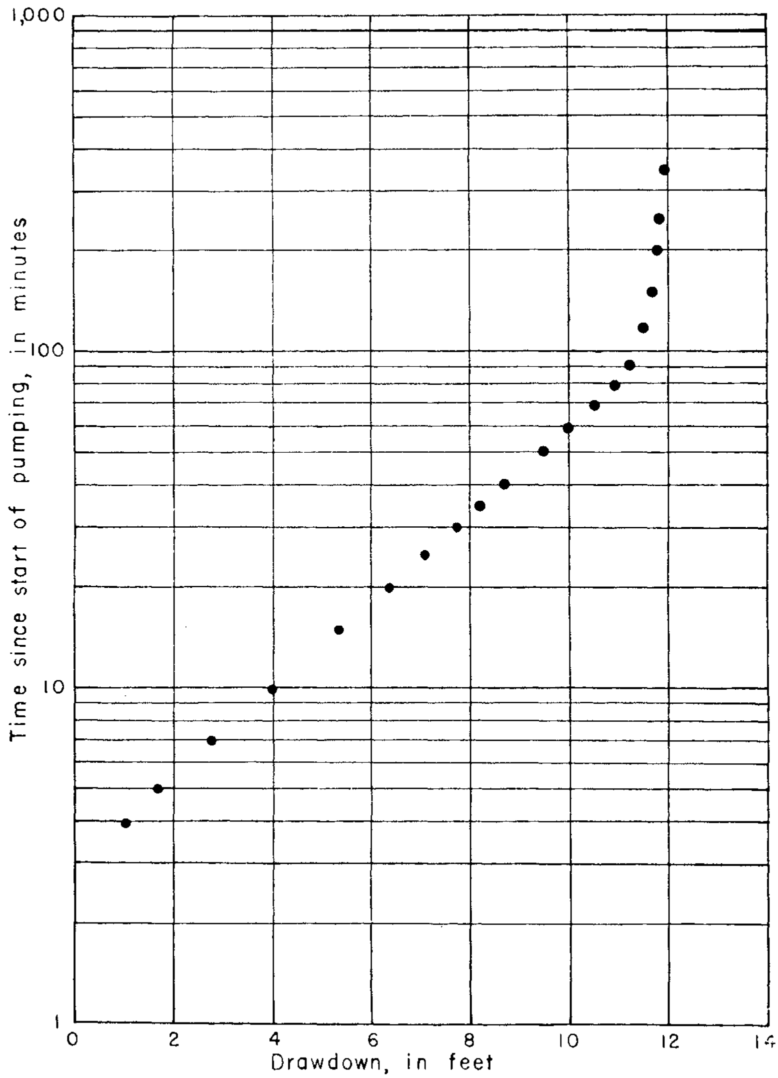

Figure 10. Time-drawdown relation for a well penetrating an aquifer that is receiving direct recharge nearby. Assumed data.

The observed drawdown in a pumped well consists of the drawdown that may be calculated from the hydraulic constants of the aquifer plus the drawdown caused by a factor called the well loss which depends importantly on the ease with which water moves from the aquifer into and up the well. Accordingly, where accurate estimates of the future yields and drawdowns are desired for pumped wells, consideration should be given to multiple-step pumping tests that permit determination of the well-loss factor and effective radius of the well. The test is conducted exactly in the same manner as heretofore described except that pumping is started at a low rate and increased several times by steps. Each increase should constitute a reasonable proportion of the capacity of the well and sufficient time should be allowed for approximate equilibrium to be established at each new discharge rate. Information on the well-loss factor may be particularly useful later if there is need to ascertain whether reduction in yield is due to screen incrustation or mechanical failure, or to check on the effectiveness of attempts to clean out or redevelop wells.

Whereas these comments indicate considerable data that are available by study of the pumped well alone, one of the main hydrologic constants, the coefficient of storage, cannot be determined commonly

