# GEOLOGIC AND HYDROLOGIC ASPECTS OF TEST-WELL DRILLING

by

P. W. Johnson, Natalie D. White, and H. G. Page



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## Introduction

Information on test-well drilling was compiled in 1957 in the esources Div., U. S. Geological Survey, Tucson, Arizona, for use in the training of participants from foreign countries. The data pertain largely to the geologic and hydrologic aspects of test-well drilling and supplement instructions on well-drilling procedures adequately covered by numerous handbooks. The material was reviewed in subsequent years by D. J. Cederstrom and C. R. Murray in the Foreign Hydrology Section, Water Resources Division, U. S. Geological Survey, Washington, for duplication and distribution where requested in the Agency for International Development and related ground-water programs.

## Preparation for Drilling

A number of conditions must be considered before starting to drill a well in order to assure reasonable success.

The location of the well site should be chosen on the basis of the best geologic and hydrologic data available. If there are other wells in the area, a general idea of the conditions at the new drilling site can be gained from the records of these wells. The water levels, depth, diameter, and production of the wells, and the geologic formations penetrated probably can be ascertained. Having these data and knowing the purpose for which the well is to be used and the amount of water needed, the diameter, depth, and method of drilling can be determined. If the well is to be drilled in an area for which there is little or no geologic and hydrologic data, it may be advantageous to consider drilling a small-diameter (4 to 8 inches, depending on the finished size) test hole. The rotary-drilling method would probably give the fastest and most satisfactory results for such a test. If successful, the test hole can be reamed out to the desired diameter. However, if a test hole is not contemplated and data are lacking for the area, the largest size hole and casing compatible with the use of the well and the depth to be drilled should be chosen to assure successful completion of the well. Difficulties in drilling or in driving the casing may necessitate a reduction in hole diameter at depth. Several reductions in a deep hole may reduce the diameter to a size that will not allow the lowering of the pump bowls. Reduction to such a small diameter would limit the usefulness of this part of the well, and for all purposes the drilling of the well should have stopped at the upper reduction point. Cost of farther drilling would be unwarranted.

## Drilling Methods

### Rotary Drilling

Deep holes are drilled ordinarily with rotary-type drilling equipment which involves a motor-driven turntable that holds the drill stem or pipe and bit (fig. 1). This rotating action, aided by the full weight of the drill stem, allows the bit to drill into the rock, crushing and grinding it. Sections of drill pipe are added as the hole is deepened, thus allowing a positive drive and control at any depth. Fluid drilling mud is continuously circulated to the bottom of the hole and returned to the surface by pumping. By this means the hole is conditioned for drilling, friction at the bit is reduced, and the particles of ground rock are carried in suspension to the surface, thereby keeping the hole clean and making continuous drilling possible. The advantages of using this type of drilling equipment are as follows: (1) holes of greater depth can be drilled; (2) drilling can be accomplished in less time; (3) better control of the drilling operation can be maintained; (4) auxiliary equipment of advanced engineering design for rotary drilling is available for obtaining drill-stem tests, cores, electric logs, and other data; and (5) the cost is relatively lower for deep holes. The outstanding disadvantage is the

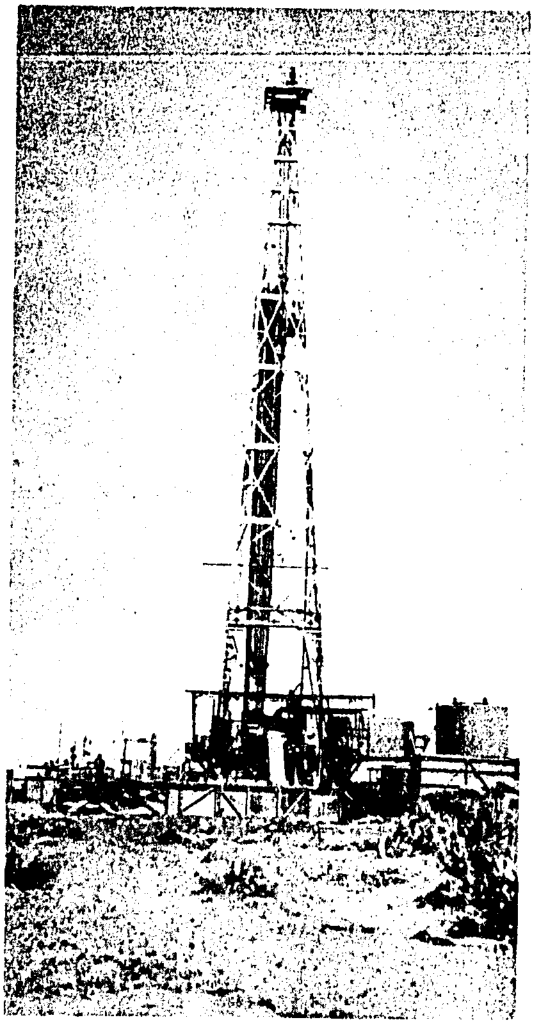

Figure 1. --Photograph showing a rotary-type drilling rig.

relative difficulty of obtaining accurate well-bore cuttings and water samples by this method.

Rotary drilling is particularly unsuitable where losses of circulation are likely, such as in fractured or cavernous limestone. However, proper mud control can overcome many such conditions. Hard rock imposes an excessive bit cost on a rotary operation and in such material, progress may be as slow as the conventional cable-tool operation. Cobble formations (river boulders or glacial till) are particularly difficult to drill by the rotary method.

In a rotary-drilling operation minor amounts of water are shut off by the drilling mud. However, if large quantities of water are encountered it may be necessary to case and cement off the water zones if drilling is to continue.

Some of the problems of rotary drilling, particularly the undesirable introduction of heavy mud into permeable water-bearing formations, are eliminated by the reverse-circulation-rotary method.

## Cable-Tool Drilling

Cable-tool drilling is used mostly for shallow holes and involves a continuous pounding or percussion procedure. A heavy bit, suspended on a cable, is raised and dropped repeatedly by means of a motor-driven jack wheel and walking beam, or some variation of this method. Water is used as a lubricant and drilling medium, and must be supplied to the hole until a sufficient ground-water source is encountered. However, when the ground-water supply becomes overabundant it must be shut off if drilling is to continue. This may be accomplished by running casing into the well and shutting off the water. The hole is cleaned periodically of broken rock particles and mud by means of a bailer. The advantages of a cable-tool rig are as follows: (1) relatively accurate well-bore cuttings can be obtained with ease by this method; (2) thin, but productive, water-bearing zones are easily recognized as the walls of the hole are not plastered with heavy drilling mud; (3) accurate water samples can be taken and simple pumping tests made by bailing; (4) larger diameter holes can be drilled with relatively smaller rigs; and (5) the cost is moderate for shallow holes. A photograph of a cable-tool rig is shown in figure 2. Its outstanding disadvantage is that the rate of drilling is commonly slow but may be compensated for by the accuracy of sampling.

## Special Drilling Techniques

Loss of circulation in rotary drilling using fluids can be eliminated in places by using air instead of fluid.

Drilling in extremely hard rock, which is very slow for the cable-tool machine and costly and difficult for the rotary, can be accomplished rapidly by the recently developed "down-the-hole"

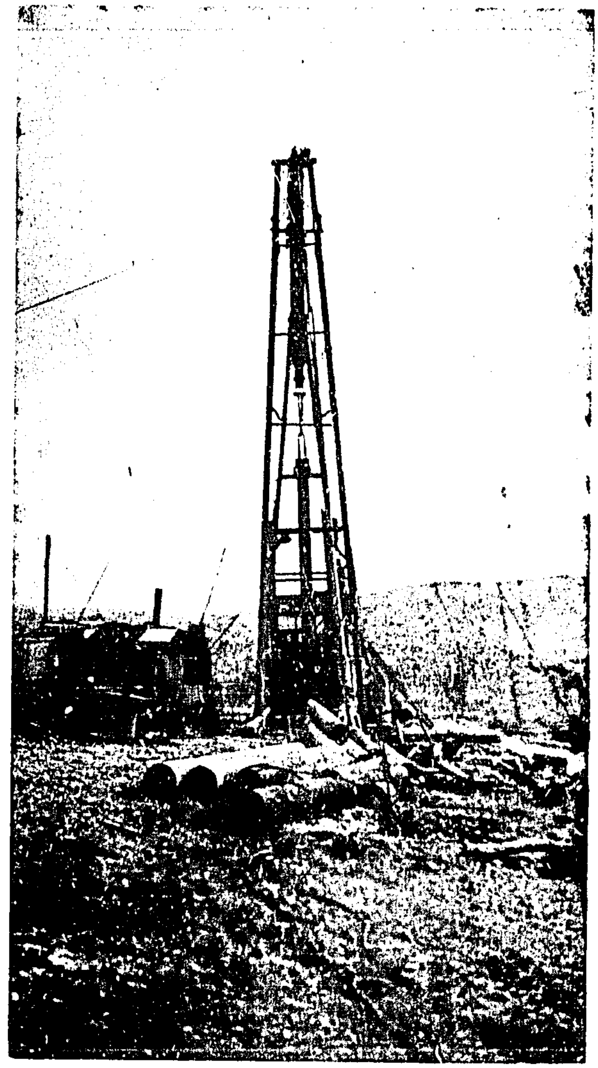

Figure 2. --Photograph shcwing a cable-tool drilling rig.

air-percussion drill.

At present, these must be considered special techniques requiring expensive equipment and specially trained operators. These techniques should be utilized only after considerable study and after it has been demonstrated beyond any doubt that the slower and more conventional methods are impractical.

## Collection of Well-Bore Cuttings and Well Cores

One of the most valuable sources of geologic and hydrologic information is in the collection of well-bore cuttings and well cores. An actual determination of the type of rock penetrated may be made only by this means. Due to the advanced techniques of well logging, there is a tendency to minimize the importance of well samples, but these advanced techniques are only supplemental tools; accurate determination of lithologic character is possible only with actual samples of the formation.

The ideal situation in sampling is to collect representative samples from known depths, at intervals of such frequency as to obtain the complete lithologic character of the formations penetrated. This is best accomplished by the coring method by which a solid piece of the formation in a continuous length is obtained. Such sampling is not beyond the scope of some operations. However, the technique is costly; therefore, its use usually is limited to situations where special subsurface geologic and hydrologic conditions warrant the expense. However, a close approximation of ideal sampling can be achieved by the careful collection of well-bore cuttings. Well-bore sample cuttings are a representative part of the disaggregated formations penetrated and are commonly collected at intervals of 5 to 10 feet, unless change of formation or other conditions warrant a smaller interval.

Samples should be collected from all wells and should be discarded only after deliberate thought and study and generally only where the proximity of other wells has provided similar samples of sufficient depth to furnish ample lithologic and stratigraphic coverage of the area. Therefore, proper preservation and storage of samples should be maintained.

The various means by which well-bore cuttings or well cores are collected will be discussed in relation to the drilling method used.

## Rotary-Drill Sampling

### Well-bore cuttings

The collection of well-bore cuttings from a rotary-drilling operation is difficult, and for many years it was considered impossible to obtain reliable samples by use of this drilling method. To obtain a representative sample from unconsolidated formations by this method still presents a problem. However, because the techniques for collecting samples have been improved, it is now possible to obtain fairly good samples in consolidated formations. Well-bore cuttings are collected by obtaining a sample of the drilling mud after it returns to the surface and before it empties into the settling pit. In recent years, various devices called "shakers" have been designed for the collection of samples at the pit. These devices may vary in method and design, but essentially they are based on the principle of separating by vibration the well-bore cuttings from the drilling mud and collecting the cuttings. Whatever method is used, samples should be collected at regular intervals of from 5 to 10 feet or, in critical zones, at intervals of less than 5 feet. All samples should be washed carefully and thoroughly after they are collected.

The problems involved in the collection of cuttings from a rotary rig are discussed below.

Contamination from upper parts of the well.--The degree of contamination of the sample from upper parts of the well depends largely on the type of material encountered in drilling. Soft formations have a tendency to cave and account for a greater amount of extraneous material entering into the drilling fluid and coming to the surface during the course of circulation. Material from the upper formations will also contaminate the sample when the drilling mud is not sufficiently heavy to cushion the impact of the drill pipe against the walls of the well. Much contamination can be eliminated if the mud pits are of sufficient size to insure the settling of all the particles of the cuttings before the mud is recirculated into the hole. Ordinarily, significant caving does not occur, but if it continues casing of the hole may be required.

Accurate determination of depth of sample. --In order to determine accurately the depth from which a sample is taken, a measurement must be made of the "lag time"—the time required for material to reach the surface after it is collected at depth. Lag time is dependent on: (1) the size of the hole; (2) the condition of the hole; (3) the type of formations penetrated; (4) the type and viscosity of the mud; and (5) the actual depth. Accurate labeling of the sample with the actual depth cut rather than the depth of the well at the time the sample came to the surface can be accomplished only by making periodic checks of the lag time. Measurement of the lag time may be accomplished by placing some easily identifiable substance, such as cut up straw, into the intake drilling-mud pipe, and recording the time required for this material to again reach the surface. Lag time may also be determined by the following procedure: (1) stop the drill; (2) circulate the mud until it is absolutely free from all cuttings; (3) resume drilling for a few inches; (4) stop drilling; and (5) measure the time required for the cuttings to reach the surface. This procedure also has the advantage of furnishing an accurate sample of the formation at the depth of the bit and is generally used where greatest accuracy of sampling is desired. It is impossible to accurately calculate the lag time by any method except actual timing. Changing conditions in drilling will make it necessary to check the lag time frequently. A record of the drilling time at intervals of 10 feet, or less in critical zones, can be an important aid in determining the need for checking the lag time.

Powdering of the sample. --The powdering of a sample to a size which is too small for effective examination under the microscope is due largely to the use of mud of improper quality. It is essential that a rigid control be kept on the type and viscosity of the drilling mud so that the particles of the sample are kept in suspension and brought to the surface without regrinding. On the other hand, the mud must not be so heavy that solid particles will fail to settle in the mud pit and are carried through the system a second or third time. To insure this control, the geologist should work closely with whoever is in charge of the mud.

Loss of the sample. --Sample cuttings may be lost for a number of reasons. In highly fractured or porous zones the drilling fluid may enter fractures or cavities in the formation and fail to return to the surface. When the drill penetrates areas or zones of high hydrostatic pressure, cuttings may be lost by being blown out of the hole. Samples may be lost or partially lost when very thin bedded, fine, or soft material is penetrated. Where soft clays are penetrated, solid particles may not be brought up and good sampling is impossible. Where clayey sands are penetrated, only the sand fraction may remain after washing. Thin beds are penetrated very quickly and the amount of sample is relatively small compared to the extraneous material present in the drilling mud. These beds may go unnoticed, especially if they lie between regular sampling intervals.

Separation of particles.--The relative change in position between the finer particles and the coarser particles of the sample during their upward movement in the circulating fluid is known as separation. For instance, returns from a mixed-gravel formation may be entirely fine sand at first, but after a period of several minutes the coarser element will appear. This problem can be remedied to some extent by the use of proper mud, a heavier mud tending to bring all fractions up together. Too thin a mud will leave a heavy fraction on the bottom to be ground up and "lost." Even under the best conditions some change may occur in the relative positions of the fine and coarse sediments; therefore, it is necessary to take this into account when identifying the sample.

Well cores

One of the advantages of using the rotary-rig method of drilling is the versatility with which it can be adapted to other phases of testing and coring. Well cores can be obtained in at least five general ways— the conventional, diamond-drill, wire-line, reverse-circulation, and side-wall methods. The diameter and length of these cores vary. A conventional core usually ranges from 2-3/8 to 3-9/16 inches in diameter, diamond cores range from 2-7/8 to 4-7/8 inches, wire-line cores range from 1 inch to 2-3/16 inches, side-wall cores range from 1/2 inch to 1-1/2 inches, and reverse-circulation cores range from 2 to 5 inches, depending upon the size of the drill stem. Cores may vary from the 1-1/4-inch length obtained in side-wall coring to the 90-foot length obtained from some diamond coring.

Conventional coring requires a core-barrel assembly fastened to the bottom of the drill string and consisting of a cutter head, outer barrel, floating inner barrel, and a finger-type catcher which retains the core in the barrel when the assembly is raised. The drilling mud circulates down the drill pipe and between the two barrels to the cutting head. The type of cutter used depends entirely on the formation being cored. The length of core accommodated by this assembly is usually 21 feet. Using this method of coring, it is necessary to remove all the drill stem each time to obtain the core. It is possible to obtain a large-diameter core with a maximum percentage of recovery by this method, and the effectiveness of this type of coring has been proven in all but the most abrasive formations.

Diamond-drill coring of small-diameter holes has been used for many years in the mining industry. However, in recent years, full-size diamond and other core bits have been adapted for use with rotary equipment in oil-field and other well-drilling operations. The diamond-core-barrel assembly is much the same in principle as the conventional type, differing only in that the inner barrel is supported on two open ball bearings enabling it to remain stationary while the core is being cut. Diamond bits cut by abrasion, and it is necessary that care be taken to insure proper operational conditions or techniques. Diamond-core drilling involves the use of as little weight as possible on the bit, low pump pressures, and relatively high rotary speeds. Increased weight on the bit tends to fracture the diamonds, and too high pump pressures tend to increase washing of the core and erosion of the bit matrix. Diamond bits are made by setting commercial diamonds into a metal alloy matrix which has been molded into the desired size and shape by a process of heat and pressure. The initial cost of the equipment for this type of coring and the overall cost of operating is high; however, the longer life of diamond bits, the higher percentage of recovery, and the greater length of core—up to 90 feet—make diamond-core drilling a desirable method.

Wire-line coring was developed as a means of securing a core sample without the necessity of removing the entire drill-stem pipe from the hole to recover the core. This, of course, has a distinct advantage, but the addition of surface and subsurface equipment is necessary for this type of operation. Additional surface equipment includes a suitable hoist assembly to lower and raise the wire line. Additional subsurface equipment includes a special core-drill collar bit and core barrel, as well as a wire guide and overshot. This method enables regular drilling to be accomplished alternately with coring, as the core-barrel assembly can be lowered or raised through the drill-stem pipe. Cores up to 20 feet long may be obtained in this manner. It has been found that this type of coring is best accomplished in softer formations, although the recovery usually is not as complete and the cores are of smaller diameter.

