Methods of Collecting and Interpreting Ground-Water Data

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1544-H

Methods of Collecting and Interpreting Ground-Water Data

Compiled by RAY BENTALL

GENERAL GROUND-WATER TECHNIQUES

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1544-H

A collection of reports prepared by Peter R. Stevens, Edward A. Moulder, Mervin L. Klug, Gordon E. Andreason, Joseph W. Brookhart, Robert W. Stollman, Matthew I. Rorabaugh, and Harold E. Thomas, revised by Ray Bentall

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INTRODUCTION

Because ground water is hidden from view, ancient man could only theorize as to its sources of replenishment and its behavior. His theories held sway until the latter part of the 17th century, which marked the first experimental work to determine the source and movement of ground water. Thus founded, the science of ground-water hydrology grew slowly and not until the 19th century is there substantial evidence of conclusions having been based on observational data. The 20th century has witnessed tremendous advances in the science—in the methods of field investigation and interpretation of collected data, in the methods of determining the hydrologic characteristics of water-bearing material, and in the methods of inventorying ground-water supplies. Now, as is true of many other disciplines, the science of ground-water hydrology is characterized by frequent advancement of new ideas and techniques, refinement of old techniques, and an increasing wealth of data awaiting interpretation.

So that its widely scattered staff of professional hydrologists could keep abreast of new ideas and advances in the techniques of ground-water investigation, it has been the practice in the U.S. Geological Survey to distribute such information for immediate internal use. As the methods become better established and developed, they are described in formal publications. Six papers pertaining to widely different phases of ground-water investigation comprise this particular contribution. For the sake of clarity and conformity, the original papers have been revised and edited by the compiler.

The first of the papers is based on experience gained during drilling operations on the Navajo Indian Reservation in northeastern Arizona and northwestern New Mexico. It describes not only the methods of collecting, examining, and describing the rock cuttings but also some of the uses made of the subsurface information obtained by drilling.

The second paper describes the equipment used and the procedure followed in installing shallow water-level observation wells by a combination of jetting and rotary-drilling methods. The technique was developed during the course of drainage studies in two areas in eastern Montana.

The third paper, which is based on observations at Easton, Md., discusses the phenomenon of reverse water-level fluctuations—that is, the water level in a well that taps a deep aquifer rises whenever water is pumped from a nearby well that taps a shallow aquifer. Two possible explanations for such reverse water-level fluctuations are presented, and it is suggested that fluctuations of this type may provide data from which the hydraulic constants of an aquifer could be computed.

The fourth paper relates the distribution of underground temperatures to the velocity of the ground water. Theoretically, temperature measurements can be used for calculating flow velocity, and a combination of head and temperature measurements can be used for calculating aquifer permeability.

The fifth paper discusses the factors that should be considered in designing a water-supply installation that is to be supplied by streambed percolation. Data collected during the first 5 years of operation of a horizontal-type collector southwest of Louisville, Ky., are used to illustrate the effects of the various factors.

In the sixth paper a long-term record of water-level fluctuations in a single well in Ogden Valley, Utah, is used as the basis for developing a water budget for the artesian aquifer tapped by the well. Adjustment of the water-level record for all the known pressure effects results in a hydrograph that reflects changes in storage only. The changes in storage are then related to the various factors that add to, or subtract from, storage in the aquifer. This paper is an example of knowledge that can be gained by integrating and interpreting data and observations.

EXAMINATION OF DRILL CUTTINGS AND APPLICATION OF RESULTING INFORMATION TO SOLVING OF FIELD PROBLEMS ON THE NAVAJO INDIAN RESERVATION, N. MEX. AND ARIZ.

By Peter R. Stevens

ABSTRACT

Only by drilling test holes and wells can detailed information on subsurface geologic and hydrologic conditions be obtained. The value of the information thus collected depends on the care exercised in sampling the rock cuttings, the thoroughness of the microscopic examination, and the accuracy and completeness of the lithologic and hydrologic descriptions. The more subsurface information compiled for an area, the better the understanding of the stratigraphy and geologic structure and the greater the success in locating water supplies from ground-water sources. This paper is based on experience gained in making a geologic and hydrologic study of the Navajo Indian Reservation, N. Mex. and Ariz.

SCOPE AND PURPOSE OF PAPER

During the course of geologic and ground-water studies in the Navajo Indian Reservation in northwestern New Mexico and northeastern Arizona, many wells and test holes were drilled. So that the maximum amount of subsurface information could be realized from the drilling operations, samples of the rock cuttings brought to the surface were examined and described and observations pertaining to the development of ground-water supplies were recorded.