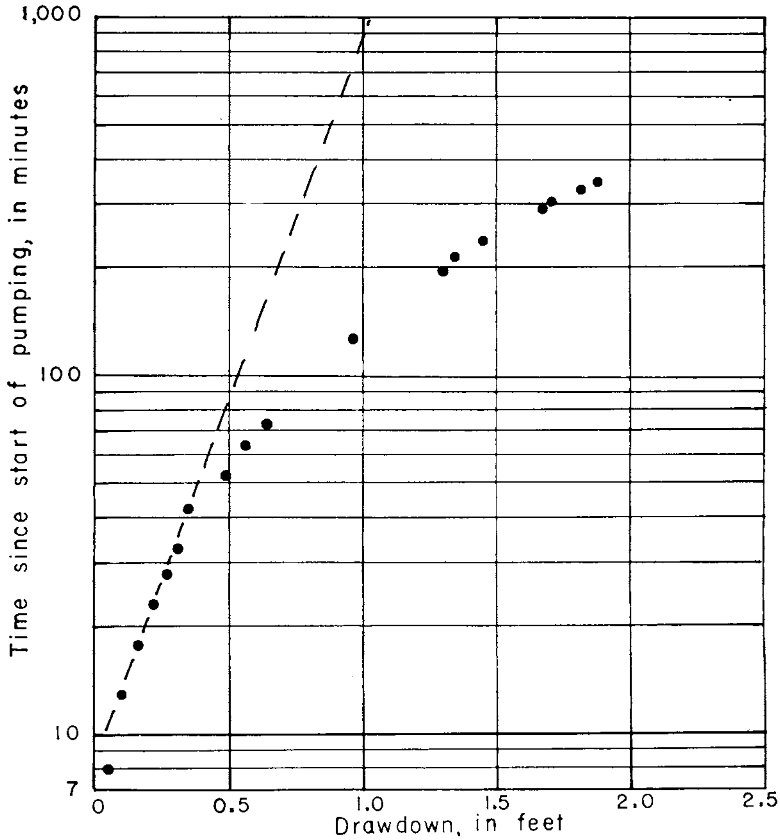

Figure 11. Time-drawdown relation for data from a test at a Fairfield, Iowa, city well that penetrated a gravel aquifer having a markedly restricted extent.

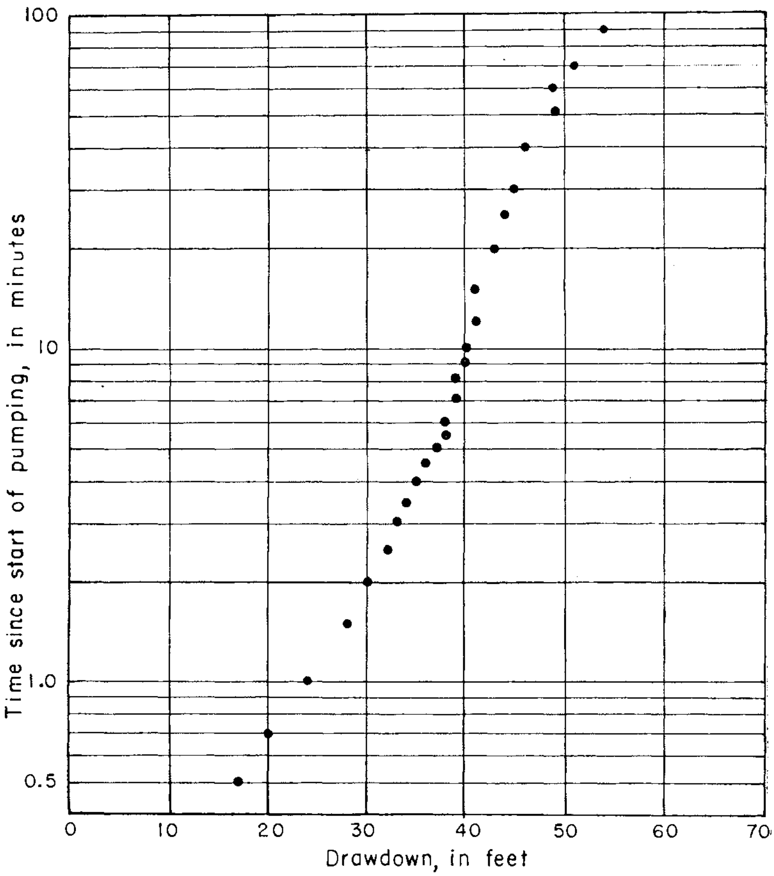

Figure 12. Time-drawdown relations at a moderately deep well where the pumping rate fluctuated during the test. The decrease in the pumping rate after about 7 minutes simulates the effects of recharge.

without water-level data on a nearby observation well. Thus, for most pumping tests provision should be made for one or more observation wells. For deep rock wells, a nearby well may be shut down and arrangements made for a small opening to permit measurement of the water level. Inexpensive drive-point wells are most practicable in the case of shallow gravel wells, and commonly several should be located 30 to 100 feet from the pumped well.

For some shallow wells where the aquifer is partially dewatered under water-table conditions, an adjusted drawdown (s_0) must be used in the formulas instead of the actual drawdown (s), where

$$s_0 = s - (s^2/2m)$$

and m is the thickness of the saturated aquifer.

The field of quantitative studies relating to wells is a recent development, and modifications and improvements of the methods are described frequently. The comments given in this memorandum review some of the elementary principles and techniques; however, there are many other modifications that may be used. Accordingly actual pumping tests in special cases may deviate somewhat from the methods and calculations given here and the interpretations may be complex. Care should be taken, therefore, to avoid misuse of the quantitative data such as may occur when interpretations and calculations are made by those not well grounded in the basic principles of ground-water hydrology and not familiar with the assumptions and limitations inherent in the formulas. A list of some of the many important papers in this field is appended for those interested in increasing their familiarity with quantitative studies.

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