The other two types of coring mentioned—reverse-circulation coring and side-wall coring—will not be discussed in detail, as both types are for very specialized and limited instances. The techniques involved are described in "Subsurface Geologic Methods" (LeRoy, 1950, p. 615-619).

## Cable-Tool Sampling

### Well-bore cuttings

The collection of well-bore cuttings from cable-tool wells can be accomplished with comparatively few difficulties. Samples should be collected from the first bailer load when cleaning the hole. The usual sampling interval is 10 feet; however, samples at a 5-foot interval or even a 1-foot interval might be necessary—depending on the type, thickness, and importance of the formations being penetrated. The technique for sampling may be as follows: (1) collect the sample in a pail as the bailer is dumped; (2) drain the sample of excess water; and (3) put it into a sample sack labelled according to the exact depth from which the sample was obtained. However, many formations penetrated will grind up into a mud and very commonly the sample must be washed gently and the water drained two or three times before a sample reasonably representative of the formation is obtained. The remainder, after washing, may be hard-rock chips, unbroken grains of quartz or other granular materials, and pieces of clay which have been torn loose but not mashed into a mud. The mud washed off must be mentally evaluated and noted. This technique is also invariably followed by cable-tool drillers and seems highly satisfactory from the standpoint of hydrologic and geologic investigations.

If formations are not washed free of drilling mud, an incorrect log will be recorded; the samples will cake upon drying and be difficult to use in further studies. Samples collected from cable-tool wells which have penetrated consolidated formations will ordinarily be quite accurate. However, when soft formations are encountered samples may be less reliable unless casing is run into the hole as drilling proceeds. The character of cable-tool samples usually differs with the sharpness or condition of the bit and the hardness of the formation being penetrated. Hard formations require greater cutting time and the repeated pounding by the bit causes a rounding and grinding of the cuttings.

Obtaining accurate samples of water-bearing formations is of greatest importance. The dart valve and flat-flap bailer will not pick up the larger pebbles of the common water-bearing gravel or gravelly sand, and hence the appraisal of the character of the formation may be in error. The "sand pump" or bailer equipped with a plunger rod can exert a forceful suction on loose bottom material and will furnish an excellent sample of very coarse material. Care must be exercised in its use, however, as sudden action will tend to cause the formation to run up the hole. Slow action and maintaining a high head of water in the hole will reduce the hazard inherent in its use.

The mudding off of thin permeable zones is ordinarily considered a hazard of rotary drilling. However, many instances are known where cable-tool drillers have unwittingly passed through thin water-bearing sands or gravels because they failed to keep a clean hole. Careful and constant attention should be given to the danger of carrying down drilling sludge, fine sand, or other material and masking the next lower formation, and to the danger of minor caving masking a lower zone. A clean hole with casing following closely generally is necessary to yield the highly accurate data possible from testing by cable-tool holes.

### Well cores

It is possible to obtain cores with a cable-tool rig, but in order to do so special equipment is needed; therefore, coring is not done frequently with cable tools. (Further information concerning this process may be obtained from Baker Oil Tools Inc., Box 3048, Houston 1, Texas.)

## Examination of Cuttings and Cores

The primary purpose of examining cuttings and cores from wells is to determine the type of rock encountered. This information, and all the details obtainable, may be used further to help ascertain the hydrologic characteristics, the formation name and age of the rock, the structures present, the history of emplacement, the source of its constituents, and the potential natural-resource value of the rock. In addition, some information may be gained about the chemical quality of the water which the rock may store or transmit. For more detailed correlation, the analysis of the cuttings and cores should always be supplemented with all other available data relating to the geology of the area, drilling conditions, and other exploratory tests.

## Methods of Analysis

Some analysis is possible in the field during and immediately upon completion of the collection of the samples or cores. These brief examinations are usually sufficient to determine the type of material being drilled, and to establish the future course of the drilling operation. In the laboratory the samples or cores can be studied in whatever detail is warranted, depending on the nature of the problem.

### Megascopic analysis

The cuttings may be examined with a hand lens (10X) for size, angularity, color, and mineral constituents in the field. From this examination the tentative rock type can be determined. Further testing to determine (1) type of cementation, (2) presence of carbonate rocks, and (3) more specific identification of minerals present can be accomplished through the use of acid, hardness, and other hand-specimen field tests.

In the laboratory similar but more detailed megascopic observations may be made on the cuttings and cores. A binocular microscope with magnification of from 10X to 90X is used, and is here considered under megascopic analysis in contrast to analysis with a petrographic microscope.

Samples may be split and the parts washed free of their normal mud content, and the washed residues may be examined to advantage. Washings may be done in a manner appropriate for recovering foraminifera or other microfossils for further study under the binocular microscope.

## Microscopic analysis

Microscopic analysis is the examination of thin sections or grains submerged in index oils with a petrographic microscope. Thin sections may be made of cuttings, chips, or cores, and grains for examination may be obtained from disaggregated rock pieces or from unconsolidated sediments. This method of analysis is useful in identifying minerals, mineral relations, structures, cement, fossils, roundness of grains, and percentages of minerals of certain grains.

Inasmuch as examination using only the hand lens normally yields the information needed in routine ground-water investigations, the time-consuming microscopic examinations generally are undertaken only to solve special problems. However, microscopic analysis is used widely in other related fields.

## Mechanical analysis

Mechanical analysis is a grain-size analysis of a sample. For application to hydrologic problems, size analysis by sieving and the resulting statistical analysis by histograms, frequency distribution, and cumulative curves, appear to be most satisfactory. In addition to sieving methods, size analysis may be accomplished by microscope, direct measurement, or other methods employing the settling velocity of particles, such as decantation, air or water elutriation, pipette, sedimentation cylinders, hydrometer, and photocell. The information gained from the size analysis includes the average grain size (median), the grain size of the greatest percentage of the sample (mode), the degree of sorting of the grains, the percentage of fine material detrimental to the passage of fluids, and the statistical parameters consisting of the coefficients of sorting, skewness, and kurtosis.

Plotting of data and making calculations of various factors or parameters may be carried to considerable lengths and may be helpful in working out correlations, the origin of the formations, and other geological questions of greater or lesser importance. However, most hydrologists will be interested primarily in the size distribution, as it governs the selection of well screens and determines the necessity of gravel (or sand) packing of wells.

Other analyses

Some of the analyses mentioned above require expensive complex equipment, specialized personnel, or ample time; these may not be available to the average person working on hydrologic problems. However, there are many other simpler tests and analyses useful for various aspects of geologic or hydrologic work—a few of these are discussed briefly below.

Heavy mineral analysis.--There are several methods of separating groups of minerals to facilitate their identification. One of the most satisfactory, from the standpoint of economy and effectiveness, is a separation based on mineral specific gravity, followed by further separation of magnetic minerals. The gravity separation is most effective in a heavy liquid—acetylene tetrabromide (tetrabromoethane) being an excellent one. There are many types of separation apparatus available, but the simple separatory funnels are adequate. Magnetite may then be removed from the heavy minerals, and ilmenite and other moderately magnetic minerals identified by their agitation, with a 12-volt electromagnet. Following separation, the minerals are identified microscopically.

Chemical analysis.--The simplest chemical analysis, usually conducted as a matter of routine on cuttings and cores, consists of a test with dilute hydrochloric acid to determine the relative amount of carbonate present as cement or mineral constituent. This test may be extended to a complete digestion of all HCl-soluble material in the rock sample and calculation of that percentage. The liquor, consisting of the acid of digestion plus rinse water, containing the soluble minerals in solution, then can be analyzed chemically for its constituents.

A specialized group of chemical analyses are stain tests, which involve the application of certain chemicals to minerals, and produce different colors on different minerals. The clay minerals and the pairs—orthoclase:quartz, calcite:dolomite, calcite:aragonite, and anhydrite: gypsum—are some of the minerals differentiated and identified with the aid of stain tests. These tests are not always certain and are seldom used in routine well-sample analysis.

Another technique, similar to, but more detailed than, the stain tests, is microchemical analysis, wherein reactions of minerals to various chemicals are examined microscopically in order to identify the minerals.

Another procedure also useful for identifying minerals is blowpipe analysis. In this process, minerals usually are powdered, mixed with certain chemicals, and burned in the oxidizing or reducing flame of a blowpipe over a gas barner and the reactions noted.

In order to determine its identity, a rock or mineral may in some problems warrant a complete chemical analysis, which is expensive and time consuming, hence seldom employed in hydrologic work.

Specific-gravity determinations. --In a few instances mineral identification may require determination of the specific gravity. There are several methods for this determination; the simplest involves the weight and volume of the specimen in water, using a pycnometer or LeChatelier flask.

Ignition tests. --Burning of samples is sometimes employed to identify hydrocarbons—oil, coal, etc. —which have different colors and leave different types of residue upon burning.

Fluorescene tests. --Oil and various minerals will fluoresce differently under ultraviolet light, and this may be used as an aid to identification.

Pipette analysis. --One relatively simple test, requiring a minimum of extra equipment for the average laboratory, deserves mention as a supplement to mechanical analysis as discussed earlier. This is pipette analysis, a procedure effecting a size analysis of sample material too fine grained to be separated by sieves in ordinary methods. In this method a pipette is used to remove samples of suspended material after the sample is shaken in liquid and allowed to settle for fixed periods of time. Differences in settling velocities depending on particle size are used as a basis for calculating the percentages of very fine particles present after removal from the sample, drying, and weighing.

Porosity and permeability tests.--A number of tests have been devised for determining the porosity and permeability of solid rock and unconsolidated samples. In well samples, cores lend themselves most readily to such tests. All are specialized techniques usually requiring trained personnel. Simpler porosity tests include measuring the volume of water required to saturate a dry sample, specific gravity of a dry sample compared with that of the sample saturated or with that of its constituents, and use of the McLeod porosimeter. Permeability usually is measured by the rate of flow of a fluid (usually water or air) through a column of the sample, using a permeameter of some form.

## Results of Analysis

The immediate result of analyzing samples is a record of the drill hole. The degree of refinement of the data depends largely on the comprehensiveness of the analysis. Several methods are employed to record the character of the geologic column of a well, each useful in its own way, depending upon the detail desired and the purpose for which it is to be used.

### Lithologic logs

One of the more common methods of recording the results of sample or core analysis is a lithologic log. These logs can be made in various ways to give a record of the drilled hole.

Descriptive log.--In the descriptive log each sample from a well is described, usually from top to bottom of the hole. In addition to information that identifies and locates the well, the characteristics commonly noted for each sample include (1) depth, (2) formation name, (3) rock name, (4) grain size and character, (5) mineral composition, (6) color, and (7) nature of cementing materials. Most workers compile these data on a convenient form (fig. 3).

This type of log is relatively easy to compile, file, reproduce, and understand; however, it does not lend itself as readily to a

WELL SAMPLE ANALYSIS

U. S. Geol. Survey, Arizona Ground Water District

Lab No_____ Owner & No____________________ ABCD Loc____________ Sheet___ of_____

Loc____ ¼____ ¼____ ¼ Sec____ T____ R____ County__________ Rig________ Contractor__________ Analyst________

Analysis begun________ completed________ Remarks____________________

| Unit Name | Depth | Rock Name | % (est, calc) | | | Texture | Composition | Color (dry) | Cement or bond (amount) | Driller's name: Log: | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | silt clay | sand | grav | size, round, shape packing, fabric, P & F | % of each (est.calc) | | | | |
| | | | | | | | | | | | |

Figure 3.--Form for descriptive log.

comparison with logs of different holes as other types of logs.

Strip log.--A strip log is usually a 3-inch wide, long strip of thin cardboard, with space at the top for identifying and locating the well being analyzed. The left side of the strip is usually ruled to a given scale representing depth from the earth's surface to accommodate a graphic representation of rock type and depth, while the right-hand part of the strip may be blank for written descriptions or lined for showing graphically grain size, porosity, cores, drilling data, engineering data, etc. Variations in the style and use of the strip log are sufficiently numerous as to make possible the recording of almost any type of information desired, through the use of symbols, colors, and abbreviations.

This type of log is very popular because of the graphic picture it presents, making comparison between holes relatively simple.

Sample-chip log.--The sample-chip log is actually a variation of the strip log; the difference is that it has chips or grains of the well sample glued to the left side of the strip at their represented depths. Any desired information pertaining to the sample may be entered on the right side of the strip.

These logs are excellent for correlation between wells, but present problems in filing. Sometimes they are mounted on wood strips and hung on hooks in rows, similar to garments on a clothes rack.

## Additional Information to be Gained from the Driller

Many times valuable information can be gained from the driller. Many drillers are thoroughly aware of the value of information which can be recorded during the drilling process, and they only need encouragement to keep excellent records that will be most helpful in determining the geologic conditions present. Other drillers may need some training and experience in recording data and in realizing its importance and value.

### Driller's Log

A driller's log is an endeavor on the part of the driller to interpret, record, and tabulate, to the best of his ability, the rock types encountered in the well (fig. 4). Although the descriptive terms used by the driller may not correspond with those of the geologist, the consistent use of the same term for each rock type will lend validity to his log for purposes of correlation, and in any event, his terms commonly can be converted to standard terminology. The geologist should also assess each driller's concept of rock grain size and color perception. A driller's interpretation of the lithology

| | Thickness (feet) | Depth (feet) |
|---|---|---|
| Well location ________ | | |
| Soil .................................. | 8 | 8 |
| Caliche .............................. | 12 | 20 |
| Sand .................................. | 9 | 29 |
| Coarse gravel, boulders, some sand, water .............................. | 31 | 60 |
| Shale .............................. | 30 | 90 |
| Blue shale ............................ | 10 | 100 |
| Cemented gravel ...................... | 15 | 115 |
| Gray lime, water strata ................ | 10 | 125 |
| White lime ............................ | 12 | 137 |
| Gray lime ............................. | 4 | 141 |
| Buff sandstone ........................ | 12 | 153 |
| Brown sandstone, hard .................. | 5 | 158 |
| Sand and gravel, good water zone .......... | 11 | 169 |
| Good sand, gravel and boulders ............ | 26 | 195 |
| Red sandstone ......................... | 15 | 210 |
| TOTAL DEPTH | | 210 |

Figure 4.--Typical driller's log.

in areas where he has drilled many wells can be very useful. In many instances, the driller's log is the only information that is recorded during the drilling of a well; therefore all drillers should be encouraged and helped to the fullest extent possible in this phase of their work.

## Drilling Speed

The speed at which drilling proceeds through various formations is indicative of the rock types penetrated. Each formation has certain characteristics, and observation of the reaction of the drilling machine will indicate the lithologic characteristics and the boundaries of the formations being drilled. For example, a sandy clay will tend to cut smoothly and quickly, a hard nonsandy clay will cut smoothly and slowly, and when penetrating sand the drill stem has a tendency to jump and "chatter." A refinement of visual observation is a systematic time log.

In recent years, the value of accurately recording drilling speed or drilling time has been recognized, and several types of instruments for the purpose of mechanically recording a drilling-time log have come into use. The mechanical recorders that have been developed in the last decade not only accurately record the drilling time or rate of penetration foot-by-foot, but also show additional data such as (1) the depth of the hole to the nearest foot at any time during drilling, (2) the time consumed in making connections, (3) round trips for bit changes, and (4) downtime for repairs.

There are many uses for drilling-time logs. They provide an accurate record for the analysis of operations and the study of downtime. They reflect the types of formations penetrated and their depths. This foot-by-foot information is valuable for correlation purposes and coring operations.

## Record of Water-Bearing Zones

A record of the depths at which water is found in the hole is part of the information needed to determine the hydrologic characteristics of the area being drilled.

The determination of water-bearing zones at various horizons is important to the potential production of the well and the quality of the water. In an effort to record these data, accurate water-level measurements should be made during the course of drilling. These measurements should be made after the rig has been shut down for a period of time sufficient to allow the water in the hole to reach its static level. Periodic measurements will indicate in which zones the water is under artesian pressure, and the zones of greater or lesser permeabilities.

## Casing Record

The driller should accurately record casing data including (1) diameter, (2) number of reductions, (3) accurate position of each string, (4) total depth, and (5) complete description of the screen and its position or the depth and extent of perforated casing. These data are necessary for selection of pumping equipment and must be known if work is done on the well in the future, such as deepening, redevelopment, or other work.

## Well Testing

Several types of testing relating to the quantity and the quality of the water encountered can be conducted during the drilling of a well.

During the course of exploratory drilling by the cable-tool method, much can be learned about the water-bearing characteristics of the formations. Tests of the quantity of water available from the open hole generally will be indicative of the amount of water that might be available from a fully developed well. Such tests are easily made by bailer, cylinder pump activated by the rig, centrifugal pump, or other methods. However, there is danger of pulling in loose sandy formations by vigorous action.

Following a controlled test with a pump or a long bailer test in which the discharge has been carefully noted, recovery of water levels may furnish data for the determination of transmissibility.

Tests on water capacity during the course of rotary drilling are much more difficult to perform and may be much less reliable. Ordinarily, it is necessary to insert a packer (anything from a wrapping of burlap or cut-up inner tube around the lower part of the drill stem to a fabricated expandable packer) above the bit and pump through the drill stem.

In either instance, the success and reliability of the test will depend on the effectiveness of the casing in shutting off water from above the stratum tested and in preventing caving. Therefore, testing for water quantity or securing water samples ordinarily will be easier and more accurate in a hole drilled by the cable-tool method in which the casing follows the hole rather closely. The search for thin permeable strata or any stratum yielding small quantities of water is not too difficult for a skilled and careful cable-tool operator, but may be impossible in a rotary operation. In rotary-test holes the detection of thin or less permeable strata may depend, to a large extent, upon a subsequent electric log.

If possible, water samples should be taken whenever water is encountered during drilling for the determination of the chemical quality. This information will indicate whether the water is potable or whether drilling must proceed further in an effort to find more suitable water. This procedure will also determine the presence of any salt-water zones; these zones can then be cased and cemented off in order to prevent the contamination of fresh-water strata. Conductivity measurements in the well may also be used to determine the zone or zones of poor water that should be cemented off.

In all circumstances, the recording of pumping tests and water sampling should include all data on the total depth of the hole, position of the casing, pumping time, and any other facts pertaining to the physical condition of the well and hydrologic response at the time of the test, in order that the results can be properly evaluated.

If all the above tests are made during drilling and the data collected and recorded from each well drilled in an area, much can be learned about the regional hydrology.

## Well Logging

The main purpose of any type of well logging is to identify the formations traversed by the borehole and the fluids they contain. Well logs should be continuous records, giving complete details pertaining to the type and thickness of the rock encountered.

The geologist uses well logs principally for (1) stratigraphic correlation from hole to hole, (2) lithologic identification, and (3) for the determination of the subsurface geology of an area. It is possible to reconstruct the geologic history of an area through the correlation of a sufficient number of well logs. The types of fluids contained in the rocks, as well as the chemical quality of the water in granular aquifers, can be determined from some types of well logs. In the petroleum industry, production engineers use well logs to identify zones of porosity or saturation in the well which may warrant further testing. These are only a few of the uses for well logs, but they are, perhaps, the ones of most interest.

There are several different methods of well logging in use at the present time in addition to actual study of samples of the material penetrated. The ones to be discussed here include (1) electric, (2) gamma ray, and (3) contact logging.

## Electric Logging

The most efficient and widely used type of geophysical well log is the electric log (fig. 5). This is particularly true if supplementary information is available. The electric log usually consists of several resistivity curves and a spontaneous-potential curve. Every substance or material conducts electricity in varying degrees. Resistivity, being the reciprocal of conductivity, is the property of matter that opposes the flow of electricity. Resistivity depends on the nature of the material and on its temperature; however, for practical purposes, the temperature

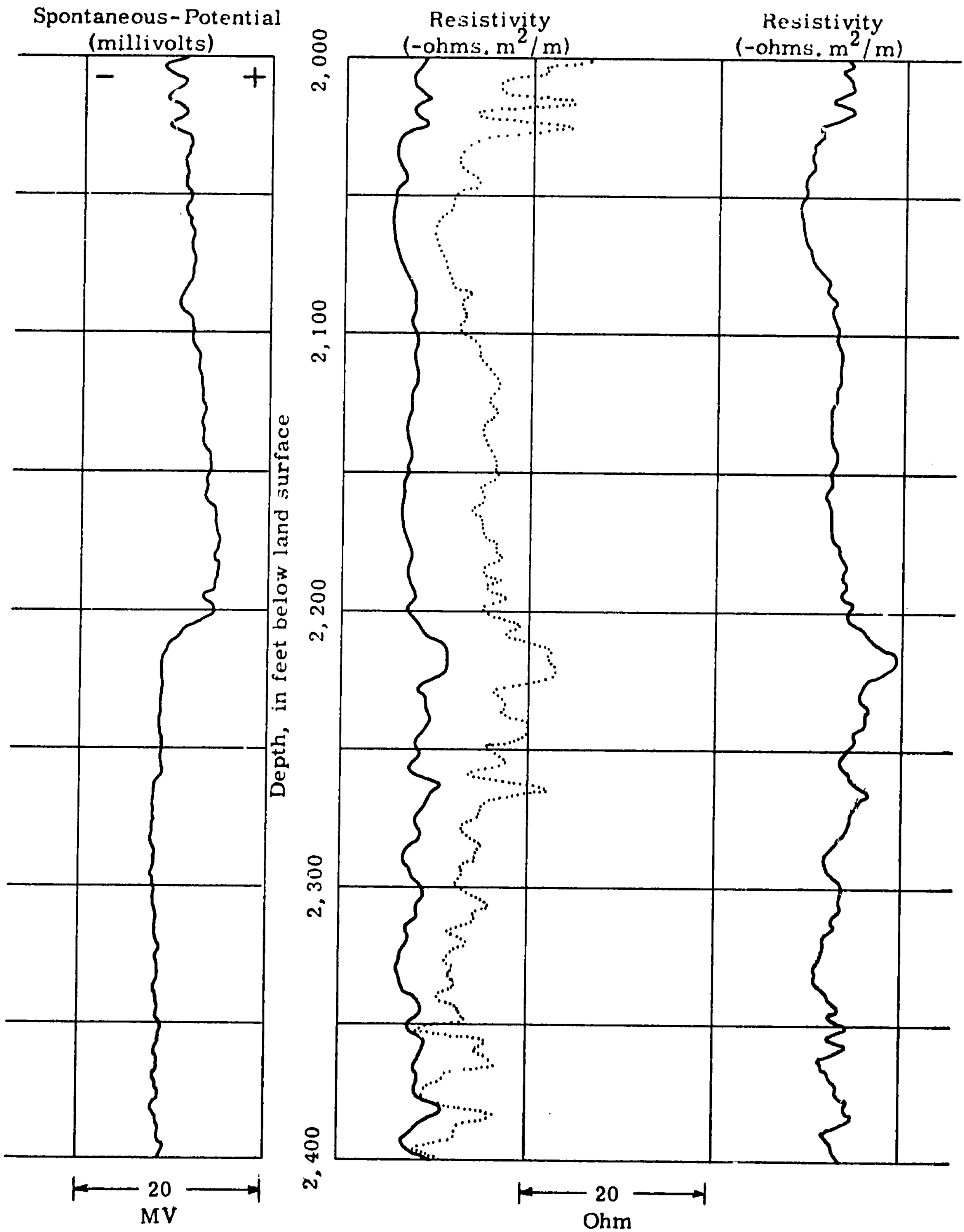


Figure 5. —Segment of an electric log.

has very little effect and generally can be ignored. Therefore, the resistivity-curve part of an electric log is a measurement of the resistance per unit volume of the formations penetrated. Resistivities usually are expressed in ohm-meters, and two or three resistivity curves usually are recorded for each log. The spontaneous-potential (SP) curve is a measure of the natural potentials of electrochemical origin that are encountered in the borehole. These parameters can be measured only in the uncased part of a borehole that is filled with a conductive fluid, usually drilling mud.

The procedure for obtaining an electric log is to lower a system of electrodes, spaced at predetermined intervals, into the borehole on an insulated cable. As the electrode system moves downward in the borehole, electrical currents are emitted from one or more electrodes, creating electrical-potential differences in the formation which are picked up by another electrode and recorded photographically on a film as readings of resistivity or traced directly by pen onto graph paper. As the electrodes move down the borehole, the resistivities of different formations will not cause abrupt changes on the graph exactly opposite the interface between formations; the resistivity curve on the graph will show a gradual transition that extends for a short distance above and below the interface. The measured values are average values or "apparent resistivities," and may be different from the true resistivity values of the various formations. This is due to the influence of factors such as the physical characteristics of the electrode system, drilling-mud resistivity, diameter of the borehole, and thickness of the bed. For this reason, it is the general practice to use several electrode systems, differently spaced and run simultaneously in the borehole, in order to record a combination of resistivity curves. The same electrode system also measures and records the spontaneous- or self-potential curve—a measure of the electrical currents that flow between adjacent dissimilar beds. These currents are natural phenomena that cause changes in the electrical potential of the borehole mud, and are not induced by the electrode system; hence, the term "spontaneous- or self-potential curve."

One of the basic uses of an electric log, as stated previously, is to determine the types of formations which the borehole penetrated. A study of the resistivity and spontaneous-potential curves will serve this purpose. The spontaneous-potential curve may be used to distinguish between permeable zones of sand or gravel and impermeable zones, such as shale, clay, and cemented sandstone. The resistivity curve will differentiate formations according to the water contained in them.

The electric log may be used to determine the upper and lower boundaries of the sand and gravel formations present in the borehole. The electric log will also help to determine which water-bearing formations contain fresh water and which ones contain saline water. A formation that contains no water will have a very high resistivity, and one that contains highly saline water will have a very low resistivity.

An electric log is an additional look at the formations. It is not a substitute for carefully collected samples of earth formations, nor should it be a substitute for accurate testing of water zones for quality and quantity.

The graphical records of the electrical changes that occur as the electrodes move down the borehole require considerable interpretation to be of any significance in terms of hydrologic characteristics. The interpretation of electric logs has received considerable attention in recent years. Many papers have been written on the subject, and further discussion is beyond the scope of this paper. The references listed in the bibliography adequately cover this subject.

## Gamma-Ray Logging

Small quantities of radioactive materials, which emit natural gamma rays in minute but varying degrees, are present in all the earth's substances. The variance in the intensity of gamma-ray emission from the different types of earth materials is the basis for gamma-ray logging. Shale or silt formations emit a higher intensity of gamma rays than sand, sandstone, or limestone formations. Gamma-ray logs can be used to establish geologic correlations between the formations. They are used extensively for this purpose as a supplement to standard electric logs (fig. 6).

One of the chief advantages of the gamma-ray log is that it can be used in a cased hole as well as an open hole, and it is not affected by the type or the lack of drilling mud in the hole. For this reason, gamma-ray logs are particularly useful in providing a means of logging cased wells for correlation with electric logs of nearby wells.

In logging a hole by the gamma-ray process, the recording instrument must be moved slowly in the hole to record an average rate of emission, because the gamma rays are emitted from the formations at random intervals in an erratic pattern. The instrument best suited for recording gamma-ray emissions is the scintillometer, although geiger counters or ionization chambers are used to some extent. However, beds as thin as 2 feet can be defined with a high degree of accuracy with scintillometer equipment.

## Contact Logging

Contact logging has been developed primarily as a supplement to conventional electric logging and operates on essentially the same

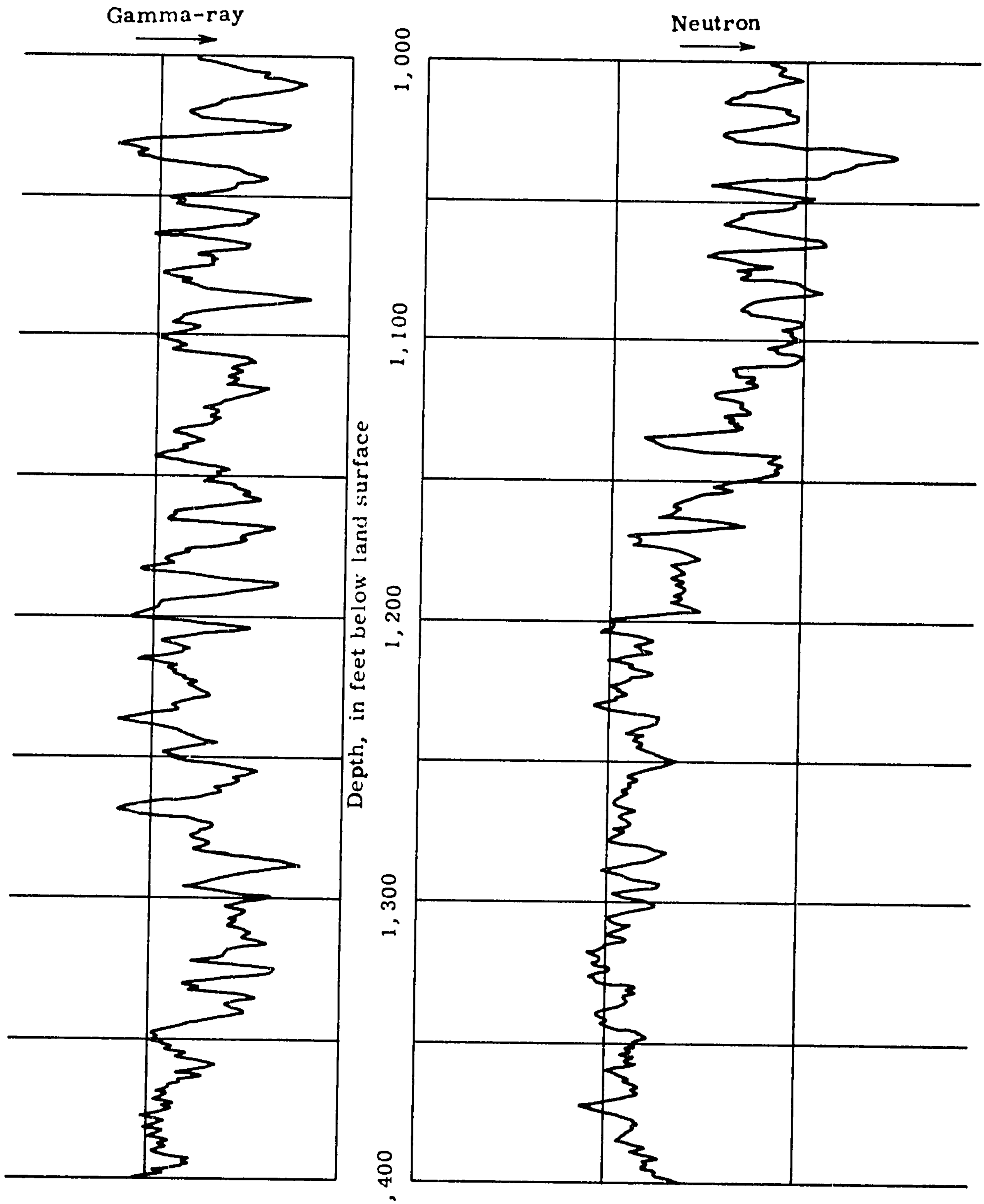


Figure 6. —Segment of a gamma-ray log. (Abscissas indicate intensity of variation.)

principles but on a smaller scale. The contact log is a resistivity log with electrodes spaced at short distances and inserted in a rubber pad that is pressed against the wall of the borehole. It is not necessary for the current from the electrodes to pass through the drilling mud. Two electrode systems with two depths of investigation are used to record two logs simultaneously. These logs are particularly useful for differentiating thin permeable zones within impervious beds where thin permeable zones are less conductive (more resistive) than the drilling mud.

## Other Methods of Logging

Many other methods of logging are being introduced—mostly for specialized jobs. In all instances these logs are a useful supplement to the collection and interpretation of well data. Detailed information on the uses of these various types of logging methods may be found in the references listed in the bibliography.

## Interpretation of Data

The various data collected during the drilling of a well are valuable in any geologic and hydrologic investigation of an area; however, it is the evaluation and interpretation of these data that help to establish the regional characteristics that determine the availability of water in an area.

## Geologic Interpretation

The areal and subsurface geology may be clarified considerably if the character of the geologic section is recorded in a way permitting easy comparison between wells or surface exposures.

### Stratigraphic correlation and differentiation

All types of well logs are very useful as an aid to stratigraphic studies. Vertical identification and differentiation of stratigraphic units or horizons are accomplished by the study of well logs. When well logs are connected in the form of fence diagrams or built-up peg models (dowels or soda straws), they indicate lateral correlations and variations in rock units and assist in the solution of stratigraphic problems.

### Structural indications

The study of well logs may indicate the actual location of faults and joints, the dip of beds, and other structural characteristics. Core samples are particularly useful for showing structural features.

### Geologic history

The geologic history of the area may be reconstructed through the proper study of well logs. Included in this history are the environments of transportation and deposition, or emplacement and paragenesis of igneous rocks, and the type and source area for the rock constituents. Microfossils found in well cuttings may be the only conclusive key to the geologic history of some areas, and, in any event, will furnish additional details of the geologic history. Macrofossils, not usually found in abundance, may furnish still more information on the geologic history.

## Hydrologic Interpretation

The primary goal in drilling a water well is to obtain a permanent supply of adequate water. A thorough knowledge of the geohydrologic characteristics of the area involved will greatly enhance the chances of reaching this goal.

The interpretation of the geologic data has provided a framework on which to interpret the hydrologic data collected during drilling, and, thus, to evaluate the hydrologic characteristics that determine the availability of water. The delineation of the water-bearing zones and the records of the water-level measurements made in the well during drilling, when compared with other well data in the area, may give some information about the occurrence and movement of the ground water and may indicate the presence of artesian or nonartesian conditions. The depth to the water table or the amount of artesian pressure also will dictate the types and sizes of pumps needed to efficiently produce the amount of water desired. The drawdown and recovery data recorded during the drilling of a well can be interpreted into at least a qualitative evaluation of the permeability of the aquifer penetrated. Bailer tests of water-bearing zones at various horizons in the well may indicate the loss or gain of water from one zone to another. Interpretation of the quality-of-water data indicates the suitability of the water for various uses.

The above-described data and methods of analysis may help to determine the production characteristics of individual wells, but in order to fully evaluate the aquifer characteristics further tests should be made as discussed in a later section of this report.

## Well Completion

Well completion is the work that must be performed after the drilling of a well to finish it for subsequent use. It includes setting the casing and cementing or grouting it, selecting and installing the well screen or perforating the well casing at selected zones, gravel packing, and providing for quality-of-water control.

### Setting Casing

The chief purpose of casing is to prevent the collapse of the well wall. Casing also prevents surface drainage from contaminating the water in the well. Aquifers that contain water of poor quality can be closed off with casing.

When the cable-tool method is used to drill a well, casing usually is driven into the well during the drilling process. The casing usually is seated by driving it a few inches into a hard-rock part of the formation to hold it. It should be driven far enough into the rock to shut out all surface water, silt, and sand that might enter the well. The geologic formations penetrated sometimes may determine the amount of casing needed, although generally the well should be cased the total depth.

When the rotary method is used to drill a well, the casing usually is set in the hole after the drilling operation is completed except when surface casing must be set through some of the upper formations before drilling can continue. To run casing into a rotary hole, a sub is attached to the hoisting plug and screwed into a joint of casing. It is then lowered into the hole in the same manner as the drill pipe.

The annular space between the outside of the casing and the drilled hole should be filled by cementing or grouting. The grout is a fluid mixture of cement and water of a consistency that can be forced through the grout pipes and placed as required. The purposes of grouting and sealing the casing in water wells are: (1) to prevent seepage of polluted surface water down along the outside of the casing; (2) to seal out water of poor chemical quality in strata above the desirable water-bearing formation; (3) to make the casing tight in a drilled hole that is larger than the pipe used; and (4) to form a protective sheath around the pipe to protect it from corrosion.

## Well Screens

Wells finished in unconsolidated formations such as sand and gravel prove best when equipped with well screens. A well screen allows water to pass from the aquifer into the well, but at the same time it supports the water-bearing formation and prevents it from caving. The well screen also prevents fine-sand particles from entering the well.

The well screen is a highly specialized piece of equipment and, thus, its selection frequently is a complicated matter. The screen should be made of a metal that will be least subject to corrosion by the type of water in the well. Selection of a well screen of the proper length, diameter, and size of openings for a particular well must be based to a large extent upon knowledge of the characteristics of the water-bearing formation in the well. This knowledge is obtained from an analysis of the well cuttings collected during drilling.

Generally, the diameter of the well screen is the same as the diameter of the well casing. The gradation or grain size of the water-bearing sand or gravel governs the size of screen-slot openings. The relation between the slot size and grain size of the material around the screen greatly influences the development of the formation from which the well draws water, and, thus, the yield of the well may be directly affected by the slot size of the screen. If the openings used are too small, the yield of the well will be limited by inadequate development and cementation soon may close the openings. Openings that are too large require an excessive amount of development and it may be impossible to clear the well of sand. The length of the screen depends primarily on the thickness of the water-bearing formation. For a relatively thin layer, the length should be about equal to the thickness of the water-bearing formation; for a thick formation, the length of the screen should be equal to about half the thickness of the aquifer. The thickness of the zone or zones comprising the aquifer is best ascertained by electric logs.

The best known and simplest way of installing a screen in a well is the pullback method. It may be used in either a cable-tool or a rotary-drilled hole. After the well casing has been sunk to the full depth of the well, the hole is cleaned to the bottom of the pipe with the bailer. The screen is then lowered inside the well casing, using the sand line. After the screen is set on the bottom, the casing is pulled back far enough to expose the screen in the water-bearing formation.

## Perforating the Casing

In some areas well screens are not used. The reasons for this are: (1) the cost of having a well screen designed for a well is appreciable; (2) many drillers and well owners have not yet been convinced of the advantage of using them; and (3) some drillers do not have the technical skills needed to select and install the screens or to develop a well in which a screen has been installed. For these reasons, the practice of perforating or slotting the casing is sometimes used. There are many ways in which the perforating is done. Many times the slots are cut with an acetylene torch before putting the casing in the hole. In some ways this method is the best because the size and the placement of the perforations can be controlled. Another method is to cut the slots in the casing after it is put into the well. A special tool—usually a Mills knife—is used to slash the casing at the desired depth. This method is probably cheaper because it takes less time but there are some disadvantages. The metal from the cut is curled outward toward the wall of the hole and may provide an effective trap which, when filled with sediments, will keep the water from going into the well. The spacing or size of the cuts cannot be fully controlled. The size of the cut in many instances is much larger than it should be for the fine-grained sediments that compose the aquifer. This condition limits the development of the well.

The casing can also be perforated while in the hole by the shot method. While this method is commonly used in oil wells, it is rarely used in water wells. The method is more readily adapted to rotary drilling and requires special equipment which shoots off at the same time numerous bullets that perforate the casing around its circumference. The size of the shot holes cannot be varied greatly, and again, where the aquifer is composed of fine-grained sediments, the chances for fully developing the well may be limited.

## Gravel Packing

The practice of gravel packing a well is becoming more prevalent with time and is being done in wells that have well screens and in those with perforated casings. A large-diameter well (16 to 36 inches) is drilled and a casing at least 4 inches smaller than the hole is centered in the hole. Gravel of uniform size—pea or larger, depending on the type of material penetrated in the borehole—is packed into the annular space between the casing and the well wall. The well is then developed. The gravel forms a natural screen, which allows the fine-grained sand to pass through the gravel into the well and then to be pumped out. The larger grained particles of the formation are trapped by the gravel, thus forming a porous zone which permits the water to flow into the well.

## Quality-of-Water Control

It is important to analyze the water to ascertain the chemical quality and the bacteriological content. There are certain standards that have been recommended for water, depending on its use (Wilcox, 1948; U. S. Public Health Service, 1946). It is not always possible to obtain water of such high standards and it may be necessary to treat the water before using it. Sometimes this may not be economically feasible, but for domestic and industrial water supplies it usually is. In some wells the water may be or may become contaminated. If the contamination is due to drilling or casing, the well can be treated. This is especially important where the water is to be used as a domestic supply. It is equally important to test the water for bacteria regardless of its use if there is any reason to believe that a shallow source of polluted water is entering the well, as for example, from areas of waste disposal. If the source of such contamination cannot be cleaned up, this zone of unsanitary water should be cemented off.

## Well-Development Methods

The development of a well requires considerable knowledge and experience. In many instances, the need for well development is not understood; therefore, owners are sometimes unwilling to pay the additional cost that is necessary for well development. However, in order to get the best results from a well, it is just as important to develop the well properly as it is to drill it correctly. In many instances, the yield of a well per foot of drawdown has been more than doubled after proper and thorough development. Well development consists of the removal of mud, silt, or sand from around the well screen or casing perforations, thereby creating a natural filter of coarser and more uniform sand or gravel. As a well is pumped, the flow of water is in one direction, and there is a tendency for the fine-grained particles to move toward the well and clog up the openings in the coarser grained material. To prevent this, the direction of water movement must be intermittently reversed by agitation, dislodging the smaller particles, and allowing them to be drawn eventually into the well and pumped or bailed out of the system.

In many instances, optimum facilities for developing a well—for example, a turbine or other complex-type pump—may not be available. In such instances, much can be accomplished with a simple cylinder pump activated by the spudding action of the cable-tool rig.

A 6-inch well will accept a cylinder large enough to discharge as much as 70 gpm (gallons per minute), and a 4-inch well will accept a cylinder that will discharge as much as 35 gpm.

The advantages of cylinder pumps are that they are cheap, easily transported, quickly installed in a well and subsequently removed, very effective in the moderately small-discharge range, will develop a well to a fair degree by reason of their pulsating (one direction) action, and will pump sand without undue wear. The disadvantage is the limitation in discharge rate; they are not too practical for development except where used with a cable-tool machine.

It is advisable to install a cylinder pump where there is a doubt that the well will yield enough water to satisfy the minimum discharge of the turbine pump at hand, thus eliminating loss of time and effort in installing a turbine pump in an unsuitable well.

Complete development is achieved when the well will yield the greatest possible amount of water per foot of drawdown without pumping sand. Often a well is only partially developed, due to the lack of equipment to pump at the high rate necessary for complete development. In fact, complete development—requiring considerable cost, effort, and time—probably is achieved in a relatively few wells. However, currently more wells are being developed to the stage of "nearly complete development" that is economically feasible.

A well is stabilized when it no longer pumps sand, silt, or mud. Thus, an undeveloped well may be stabilized at a very low yield, but when the pumping rate is increased sand may appear in the water. The well generally will stabilize at a higher pumping rate after further development. Presumably, a well may be developed to its maximum feasible discharge (pumping at maximum practical drawdown) but still not be stabilized. Therefore, it is a common practice in many areas to pump a well at a very high rate during development (overpumping), and then to fix the permanent discharge rate at a lower level.

When a well has been developed to its maximum by any one particular method, further development by more rigorous methods may be attempted depending on the availability of equipment and possible economic benefits. Much time and money might be spent with little benefit; on the other hand, limited work might yield large benefits. Experience and judgment frequently must be relied on to decide whether additional methods of development should be tried.

Several methods of well development currently used are discussed below.

## Pumping Method

The most common method of well development is agitation by pumping. When a water-bearing formation is penetrated, whether or not a screen is set, bailing or pumping will produce sand and water. Fine particles tend to be drawn in with the water at first but generally the water will clear. However, the well at this stage has a relatively low efficiency and is stable only at a very low discharge rate.

Initial development of such a well will consist of pumping, preferably by turbine pump with open-end impellers, at a steady low rate until sand no longer appears in the water. Without stopping, the pumping rate is increased, causing mud to again appear in the water, and continued at the higher rate until the water again runs clear. This process is continued until the maximum capacity of the pump is reach-

During this process, it is common to look for a "break" in the formation; that is, the well may discharge a rather small amount of water and a little sand at first, but after a period of time—10 minutes to an hour—the removal of fine particles near the entrance of the well will allow a relatively large annular mass of the formation to move toward the well, releasing the fine particles and producing a strong flow of sand with the water. At this point, it is imperative for the flow to continue through the cycle; stopping the pump will result in sand-locking the turbine, as well as filling the lower part of the hole with fine particles, necessitating removal of the pump and bailing out.

Following such a "break," the volume of water discharged increases appreciably, and the well will have undergone extensive development. Immediately subsequent increases in the discharge rate frequently produce only a small amount of sand.

When uninterrupted pumping, stepped up gradually to the highest possible rate, has produced clear water for a period of time the well has been developed as much as possible by this method.

## Surging Action

Surging action is one of the most effective methods used for well development in wells finished in sand and gravel formations. The method consists of alternately forcing the water out into the surrounding formation and then allowing it to flow back into the well. This action loosens the fine sand or gravel particles around the perforations in the casing and carries the finer particles into the well where they can be removed. There are several means of effecting this surging action in a well.

### Backwashing

A method commonly used following uninterrupted pumping is that of backwashing or intermittent pumping. When maximum development by uninterrupted pumping has been achieved, the pump is shut off, and the water level is permitted to recover. The well is surged by a series of rapid starts and stops, after which a steady run is made to bring out any additional sand that has been worked free. Eventually, this process will fail to produce observable sand and the well is developed as much as possible by this method.

While the above pumping procedure is being carried out, it will be well to check the bottom of the hole for accumulation of sand. Where excess sand accumulates, depending on the construction of the well, it will be necessary to remove the pump and clean out the sand before continuing development.

During development by the backwashing method, the pump must not be started until its reverse motion, following shutoff, has ceased. Otherwise there is danger of unscrewing or snapping off the turbine shaft.

## Surge block

Following development by pumping, the surge block or surge plunger (fig. 7) probably will be one of the simplest, yet effective, devices designed for developing wells. This device is fundamentally a piston which surges the water in the well and the formation, thus producing an action which loosens the finer formation particles and brings them through the screen into the well where they can be removed.

Surge blocks may be classified according to two principles of design: (1) the solid surge block, and (2) the valved surge block (fig. 7). Variations in design may exist in either of these types, but the

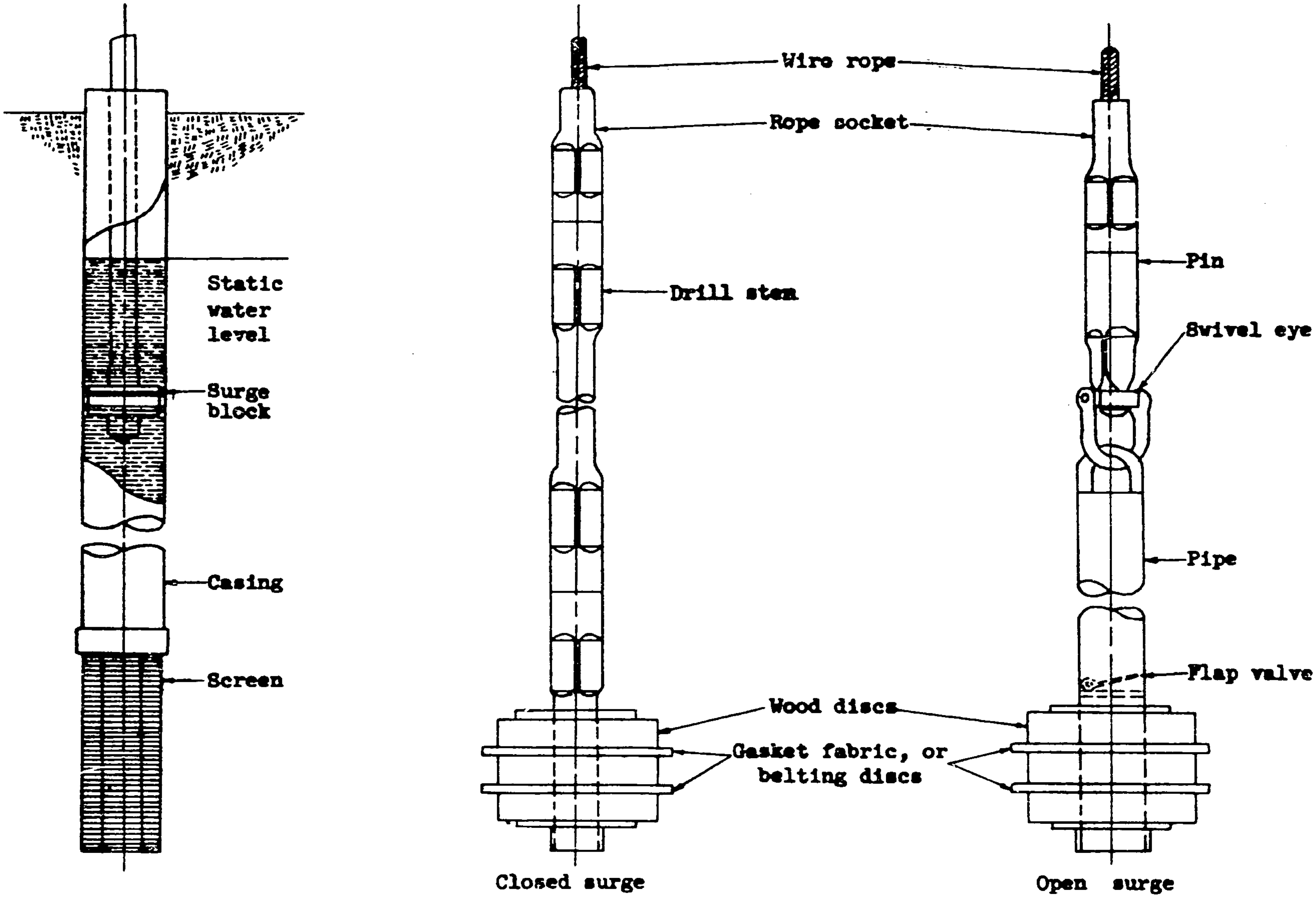


Figure 7 . Generalized diagram showing the assembly of an open and a closed surge block of the type used in well development.

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basic features of each are about the same.

The solid surge block, when operated up and down in a well casing, exerts an equal, or approximately equal, force on the inward and outward movement of the water through the screen. This relatively rapid and forceful agitation of the water inward and outward through the well screen or casing perforations disturbs the finer sand particles, thus preventing bridging and closing of the openings between the larger particles and drawing the finer particles into the well. The repeated application of this surging force will rearrange the materials around the well. As the finer material is drawn into the well, the pore spaces in the sand and gravel left around the screen will be larger, thus allowing the water to move more freely.

In wells of comparatively low yield, there is a tendency for the solid surge block to force water out of the well and back into the formation or up along the casing; a valve-type surge block will overcome this difficulty.

There are many types of valved surge blocks, but ordinarily they consist of a block with drilled portholes covered with a leather flap. This type of plunger produces a mild action on the downstroke of the plunger because water escapes through the valves, causing the water leaving the well to have a low velocity.

Both types of surge block are used primarily with a cable-tool rig. One should be prepared in advance with a surge plunger, possibly made on an old pin joint (Johnson, Edward E., Inc., 1941, p. 8), but circumstances may cause the fieldman to be without such a plunger and to be dependent upon what is at hand. In such instances the drill stem or weighted bailer may be wrapped with burlap, old rope, or inner tube and used as a surge plunger.

The surge block may be operated by lowering it into the well until it is about 15 feet into the water, and then working it up and down in the casing. The rate of surging should be slow at first and should be increased gradually until it reaches the greatest speed at which the tools can be operated. As the casing begins to fill up with sand, surging should be halted and the sand removed with the bailer. The operation should be repeated until little or no sand is brought into the well. After surging is completed, the well should be pumped at its maximum rate for a short time to aid in the final cleaning.

Compressed air

The use of compressed air (fig. 8) as a means of developing a well is effective when properly done, but unless conditions are right and adequate equipment is used, the process is of little, if any, value.

It is not practical in this paper to give detailed instructions on the techniques of development by air. Publications, such as Bulletin

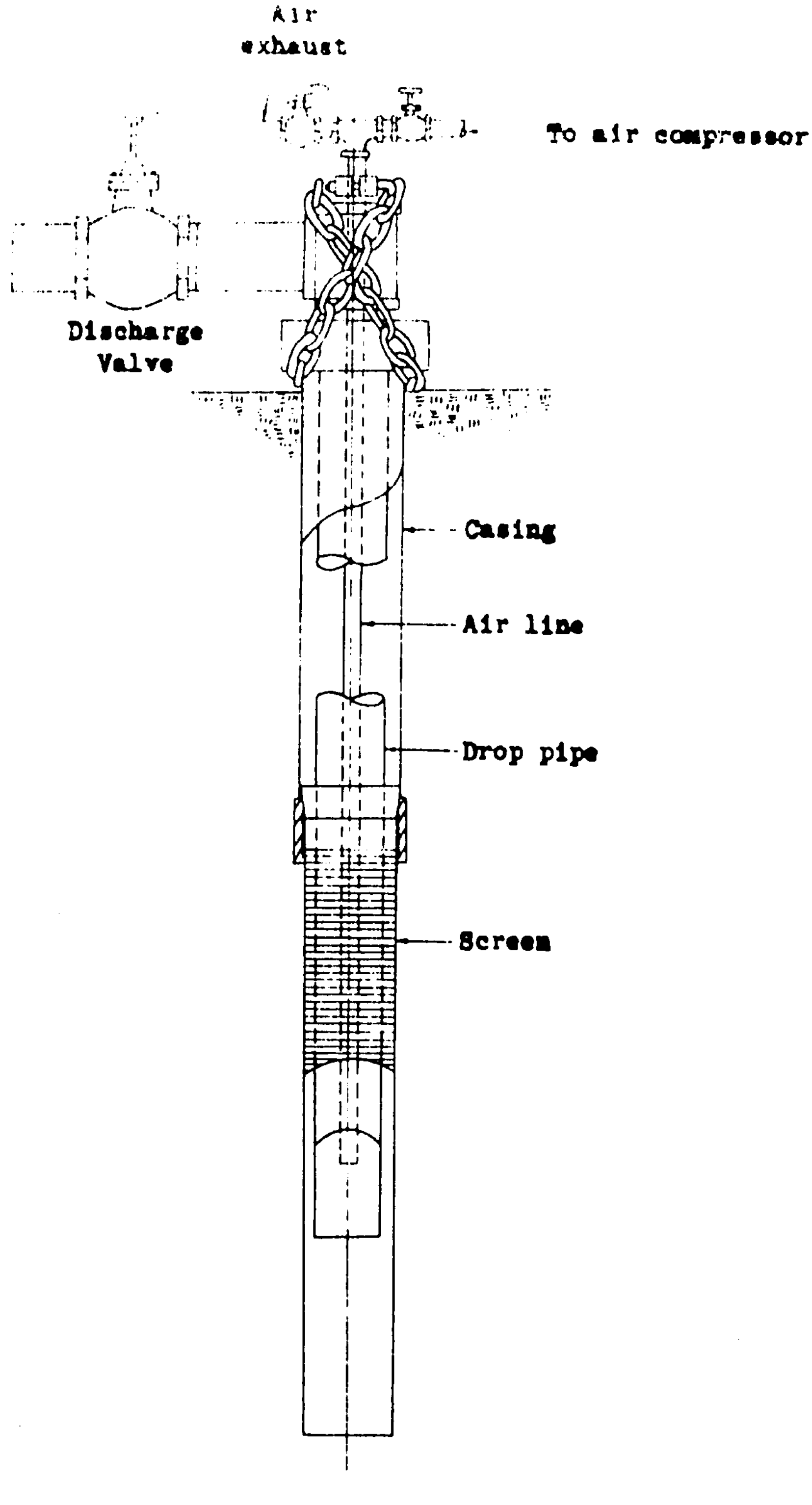


Figure 8. -- Generalized diagram showing an assembly of the type used for the development of wells by compressed air.

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1033 (Johnson, Edward E., Inc., 1941), should be consulted for detailed instructions and discussion. It can be pointed out, however, that this method of development is considered best by many drillers, but it is not as easy to use as some other methods because it requires a fairly elaborate pipe hookup and a large air compressor. Furthermore, it can be used to best advantage only where a substantial part of the total depth of the well is filled with water. Using one of the air-development techniques, the entire length of a screen may be developed—a few feet at a time—by releasing the air at different depths in the well. A series of fissures that contain water in a dense formation might be treated in the same way.

Dry icing

Dry ice can be used to produce an action similar to that of an air-lift pump. It is broken into chunks, put into a burlap sack, and lowered into the well. A "geyser" effect may be obtained by successful manipulation and it will loosen the material around the screen. Care must be exercised not to freeze the water in the well, which happens if many chunks of ice accumulate on the bottom.

Dry ice can be used as a means of creating a surging action in a well with a more elaborate setup. The best results will be obtained by capping the well, preferably with a pressure gage and relief valve, so that as pressure is built up the escape of gas through the water-bearing formation and consequent air locking can be prevented. This method of well development has not always proven successful, but it has been effective in some wells.

Acidizing

The use of acid often increases the yield of water from wells in limestone aquifers by cleaning well screens or casing perforations and opening the water-bearing formations directly around them. The acid treatment is described here under "Surging Action" because it must be combined with some type of surging of the well to be effective.

The following conditions are necessary for the acid treatment of wells: (1) the well screen and casing must be constructed of metal which will not be damaged by the acid, (2) there should be some knowledge of the kind of incrusting material, and (3) any wells in the same water-bearing formation which are within about 100 feet of the well or wells being treated should be shut down.

The acid is introduced into the well through black pipe which extends to the bottom of the screen or perforated part of the casing. The acid is permitted to remain in the well from 1 to 2 hours and is then stirred with the pipe that was used to place it in the well. This procedure should be repeated several times, and the well should then be surged with a solid surge block for about 10 minutes, while a small stream of water is allowed to run into the well. It should then be surged moderately for a short period, bailed clean, and pumped from 1 to 2 hours.

## Other methods

The use of various chemical inhibitors for cleaning and developing wells has become increasingly widespread in recent years. Use of these materials has several advantages: (1) the method can be used on wells where the pump is already installed, (2) no special equipment is needed, (3) the materials can be handled safely, (4) the work can be done by the well owner, and (5) it is relatively inexpensive. The most common chemical is a polyphosphate detergent. This chemical in solution attacks calcic compounds, brings them into solution, and puts clayey material into suspension. Therefore, the chemical may be effective either in the development of new wells (breaking up drilling mud and attacking interstitial shale or clay), or in the cleaning of old wells where the screen or casing has become incrusted. The chemical is introduced into the well, and the well is surged and pumped alternately. Turbid water noted after surging is an indication of the removal of fine material, and as long as the turbidity is present pumping should be continued. The procedure may be repeated several times until no further improvement in the yield of the well is noted.

## Fracturing

The fracturing method is a common means of developing wells and has been used in oil-producing wells for many years. Essentially, this method involves the exertion of controlled force—either by the use of explosives, pressure, or other means—to expand the openings in the potential productive zones of the formation, thereby causing a better avenue of flow into the well. This method has also been utilized to some extent in the developing of water wells.

Variations and refinements of this method have been achieved in recent years due to engineering improvements and increased technical knowledge. One of the recent variations that has proven successful is the method of forcing sand into the zone that has been fractured for the purpose of keeping the pore spaces open. This procedure is known as sand fracturing.

## Aquifer Tests

Aquifer tests may be used for several purposes: (1) to determine aquifer coefficients—such as transmissibility, permeability, and coefficient of storage or specific yield—which are a guide to the water-bearing qualities of the aquifer in any given area; (2) as an aid in determining the location and character of geologic boundaries; (3) to ascertain the effects of well interference; and (4) as a guide in the spacing of wells for the development of a well field.

The term "pumping test," previously used in the Ground Water Branch, has been replaced by the term "aquifer test" because it is the aquifer, and not the pump or well, that is being tested. Briefly, an aquifer test consists of pumping one well and recording both its drawdown and the drawdown effected by this pumping in other nearby observation wells. These data, when subjected to graphical and mathematical treatment, may yield the answers to many of the questions on the characteristics of the aquifer. However, the basic theory regarding aquifer tests is based on ideal conditions. These conditions seldom exist in the field, and, therefore, adjustments must be made to give optimum results. For a successful test, the field conditions must conform as nearly as possible to the stipulations of the theory.

## Preparation

The proper preparation for a successful aquifer test is essential, and can mean the difference between a reliable solution and one that is erroneous. An aquifer test requires the ultimate in foresight and planning; field data haphazardly collected generally are not usable. Field personnel need not know how to analyze the data, but they should be sufficiently acquainted with the principles involved to guarantee the collection of usable data.

The analysis and interpretation of the observed field data require a knowledge of the background and theory of aquifer testing; more is involved than simply fitting some observed data into a formula and evolving an answer. To disregard the theoretical assumptions made in the derivation of the basic equations may create problems that defy solution. Therefore, the utmost care and caution must be exercised in the selection of the test site, in the control and operation of the test, and in the determination of the length of time the test is to run.

<u>The test site</u>

Perhaps one of the most important items in the preparation for an aquifer test is the selection of the test wells, and the determination of conditions in the area of the test site. As much as possible should be learned about the geology of the area where a test is to be made. Some of the geologic conditions which, if present, will influence the test and tend to produce erroneous conclusions are: (1) anisotropic aquifers, (2) leaky aquifers, (3) changes in aquifer thickness, and (4) various boundary conditions. Therefore, whenever possible, tests should be made on wells where the theoretical assumptions underlying the derivation of formulas and field conditions most nearly coincide.

The effect of wells pumping nearby will be reflected in the aquifer-test data, and steps should be taken to avoid this influence. Other influencing factors are: (1) barometric changes, (2) tidal effects, (3) railroad trains, and (4) phreatophytes. These factors usually cannot be controlled but they must be accounted for. A water-level recording gage should be installed and operated on at least one well in the test area for some time before a test is to begin. The data from this recorder will reveal the influencing factors to be expected and long-term trends which may be taking place.

In selecting the test site, consideration also should be given to possibilities for disposal of the pumped water. The water must be disposed of in such a manner that it will not recharge the aquifer being tested.

Pumped well

The selection of the well to be pumped during a test is important for several reasons. Within the period of the test, the effect of pumping the well should cause water-level drawdowns in the nearby observation wells. Certain information—such as the amount of discharge, the best method for measuring discharge, a suitable means of disposing of the water pumped, the approximate extent of the cone of influence, and the amount of drawdown to be expected in the observation wells—can be determined by means of a short trial test before the main test is begun. If such a trial test is conducted, sufficient time should elapse between the trial and the main test for the water level to regain the approximate height measured before the trial test began.

For optimum results, the well to be pumped should penetrate the entire thickness of the aquifer. However, if the pumped well does not penetrate the entire thickness of the aquifer, it may be possible to compensate for this by the proper placement of the observation wells or by the method used in the final analysis of the data.

The equipment used on the pumped well should be capable of maintaining a constant pumping rate, because changes in the discharge of the well during the test will cause irregularities in the data.

Observation wells

The minimum number of observation wells needed for a test depends upon the type of analysis to be made; two observation wells are necessary for the equilibrium-type and one for the nonequilibrium-type test. However, the best results may be obtained by using as many observation wells as possible, spaced at distances near, midway, and far from the pumped well. Specifically, these distances depend upon the hydrologic conditions existing at the pumped well and the observation wells. The observation wells must be open and hydraulically connected to the full depth of the aquifer being tested; this condition can be checked by a "slug test."

A slug test consists of dumping a known amount of water into the well and measuring the water level and the length of time it takes for the water level to return to its previous static position. If the well is open, the interval of time required for the water level to change is dependent on the permeability of the aquifer.

Whenever possible, a water-level recording gage should be operated on at least one observation well during the test. In all wells in which tape measurements are to be made, the measuring points should be established and well marked. The accuracy of making manual tape measurements depends, to some extent, on the accessibility of the measuring points.

Driven sand points often make good observation wells if the required depth is not too great; they are comparatively inexpensive and may be completed quickly, depending upon the materials encountered.

## Equipment

Comparatively little equipment is required for conducting an aquifer test. Some means must be provided for measuring the discharge of the pumped well. If a suitable location is available in the disposal system, the discharge can be measured by use of a weir or a pygmy current meter. Other means that can be used are: (1) manometer or Pitot tube installed in the discharge pipe, (2) an orifice, (3) various types of meters such as the Cox Flow Meter, (4) trajectory, and (5) a container or drum of known capacity. The equipment or means selected for measuring the discharge will depend upon the amount of the discharge and the conditions at the well.

Equipment for measuring the water levels must be provided at the pumped well and observation wells. This equipment may be a steel tape or an electric tape for manual measuring, or a water-level recording gage for mechanical measuring.

Watches and stopwatches must be provided for each member of the field crew and synchronized so that water-level measurements can be taken at predetermined intervals during the test.

Data sheets of some kind should be provided for recording all measurements; as a voluminous amount of data must be recorded in a short period of time, the data sheets should be concise, complete, and adaptable to recording the data quickly and neatly.

## Collection of Data

### Prior to the test

Data that should be collected before the test is initiated are: (1) geologic data on the area to be tested, including well logs if available; (2) history of water-level fluctuations in the area; (3) the static water level on all wells to be used in the test; (4) expected discharge rate of the pumped well; (5) expected drawdowns in the pumped well and the observation wells; and (6) the necessary length of time for the well to be pumped in order to reach a steady-state condition.

Geologic data will give information on how nearly conditions in the area conform to the requirements of the aquifer-test theory. Data on water-level fluctuations in the area previous to the test will indicate what extraneous influences can be expected. These influences can then be accounted for in the analysis of the data. Before the test is started, the well to be pumped and the observation wells should remain idle for a period of time sufficient for them to approach and retain their static water level. The water level in each of the wells should be measured and recorded immediately before starting the test. A knowledge of the discharge rate of the pumped well will aid in selecting the proper method for measuring the discharge. Knowledge of the rate of discharge and other geohydrologic data will aid in determining the expected drawdown in the pumped well and the observation wells. With these data available, the length of time necessary for the aquifer to approach a steady-state condition can be approximated and the length of the test determined.

## During the test

The data to be collected during the test consist of the following:

(1) measuring and recording the water level in the pumped well and all observation wells, (2) recording the time the water-level measurements were made, and (3) periodically measuring the discharge to determine whether the rate is constant.

When the pump is first turned on, water-level measurements should be taken at intervals of from 10 to 20 seconds (measurements can be made that rapidly if an electric tape is used), because the water level will be dropping rapidly. During the latter part of the pumping period when the water level has approached a steady-state condition, the measurement interval may be as much as several hours.

The same procedure used at the beginning of the test should be followed during recovery of the water level in the wells when the pump is turned off. That is, measurements should be taken at frequent intervals when the pump is first shut down, and less frequently as the water level approaches the original static level.

## Plotting and Computation of Data in the Field

Before the test is completed, it will be advantageous to compute and plot part of the data. This can best be accomplished during the latter part of the pumping and recovery periods when the interval between measurements is greater. If, however, it is not possible to plot and compute all the data discussed below, the principal effort should be directed toward the accurate recording of the measurements and plotting of the drawdown and recovery curve. An example of all the procedures discussed below is given in the section "Sample Aquifer Test."

The pumping period

The water levels recorded for the pumped well during the pumping period should be plotted on coordinate paper against the time that each measurement was taken. This plot results in a "drawdown curve," and as this curve levels out it indicates that the water level in the pumped well is approaching a steady-state condition. Pumping should continue until the curve has leveled out to the point where further changes in its position are negligible.

The drawdown in the pumped well and the observation wells is computed by subtracting each succeeding water-level measurement from the static water level established for each well just prior to the test. Also, the elapsed time since pumping began must be computed for each drawdown measurement from the clock time. For the pumped well, the drawdown values should be plotted against the logarithm of the elapsed time since pumping began. The use of semilog graph paper will facilitate this operation. Theoretically, this semilog plot of drawdown against time for the pumped well will be a straight line. Any deviation from a straight line may indicate some form of interference, such as other wells pumping nearby, barometric effects, or geologic boundaries. This deviation could also be caused by human or mechanical error, such as faulty records or fluctuating pump discharge. In such instances, the pumping period should be extended in order to check these conditions. Extending the pumping period beyond the required minimum will cause no difficulty; however, shutting down the pump before sufficient data are collected will necessitate running a complete new test.

## The recovery period

The field plotting and computations are the same during the recovery period as during the pumping period. The water-level measurements made in the pumped well during the recovery period should be plotted against the time that each measurement was made as a continuation of the drawdown curve. The plotting of this part of the data will result in the "recovery curve" and will indicate when the water level in the pumped well has regained or approached the static water level established just prior to the test.

The "recovery" in the pumped well and the observation wells should be computed. For the pumped well, the first step in this procedure is to extend the drawdown curve. The drawdowns that would have occurred had pumping continued can be estimated from this extension. Extension of the drawdown curve is necessary because the steady-state condition is never absolute. The recovery in the pumped well is then computed by subtracting the measured water level from the estimated water level on the projected part of the drawdown curve at the corresponding time. For the observation wells, the last water-level measurement before the pump was shut down may be used as a value from which to subtract the succeeding water-level measurements. The recovery values should then be plotted against the logarithm of the elapsed time, again simplified by the use of semilog graph paper. The semilog plot will indicate the presence of factors causing interference similar to those mentioned in the foregoing section.

## Analyzing the Test Data

The final step in the aquifer test is essentially one of analysis. The computing and plotting of the data must be completed and the results interpreted in terms of the hydrologic information desired. Procedures for analyzing aquifer-test data may be divided into two general methods; according to the data used these are (1) drawdown methods and (2) recovery methods. In each of these methods, however, there are many procedures for deriving the answer to hydrologic problems.

Before discussing these procedures it might be advantageous to define some of the terms that describe the hydrologic properties of the aquifer.

The coefficient of permeability (P) of an aquifer is a measure of the ability of the aquifer material to transmit water under differential pressure. Meinzer (Stearns, 1928) expresses this term as the rate of flow of water in gallons per day through a cross-sectional area of 1 square foot under a hydraulic gradient of 1 foot per foot at a temperature of 60°F. In practice, the adjustment to the standard temperature of 60°F generally is ignored, and the term is used as the field coefficient of permeability at the prevailing water temperature.

The coefficient of transmissibility (T) of an aquifer is defined by Theis (1935) as the rate of flow of water at the prevailing water temperature in gallons per day through a vertical strip of the aquifer 1 foot wide extending the full saturated height of the aquifer under a hydraulic gradient of 100 percent. The relation between the coefficient of transmissibility and the coefficient of permeability is $T = pm$, in which m is the total saturated thickness of the aquifer.

The coefficient of storage (S) of an aquifer may be defined as the volume of water it releases from or takes into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface. In field-pumping tests the volume of material yielding the water is usually thought of as a vertical prism (Ferris, 1955, fig. 2).

Darcy's Law of the flow of water through porous material is: $v = \frac{Ph}{l}$, 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. In ground-water flow terms the expression is: $Q_d = PIA$, in which $Q_d$ is the discharge in gallons per day, P is the coefficient of permeability in gallons per day per square foot, I is the hydraulic gradient in feet per foot, and A is the cross-sectional area in square feet through which the discharge occurs. The law can also be written $Q_d = TIL$, in which $Q_d$ and I are the same as defined above, T is coefficient of transmissibility in gallons per day per foot, and L is the width in feet of the cross section through which the discharge occurs.

The following discussion will explain briefly the procedures most used for analyzing the aquifer-test data to determine these aquifer characteristics and solve other problems related to the aquifer. A more comprehensive explanation of these and other methods dealing with specific problems may be found by consulting the references cited at the end of this report.

Drawdown methods

As the name implies, these procedures are based on the use of data taken during the pumping period when the water levels in the pumped well and the observation wells were being lowered.

The nonequilibrium formula, which was developed by C. V. Theis (1935), is perhaps the most widely used procedure for determining aquifer coefficients from drawdown data. The formula is based on the similarity of the flow of fluids through porous media (Darcy's Law) to the flow of heat by conduction; therefore, some of the same mathematical formulas and theories derived for heat flow are applicable to ground-water flow.

The Theis nonequilibrium formula for the drawdown in the vicinity of a well discharging at a constant rate is:

$$s = \frac{114.6\,Q}{T} \int_{\frac{1.87\,r^2S}{Tt}}^{\infty} \frac{e^{-u}}{u}\,du$$

where

$$u = \frac{1.87\,r^2S}{Tt}.$$

s = drawdown, in feet, at any point in the vicinity of a well discharging at a constant rate.

Q = discharge of a well, in gallons per minute.

T = transmissibility, in gallons per day per foot.

r = distance, in feet, from the discharging well to the point of observation.

S = coefficient of storage.

t = time, in days, since pumping started.

Without going into the details of the derivation and proof of the non-equilibrium formula, the following will give the procedure to be used to arrive at the coefficients of permeability, transmissibility, and storage. The equations in their final form are as follows.

For the coefficient of transmissibility

$$T = \frac{114.6\ QW(u)}{s} \qquad (1)$$

where Q is the discharge, s is the drawdown, and W(u) is the "well function of u." The value of W(u) is given by the series

$$\int_{\frac{1.87\ r^2S}{Tt}}^{\infty} \frac{e^{-u}}{u} du = -0.577216 - \log_e u + u - \frac{u^2}{2 \cdot 2!} + \frac{u^3}{3 \cdot 3!} - \frac{u^4}{4 \cdot 4!} \cdots$$

where

$$u = \frac{1.87\ r^2S}{Tt}$$

Values of W(u) for values of u from $10^{-15}$ to 9.9 have been tabulated by Wenzel (1942).

For the field coefficient of permeability

$$P = \frac{114.6\ QW(u)}{m\,s} \qquad (2)$$

where

m = the average thickness of the aquifer, in feet.

For the coefficient of storage

$$S = \frac{uTt}{1.87\, r^2} \qquad (3)$$

where

$t$ = time, in days, since pumping began.

$u$ = a limit defined by the term $\frac{1.87\, r^2 S}{Tt}$.

These equations cannot be solved directly because the unknowns in each case appear on both sides of the equation. However, the coefficients may be conveniently determined by a graphical method suggested by Theis (1935). Type curves have been plotted on log-log paper (fig. 9) for values of u versus W(u), and copies of these are available from the Washington office of the U. S. Geological Survey, Ground Water Branch. Values of the drawdown (s) should then be plotted against $\frac{r^2}{t}$ if more than one observation well was used or $\frac{1}{t}$ if only one observation well was used, on logarithmic tracing paper to the same scale as the type curve. This curve of the observed data will be similar to the type curve. The data curve may then be superimposed on the type curve, and shifted until the best fit of the field data to the type curve is obtained, always keeping the coordinate axes of the two curves parallel. When the best fit of the two curves has been established, select an arbitrary point any place on the overlapping part of the graph sheets and record the coordinates of this common point from both sheets. These values

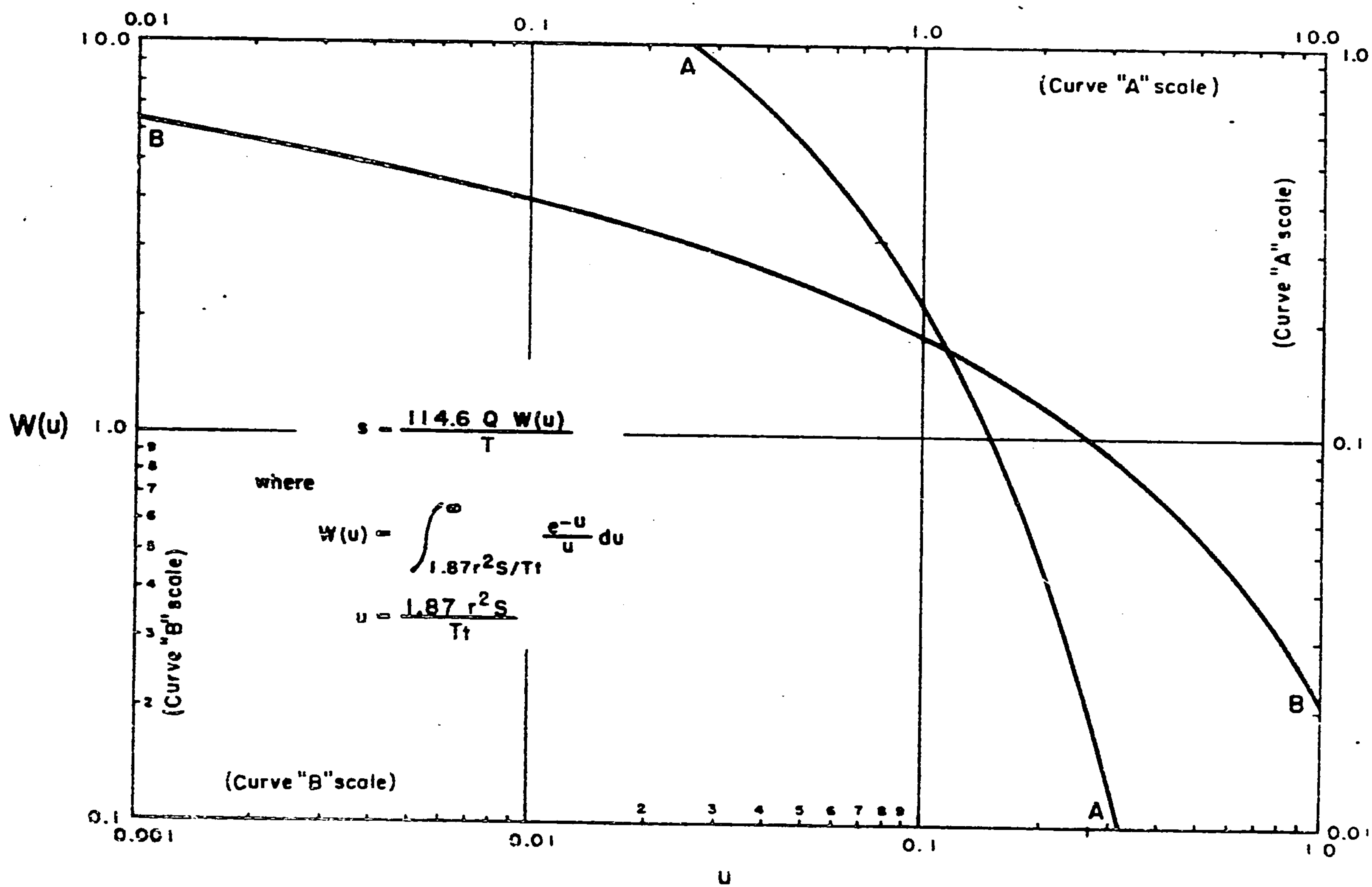


Figure 9.--Logarithmic graph of the well-function type curve

for u, W(u), s, and $\frac{r^2}{t}$ are then used in equations 1 and 3 to solve for T and S. Permeability (P) can be determined from the value for transmissibility if the total thickness (m) of the aquifer is known.

Another procedure for using the drawdown data to obtain the transmissibility and storage coefficients of an aquifer is an approximation of the type-curve solution explained in the preceding paragraph. It is useful as a corollary procedure to check the type-curve solution. It may be used when the time (t) is large in comparison to the distance (r). When this relationship is true, then u is small and the series to which W(u) is equal may be approximated by the value of the first two terms. It has been determined mathematically that if u is less than 0.02 (or $\frac{1}{u}$ is greater than 50) this procedure may be used as the straight-line approximation of the Theis-type curve coincide. The drawdown (s) should be plotted against the logarithm of $\frac{t}{r^2}$, using semilog graph paper to facilitate the operation. This plot should result in a straight line. If the change in drawdown ($\Delta s$) is taken over one log cycle and substituted in the equation $T = \frac{264\ Q}{\Delta s}$, the transmissibility coefficient is obtained. In order to compute the storage coefficient (S), the value of $\frac{t}{r^2}$ is read at the value $s = 0$ (zero-drawdown intercept of the straight line extended). This value and the computed value of T is then substituted in the equation $S = 0.301\ T\ (\frac{t}{r^2})_0$ to obtain the storage coefficient (S). The values for T and S computed by this method within its prescribed limit should be approximately the same as those computed by the type-curve method.

Recovery methods

Methods based on the use of the recovery of the water level in the observation wells after the pump is shut down are a useful supplement to the conventional drawdown methods. Recovery methods are based on the premise that when the pump is shut down and the water levels are allowed to recover, the residual drawdown at any instant will be the same as if the discharge of the well had continued but a recharge well with the same flow was introduced at the same point at the same instant the discharge stopped. In other words, recovery data are merely the reverse of drawdown data. Therefore, the same types of solutions may be used to analyze the recovery data as were used for the drawdown data. The type-curve solution may be used by replotting or inverting the type curve so that it indicates a rising trend in the water levels similar to what takes place in the observation wells. The same procedure may be followed with the straight-line solution. Approximately the same values for the various coefficients should be obtained from the recovery data as from the drawdown data.

Location of aquifer boundaries

Whenever the areal extent of the aquifer being tested is limited by the existence of some type of boundary, the plotted data will deviate from the type curve or from a straight line. The direction of the deviation will depend upon the type of boundary, i.e., an impermeable barrier will act as a discharging boundary, and a surface stream or underflow will act as a recharging boundary. Either type of boundary may be located by a procedure known as the image-well theory. The details of this procedure will not be discussed here (see bibliography).

## Sample Aquifer Test

The following illustrations and tables will show the procedure to be followed to record, compute, plot, and analyze data during an aquifer test. Tables 1 and 2 show the data recorded and computed in the field during the test. The drawdown and recovery curves for the pumped well (fig. 10) should be plotted during the test in the field if possible. The drawdown part of the curve should be extended to approximate the steady-state conditions. For the pumped well, the recovery (s') is the difference between the water level as shown on the extended drawdown curve and the measured water level at any given time after pumping has ceased. For the observation well, the last

Table 1. --Data for the pumped well
AQUIFER TEST FIELD DATA SHEET

1 Pumped well  Page 1 of 7

__ Observation well No ....

Owner John Smith  Location SW 1/4 SW 1/4 Sec. 21, T 10 S., R. 4E.

Observers Jones and Brown

Measuring point is pump base which is 0.00 feet above/below surface.

Static water level 105.00 feet below land surface.

Distance to pumped well - feet.

Discharge rate of pumped well 1,000 gpm (gallons per minute).

Total number of observation wells 1.

| Date | Clock time | Elapsed time since pumping started/stopped (minutes) | Depth to water, below land surface (feet) | Drawdown or recovery (feet) | Remarks |
|---|---|---|---|---|---|
| 2/2 | 8:00 A | | | | Pumping started |
| | 8:00:06 | 0.1 | 107.14 | 2.14 | 1,000 gpm |
| | 8:00:12 | 0.2 | 107.54 | 2.54 | |
| | 8:00:30 | 0.5 | 108.06 | 3.06 | |
| | 8:01 | 1. | 108.46 | 3.46 | |
| | 8:02 | 2. | 108.85 | 3.85 | |
| | 8:03 | 3. | 109.08 | 4.08 | |
| | 8:04 | 4. | 109.24 | 4.24 | |
| | 8:05 | 5. | 109.37 | 4.37 | |
| | 8:06 | 6. | 109.48 | 4.48 | |

Table 1. --Data for the pumped well—Continued
AQUIFER TEST FIELD DATA SHEET
Continuation sheet

✓ Pumped well



___ Observation well No. ___

| Date | Clock time | Elapsed time since pumping started/stopped (minutes) | Depth to water, below land surface (feet) | Drawdown or recovery (feet) | Remarks |
|---|---|---|---|---|---|
| 2/2 | 8:08 | 8. | 109.65 | 4.65 | |
| | 8:10 | 10. | 109.77 | 4.77 | |
| | 8:15 | 15. | 110.01 | 5.01 | |
| | 8:20 | 20. | 110.16 | 5.16 | |
| | 8:25 | 25. | 110.30 | 5.30 | |
| | 8:30 | 30. | 110.40 | 5.40 | |
| | 8:40 | 40. | 110.56 | 5.56 | |
| | 8:50 | 50. | 110.68 | 5.68 | |
| | 9:00 | 60. | 110.80 | 5.80 | |
| | 9:10 | 70. | 110.91 | 5.91 | |
| | 9:20 | 80. | 110.98 | 5.98 | |
| | 9:40 | 100. | 111.10 | 6.10 | |
| | 10:00 | 120 | 111.20 | 6.20 | |
| | 10:30 | 150 | 111.33 | 6.33 | |
| | 11:20 | 200 | 111.49 | 6.49 | |
| | 12:10 P | 250 | 111.60 | 6.60 | |
| | 1:00 | 300 | 111.73 | 6.73 | |

Table 1. --Data for the pumped well—Continued
AQUIFER TEST FIELD DATA SHEET
Continuation sheet

✓ Pumped well  Page 3 of 7

___ Observation well No. ___

| Date | Clock time | Elapsed time since pumping started/stopped (minutes) | Depth to water, below land surface (feet) | Drawdown or recovery (feet) | Remarks |
|---|---|---|---|---|---|
| 2/2. | 2:40P | 400 | 111.88 | 6.88 | |
| | 4:20 | 500 | 112.02 | 7.02 | |
| | 6:00 | 600 | 112.12 | 7.12 | |
| | 7:40 | 700 | 112.23 | 7.23 | |
| | 9:20 | 800 | 112.29 | 7.29 | |
| 2/3 | 12:40A | 1000 | 112.42 | 7.42 | |
| | 4:00 | 1200 | 112.54 | 7.54 | |
| | 8:00 | 1440 | 112.61 | 7.61 | |
| | 12:00P | 1680 | 112.72 | 7.72 | |
| | 5:20 | 2000 | 112.82 | 7.82 | |
| 2/4 | 12:00A | 2400 | 112.94 | 7.94 | |
| | 8:00 | 2880 | 113.02 | 8.02 | |
| | 10:00 | 3000 | 113.05 | 8.05 | |
| | 6:20P | 3500 | 113.14 | 8.14 | |
| 2/5 | 2:40A | 4000 | 113.21 | 8.21 | |
| | 8:00 | 4320 | 113.27 | 8.27 | |
| | 7:20P | 5000 | 113.34 | 8.34 | |

Table 1.--Data for the pumped well—Continued
AQUIFER TEST FIELD DATA SHEET
Continuation sheet

✓ Pumped well



___ Observation well No. ___

| Date | Clock time | Elapsed time since pumping started stopped (minutes) | Depth to water, below land surface (feet) | Drawdown or recovery (feet) | Remarks |
|---|---|---|---|---|---|
| 2/6 | 8:00A | 5760 | 113.43 | 8.43 | |
| | 12:00P | 6000 | 113.45 | 8.45 | |
| 2/7 | 4:40A | 7000 | 113.55 | 8.55 | |
| | 8:00 | 7200 | 113.57 | 8.57 | |
| | 9:20P | 8000 | 113.60 | 8.60 | |
| 2/8 | 8:00A | 8640 | 113.65 | 8.65 | |
| | 2:00P | 9000 | 113.66 | 8.66 | |
| 2/9 | 8:00A | 10080 | 113.74 | 8.74 | |
| 2/10 | 8:00A | 11520 | 113.82 | 8.82 | |
| 2/11 | 8:00A | 12960 | 113.89 | 8.89 | |
| 2/12 | 8:00A | 14400 | 113.95 | 8.95 | Pump off |
| | | | | | |
| 2/12 | 8:00:30A | 0.5 | 110.89 | 3.06 | |
| | 8:01 | 1. | 110.49 | 3.46 | |
| | 8:03 | 3. | 109.87 | 4.08 | |
| | 8:05 | 5. | 109.58 | 4.37 | |
| | 8:10 | 10. | 109.18 | 4.77 | |

Table 1. --Data for the pumped well—Continued
AQUIFER TEST FIELD DATA SHEET
Continuation sheet

✓ Pumped well



___ Observation well No ___

| Date | Clock time | Elapsed time since pumping started/stopped (minutes) | Depth to water, below land surface (feet) | Drawdown or recovery (feet) | Remarks |
|---|---|---|---|---|---|
| 2/12 | 8:15A | 15 | 108.94 | 5.01 | |
| | 8:20 | 20 | 108.79 | 5.16 | |
| | 8:30 | 30 | 108.55 | 5.40 | |
| | 8:40 | 40 | 108.39 | 5.56 | |
| | 8:50 | 50 | 108.27 | 5.68 | |
| | 9:00 | 60 | 108.15 | 5.80 | |
| | 9:20 | 80 | 107.97 | 5.98 | |
| | 9:40 | 100 | 107.85 | 6.10 | |
| | 10:00 | 120 | 107.75 | 6.20 | |
| | 10:30 | 150 | 107.62 | 6.33 | |
| | 11:20 | 200 | 107.46 | 6.49 | |
| | 1:00P | 300 | 107.23 | 6.73 | |
| | 2:40 | 400 | 107.08 | 6.88 | |
| | 4:20 | 500 | 106.94 | 7.02 | |
| | 6:00 | 600 | 106.85 | 7.12 | |
| | 7:40 | 700 | 106.74 | 7.23 | |
| | 9:20 | 800 | 106.69 | 7.29 | |

Table 1.--Data for the pumped well—Continued

AQUIFER TEST FIELD DATA SHEET

Continuation sheet

✓ Pumped well



___ Observation well No ___

| Date | Clock time | Elapsed time since pumping started/stopped (minutes) | Depth to water, below land surface (feet) | Drawdown or recovery (feet) | Remarks |
|---|---|---|---|---|---|
| 2/13 | 12:40A | 1,000 | 106.56 | 7.42 | |
| | 4:00 | 1200 | 106.45 | 7.54 | |
| | 8:00 | 1440 | 106.38 | 7.61 | |
| | 12:00P | 1680 | 106.28 | 7.72 | |
| | 5:20 | 2000 | 106.18 | 7.82 | |
| 2/14 | 12:00A | 2400 | 106.07 | 7.94 | |
| | 8:00 | 2880 | 106.00 | 8.02 | |
| | 6:20P | 3500 | 105.90 | 8.14 | |
| 2/15 | 2:40A | 4000 | 105.86 | 8.21 | |
| | 8:00 | 4320 | 105.81 | 8.27 | |
| | 7:20P | 5000 | 105.76 | 8.34 | |
| 2/16 | 8:00A | 5760 | 105.69 | 8.43 | |
| | 12:00P | 6000 | 105.68 | 8.45 | |
| 2/17 | 4:40A | 7000 | 105.62 | 8.55 | |
| | 8:00 | 7200 | 105.61 | 8.57 | |
| | 9:20P | 8000 | 105.59 | 8.60 | |
| 2/18 | 8:00A | 8640 | 105.55 | 8.65 | |

Table 1. --Data for the pumped well—Continued

AQUIFER TEST FIELD DATA SHEET

Continuation sheet

✓ Pumped well



Observation well No

| Date | Clock time | Elapsed time since pumping started/stopped (minutes) | Depth to water below land surface (feet) | Drawdown or recovery (feet) | Remarks |
|---|---|---|---|---|---|
| 2/18 | 2:00P | 9000 | 105.54 | 8.66 | |
| 2/19 | 8:00A | 10 080 | 105.48 | 8.74 | |
| 20 | 8:00A | 11 520 | 105.43 | 8.82 | |
| 21 | 8:00A | 12 960 | 105.39 | 8.87 | |
| 22 | 8:00A | 14 400 | 105.37 | 8.95 | |
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Table 2. --Data for the observation well
AQUIFER TEST FIELD DATA SHEET

___ Pumped well  Page 1 of 6

✓ Observation well No. 1

Owner John Smith  Location SW¼SW¼ sec. 24 T10S R4E

Observers: Jones and Brown

Measuring point is top casing which is 0.60 feet above/below surface.

Static water level 110.05 feet below land surface

Distance to pumped well 100 feet.

Discharge rate of pumped well 1,000 gpm (gallons per minute).

Total number of observation wells 1.

| Date | Clock time | Elapsed time since pumping started/stopped (minutes) | Depth to water, below land surface (feet) | Drawdown or recovery (feet) | Remarks |
|---|---|---|---|---|---|
| 2/2 | 8:00 A | | | | Pumping started at Pumped well |
| | 8:01 | 1. | | 110.05 | 0 |
| | 8:02 | 2. | | 110.05 | 0 |
| | 8:03 | 3. | | 110.05 | 0 |
| | 8:04 | 4. | | 110.05 | 0 |
| | 8:05 | 5 | | 110.06 | .01 |
| | 8:06 | 6 | | 110.07 | .02 |
| | 8:07 | 7 | | 110.09 | .04 |
| | 8:10 | 10 | | 110.12 | .07 |
| | 8:15 | 15 | | 110.20 | .15 |

## Table 2. --Data for the observation well—Continued

AQUIFER TEST FIELD DATA SHEET

Continuation sheet

Pumped well



Observation well No. 1

| Date | Clock time | Elapsed time since pumping started/stopped (minutes) | Depth to water below land surface (feet) | Drawdown or recovery (feet) | Remarks |
|---|---|---|---|---|---|
| 2/2 | 8:20 | 20 | 110.28 | .23 | |
| | 8:30 | 30 | 110.41 | .36 | |
| | 8:40 | 40 | 110.52 | .47 | |
| | 8:50 | 50 | 110.61 | .56 | |
| | 9:00 | 60 | 110.70 | .65 | |
| | 9:10 | 70 | 110.80 | .75 | |
| | 9:40 | 100 | 110.94 | .89 | |
| | 10:00 | 120 | 111.03 | .98 | |
| | 10:30 | 150 | 111.15 | 1.10 | |
| | 11:20 | 200 | 111.30 | 1.25 | |
| | 12:10 P | 250 | 111.43 | 1.38 | |
| | 1:00 | 300 | 111.52 | 1.47 | |
| | 2:40 | 400 | 111.68 | 1.63 | |
| | 4:20 | 500 | 111.80 | 1.75 | |
| | 6:00 | 600 | 111.91 | 1.86 | |
| | 8:00 | 720 | 111.98 | 1.93 | |
| | 10:00 | 840 | 112.07 | 2.02 | |

Table 2. --Data for the observation well—Continued
AQUIFER TEST FIELD DATA SHEET
Continuation sheet

__ Pumped well



✓ Observation well No 1

| Date | Clock time | Elapsed time since pumping started/stopped (minutes) | Depth to water, below land surface (feet) | Drawdown or recovery (feet) | Remarks |
|---|---|---|---|---|---|
| 2/3 | 12:40A | 1000 | 112.19 | 2.14 | |
| | 4:00 | 1200 | 112.28 | 2.23 | |
| | 8:00 | 1440 | 112.40 | 2.35 | |
| | 12:00P | 1680 | 112.46 | 2.41 | |
| | 5:20 | 2000 | 112.59 | 2.54 | |
| 2/4 | 12:00A | 2400 | 112.67 | 2.62 | |
| | 8:00 | 2880 | 112.79 | 2.74 | |
| | 10:00 | 3000 | 112.81 | 2.76 | |
| | 6:20P | 3500 | 112.88 | 2.83 | |
| 2/5 | 2:40A | 4000 | 112.98 | 2.93 | |
| | 12:40P | 4600 | 113.05 | 3.00 | |
| | 7:20 | 5000 | 113.11 | 3.06 | |
| 2/6 | 12:00P | 6000 | 113.21 | 3.16 | |
| 2/7 | 12:00P | 7440 | 113.33 | 3.28 | |
| 2/8 | 12:20P | 8900 | 113.43 | 3.38 | |
| 2/9 | 6:40A | 10000 | 113.51 | 3.46 | |
| 2/10 | 8:00A | 11520 | 113.59 | 3.54 | |

Table 2. --Data for the observation well—Continued

AQUIFER TEST FIELD DATA SHEET

Continuation sheet

___ Pumped well



✓ Observation well No 1

| Date | Clock time | Elapsed time since pumping started/stopped (minutes) | Depth to water, below land surface (feet) | Drawdown or recovery (feet) | Remarks |
|---|---|---|---|---|---|
| 3/11. | 8:00A | 12 960 | 113.65 | 3.60 | |
| 3/12 | 8:00A | 14 400 | 113 72 | 3.67 | Stop Pumping at Pumped well |
| | | | | | |
| 3/12 | 8:05A | 5 | 113.71 | .01 | |
| | 8:10 | 10 | 113.65 | .07 | |
| | 8:15 | 15 | 113 57 | .15 | |
| | 8:20 | 20 | 113 49 | .23 | |
| | 8:30 | 30 | 113 36 | 36 | |
| | 8:40 | 40 | 113.25 | .47 | |
| | 9:00 | 60 | 113.07 | .65 | |
| | 9:40 | 100 | 112.83 | .89 | |
| | 10:30 | 150 | 112.62 | 1.10 | |
| | 11:20 | 200 | 112.47 | 1.25 | |
| | 12:10P | 250 | 112.34 | 1.38 | |
| | 1:00 | 300 | 112.25 | 1.47 | |
| | 2:40 | 400 | 112.09 | 1.63 | |
| | 4:20 | 500 | 111.97 | 1.75 | |

Table 2. --Data for the observation well—Continued

AQUIFER TEST FIELD DATA SHEET

Continuation sheet

___ Pumped well



✓ Observation well No. 1

| Date | Clock time | Elapsed time since pumping started/stopped (minutes) | Depth to water, below land surface (feet) | Drawdown or recovery (feet) | Remarks |
|---|---|---|---|---|---|
| 2/12 | 6:00P | 600 | 111.86 | 1.86 | |
| | 8:00 | 720 | 111.79 | 1.93 | |
| | 10:00 | 840 | 111.70 | 2.02 | |
| 2/13 | 12:40A | 1000 | 111.58 | 2.14 | |
| | 4:00 | 1200 | 111.49 | 2.23 | |
| | 8:00 | 1440 | 111.37 | 2.35 | |
| | 12:00P | 1680 | 111.31 | 2.41 | |
| | 5:20 | 2000 | 111.18 | 2.54 | |
| 2/14 | 12:00A | 2400 | 111.10 | 2.62 | |
| | 8:00 | 2880 | 110.98 | 2.74 | |
| | 10:00 | 3000 | 110.96 | 2.76 | |
| | 6:20P | 3500 | 110.89 | 2.83 | |
| 2/15 | 2:40A | 4000 | 110.79 | 2.93 | |
| | 12:40P | 4600 | 110.72 | 3.00 | |
| | 7:20 | 5000 | 110.66 | 3.06 | |
| 2/16 | 12:00P | 6000 | 110.56 | 3.16 | |
| 2/17 | 12:00P | 7440 | 110.44 | 3.28 | |

Table 2. --Data for the observation well—Continued

AQUIFER TEST FIELD DATA SHEET

Continuation sheet

___ Pumped well

Page 6 of 6

✓ Observation well No. 1

| Date | Clock time | Elapsed time since pumping started/stopped (minutes) | Depth to water, below land surface (feet) | Drawdown or recovery (feet) | Remarks |
|---|---|---|---|---|---|
| 2/18 | 12:20P | 8900 | 110.34 | 3.38 | |
| 2/19 | 6:40A | 10000 | 110.26 | 3.46 | |
| 2/20 | 8:00A | 11520 | 110.18 | 3.54 | |
| 2/21 | 8:00A | 12960 | 110.12 | 3.60 | |
| 2/22 | 8:00A | 14400 | 110.05 | 3.67 | |
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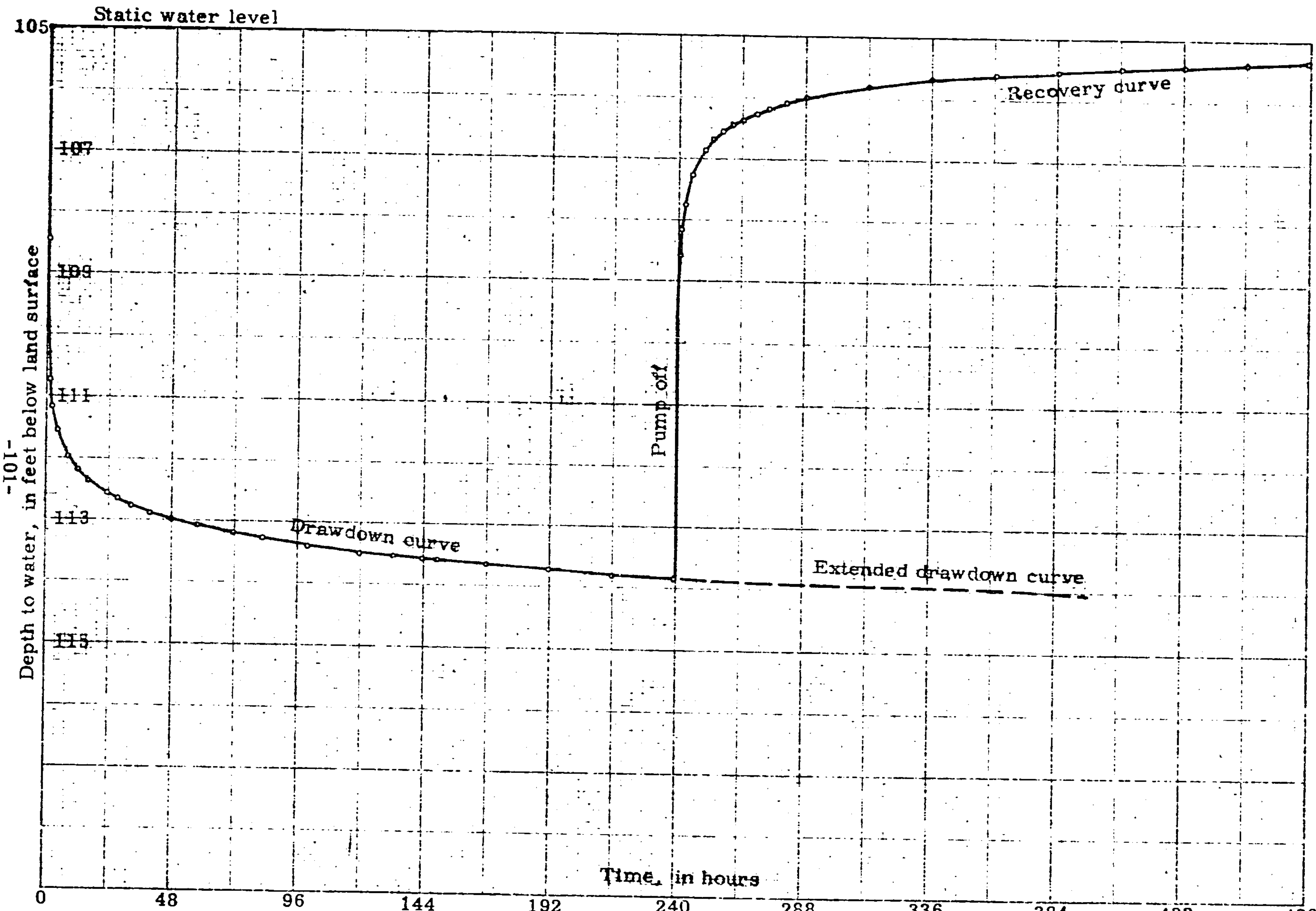


Figure 10. --Drawdown and recovery curves for sample aquifer test.

measurement during pumping may be used to determine the amount of recovery. For the pumped well plot the drawdown versus the log of time, using semilog graph paper (fig. 11). Any deviation from a straight line will show interference of some type. The recovery data are plotted in the same way (fig. 12). Figure 11 also shows the computation for the coefficient of transmissibility using the straight-line approximation method described earlier in the section "Analyzing the Test Data." The coefficient of storage cannot be computed from data for the pumped well. Figure 13 shows the data for the observation well plotted on log-log paper and the computations for T and S using the Theis nonequilibrium formula. Figure 14 shows the same data plotted on semilog paper and the computation of T and S using the modified or straight-line approximation of the Theis nonequilibrium method.

## Evaluation of Aquifer Tests

The information obtained from aquifer tests can be very useful. When the coefficients of transmissibility and storage, the thickness and extent of the aquifer, and the nature and location of boundaries are known, many problems can be solved. These include the determination of the most feasible pattern of well spacing, the effect new wells may have on existing ones, and the pumping rates

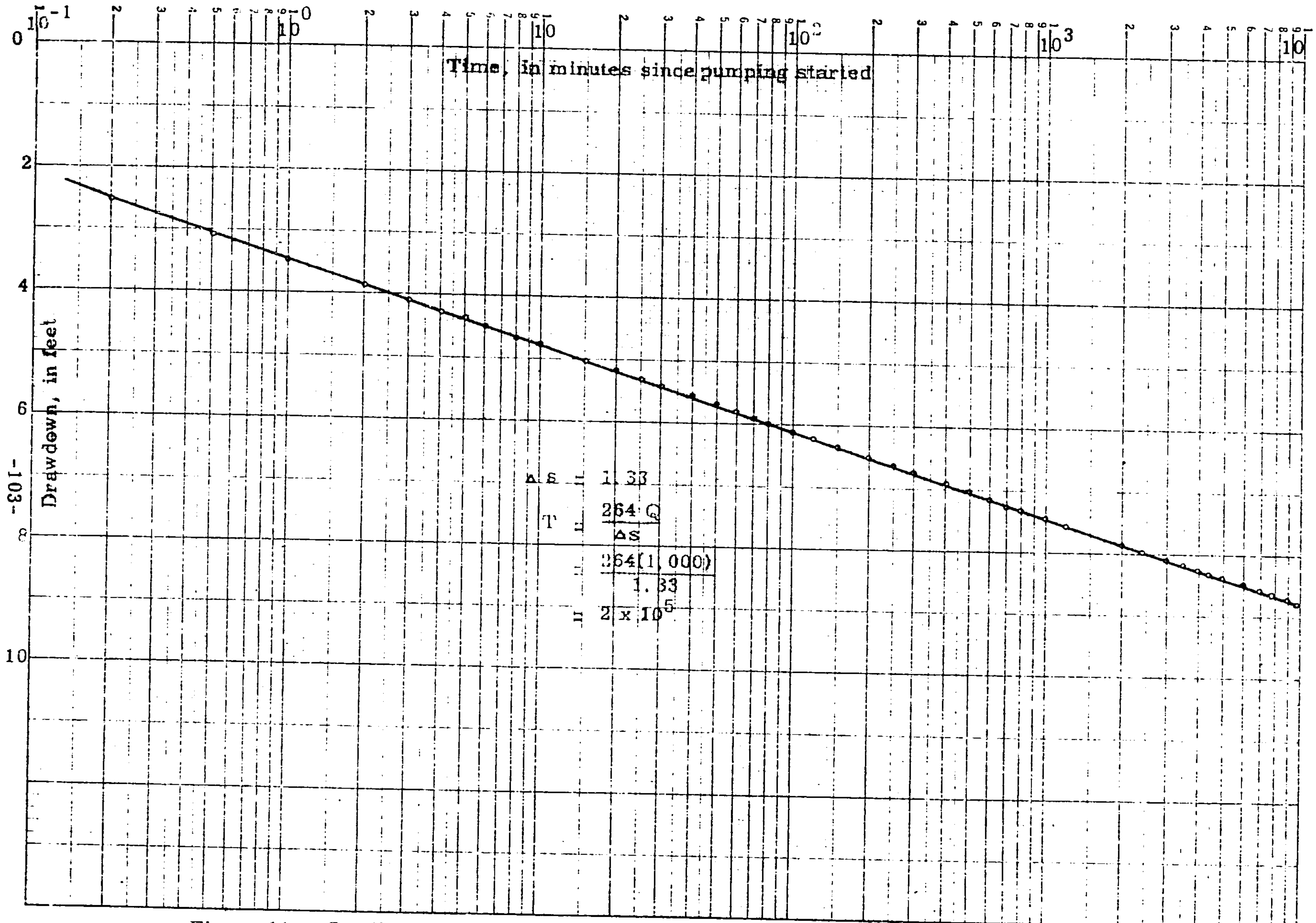


Figure 11.--Semilogarithmic plot of drawdown against log of time for the pumped well.

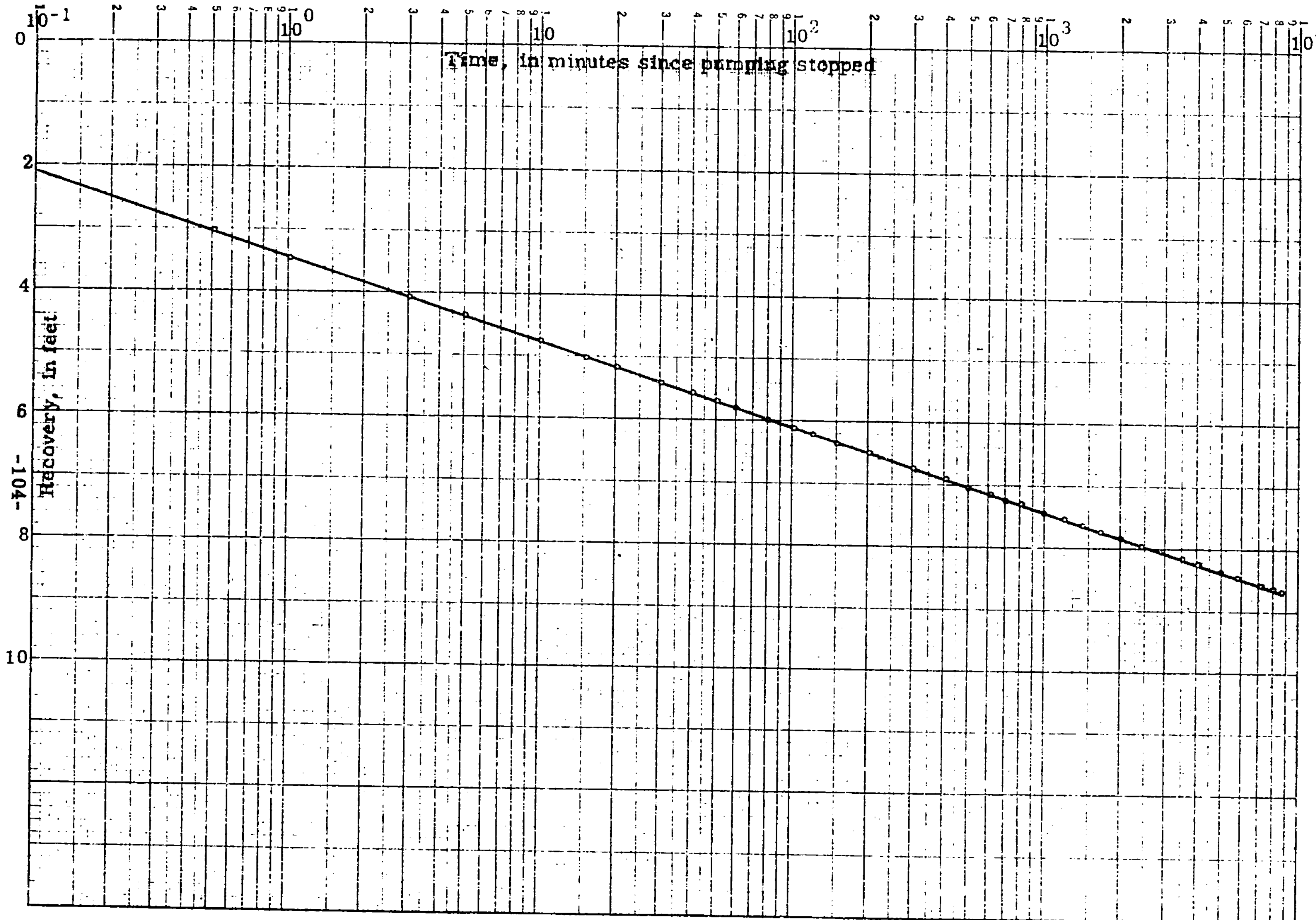


Figure 12.--Semilogarithmic plot of recovery against log of time for the pumped well.

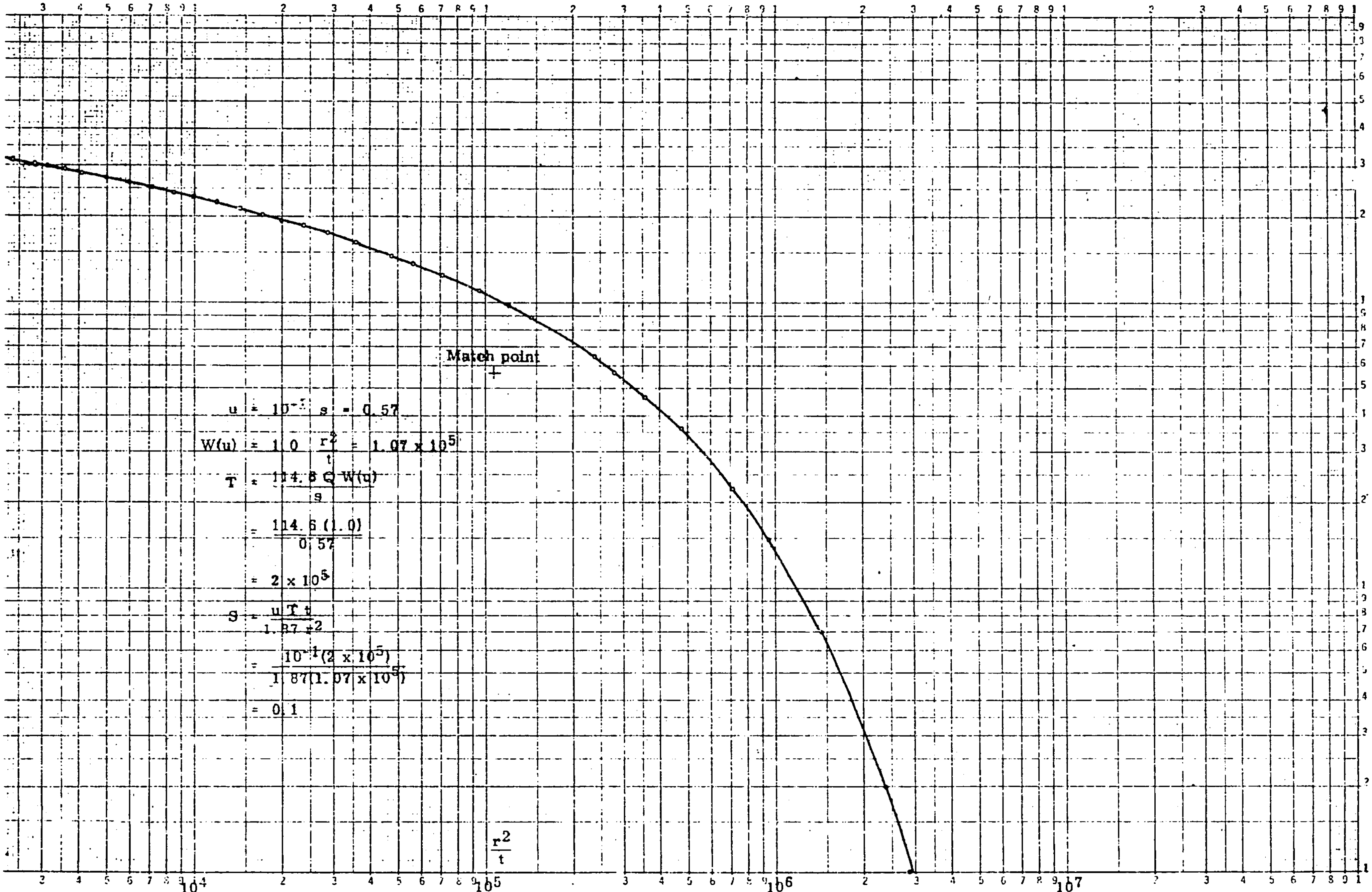


Figure 13. --Logarithmic plot of drawdown against $\frac{r^2}{t}$ for the observation well and sample computations of the coefficients of transmissibility and storage.

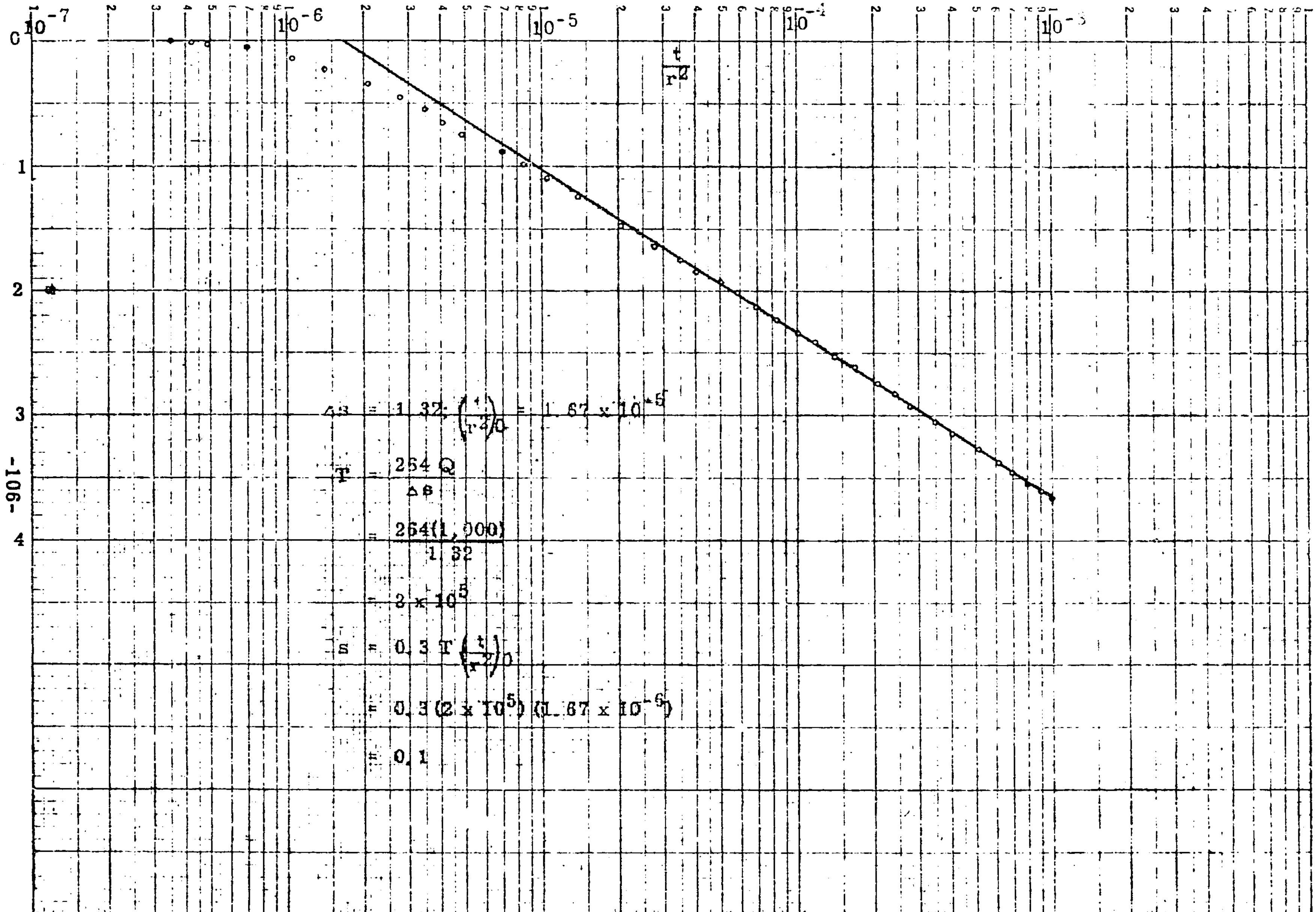


Figure 14.--Semilogarithmic plot of drawdown against log $\frac{t}{r^2}$ for the observation well and sample computations of the coefficients of transmissibility and storage.

and schedules that will give optimum results. The overall evaluation of the ground-water resources of an area with reference to potential development can be aided by the knowledge of these aquifer properties.

The foregoing paragraphs have discussed the elementary methods and procedures for testing and evaluating ground-water aquifers. Further information regarding details and specific problems involved in other methods may be found in publications listed in the bibliography.

## Selected Bibliography


Baker Oil Tools, Inc., Baker standard cable tool core barrel (a catalogue): Baker Oil Tools, Inc., Room 2640, 11 W. 42nd St., New York 18, New York.

Brown, R. H., 1953, Selected procedures for analyzing aquifer test data: Am. Water Works Assoc. Jour., v. 45, no. 8.

Bryan, F. L., 1950, Application of electric logging to water well problems: Water Well Jour., v. 4, no. 1.

Doll, H. G., 1950, The microlog—a new electrical logging method for detailed determination of permeable beds: Reprinted from Jour. Petroleum Technology for Schlumberger Well Surveying Corp.

Doll, H. G., and Martin, Maurice, 1950, Recent developments in electrical logging and auxiliary methods: Colorado School Mines Quart., v. 45, no. 4A.

Ferris, J. G., 1955, Ground-water hydraulics: U. S. Geol. Survey Ground-Water Note no. 28.

Guyod, Hubert, 1952, Electrical well logging fundamentals: Well Instrument Devel. Co., Houston, Texas.

__________ 1954, Electrical well logging: Well Instrument Devel. Co., Houston, Texas.

Jacob, C. E., 1940, On the flow of water in an elastic artesian aquifer: Am. Geophys. Union Trans., pt. 2, p. 574-586.

____________ 1944, Notes on determining permeability by pumping tests under water-table conditions: U. S. Geol. Survey open-file report.

Johnson, Edward E., Inc., 1941, The principles and practical methods of developing water wells: Edward E. Johnson, Inc., Bull. 1033.

____________ 1955, The corrosion and incrustation of well screens: Edward E. Johnson, Inc., Bull. 834 revised.

Jones, P. H., 1952, Electric-logging methods, principles of interpretation, and applications in ground-water studies: U. S. Geol. Survey open-file report.

Jones, P. H., and Buford, T. B., 1951, Electric logging applied to ground-water exploration: Geophysics, v. 16, no. 1, p. 115-139.

Kokesh, F. P., 1951, Gamma-ray logging: Oil and Gas Jour., v. 50, no. 12.

LeRoy, L. W., 1950, Subsurface geologic methods (a symposium), second edition: Colorado School Mines, Golden, Colo.

Marsh, O. T., 1961, Reliability of rotary-drilling samples from clay beds: Water Well Jour., October.

Meeks, T. O., 1952, Developing and testing irrigation wells: U. S. Dept. Agr., Soil Conservation Service, Regional Bull. 114, Geol. Ser. 4.

Meinzer, O. E., 1923, Outline of ground-water hydrology with definitions: U. S. Geol. Survey Water-Supply Paper 494.

__________ (Ed.), 1949, Hydrology: New York, Dover Publications, Inc.

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

Sawdon, W. A., Cable coring provides valuable data for both drilling and production methods: Baker Oil Tools, Inc., New York, a reprint of Baker Broadcast no. 16.

Schlumberger Well Surveying Corporation, 1949, Review of Schlumberger well logging and auxiliary methods: Schlumberger Well Surveying Corp., Schlumberger Doc. no. 2.

__________ 1950, Interpretation hand-book for resistivity logs: Schlumberger Well Surveying Corp., Schlumberger Doc. no. 4.

Slichter, C. S., 1954, Theoretical investigation of the motion of ground waters: U. S. Geol. Survey Ground-Water Note no. 22.

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

Taylor, D. W., 1948, Fundamentals of soil mechanics: New York, John Wiley and Sons, Inc.

Theis, C. V., 1935, 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., pt. 2, p. 519-524.

____________ 1938, The significance and nature of the cone of depression in ground-water bodies. Econ. Geology, v. 33, no. 8, p. 889-902.

____________ 1957, The source of water derived from wells—essential factors controlling the response of an aquifer to development: U. S. Geol. Survey Ground-Water Note no. 34.

U. S. Public Health Service, 1946, Drinking water standards: Public Health Reports, v. 61, no. 11 (reprint no. 2697).

Vorhis, R. C., 1957, Bibliography of publications relating to ground water prepared by the Geological Survey and cooperating agencies, 1946-55: U. S. Geol. Survey Water-Supply Paper 1492.

Waring, G. A., and Meinzer, O. E., 1947, Bibliography and index of publications relating to ground water prepared by the Geological Survey and cooperating agencies: U. S. Geol. Survey Water-Supply Paper 992.

Wenzel, L. K., 1936, 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-A.

____________ 1942, Methods for determining permeability of water-bearing material with special reference to discharging well methods: U. S. Geol. Survey Water-Supply Paper 887.

Wilcox, L. V., 1948, The quality of water for irrigation use: U. S. Dept. Agr. Tech. Bull. 962.

Wyllie, M. R. J., 1957, The fundamentals of electric log interpretation: New York, Academic Press Inc., 2nd ed.