The procedure followed in collecting and examining the cuttings and the uses made of the fund of geologic and hydrologic data thus obtained are outlined in this paper as an aid to those who may be making similar studies in other areas.

COLLECTION OF DRILL CUTTINGS

Drillers on the Navajo Indian Reservation ordinarily collect samples that not only represent each 10-foot increment of depth but also each apparent change in lithology. Each sample is washed and then put into a cloth bag bearing the name and location of the well and the depth represented by the sample. If a well is being drilled by the cable-tool method, the sample is obtained from material dumped from the bailer or, preferably, from the material adhering to the drill bit. On the other hand, if a well is being drilled by the rotary method, the samples are "ditch samples"—that is, they are collected from the ditch through which the drilling mud is channeled to the settling pit. To reduce contamination and obtain cuttings that are representative of the rocks being penetrated, the ditch is cleaned before each sample is collected. Because a well log can be no more accurate than the care in sampling permits, the driller who observes proper sampling procedures is most helpful. As water-well drilling ordinarily proceeds at a fairly slow pace, the person who is to examine the cuttings need not be in constant attendance during the drilling operation. Instead, the samples can be stored for examination either at convenient intervals as drilling proceeds or after the drilling is completed.

HOLES DRILLED BY A CABLE-TOOL RIG

Ordinarily all or nearly all the rock fragments in each sample collected from a hole drilled by a cable-tool rig may be regarded as representative of the rock penetrated at the indicated depth. Especially is this so if the sample was obtained from the cuttings adhering to the drill bit. As individual samples rarely contain more than two different types of rock, the relationship of one rock type to another generally is fairly obvious. The lithologic break between different rock types always can be placed within a 10-foot interval, or may be placed even more closely if the driller records the depth or, even better, collects a sample from each depth at which he detects that a new rock type has been pierced. If a succession of thin layers differing in lithology are penetrated within one depth interval, the cuttings are of mixed types. The person examining such a sample and preparing a log of the hole is able to picture and describe the lithology of the interval much more accurately if he has detailed knowledge of the stratigraphy, or if the driller has carefully noted and recorded each detectable break in rock types.

The operator of a cable-tool rig usually knows when the bit enters a permeable water-bearing material. Furthermore, he generally can estimate the quantity of water the material is yielding and can determine, within wide limits, whether the water is potable. If searching for a water supply, a driller should be provided with sample bottles and should be given instructions on how to take a sample of the water, the information to record on the sample bottle, and the importance of recording the temperature of the water being sampled. If a sample is collected from each water-bearing layer penetrated in the course of drilling, rather than merely composite samples of water from groups of water-bearing layers, a much more detailed appraisal of the water quality can be made.

HOLES DRILLED BY A ROTARY RIG

Only rarely are all the rock fragments in a sample from a hole drilled by a rotary rig derived from the rocks penetrated in the indicated depth interval. As the cuttings from the indicated interval almost invariably are mixed with cuttings from overlying intervals, considerable judgment must be exercised in describing which cuttings are representative of that interval. Although errors in interpretation are possible, they are reduced to a minimum if the examiner of the samples has a thorough knowledge of the stratigraphy of the area.

When samples from a hole drilled by a rotary rig are studied, they should be examined in the order of increasing depth so that the first appearance of each different rock type can be noted. A new type of rock particles, not present in previous samples, represents an addition to the stream of particles rising in the drilling mud and indicates that the bit has penetrated a lithologic boundary within the depth interval represented by the sample.

If the strata represented by the samples from successive depth intervals are composed predominantly of shale but partly of sandstone, the presence of a few grains of sand may mark the top of a sandstone layer. Generally, a few fragments of sandstone can be found in the sample and, if examined, they reveal the character of the sandstone and give some indication regarding its potentialities as an aquifer. If the sandstone is thick, succeeding samples will include increasingly large percentages of sand or sandstone fragments, but if the sandstone is thin, the percentage will remain small. If a record of the time required to drill each depth interval, or fraction of a depth interval, is maintained as drilling proceeds, the information provided by that record aids the examiner of the samples to prepare a more accurate log of the rocks penetrated.

The identification of water-bearing zones in a well drilled by a rotary rig is very difficult. Frequently water-bearing zones are penetrated without their existence being recognized by the driller. Such zones, especially if they are sandstone layers interbedded with shale layers, cannot be detected until the drilling mud is flushed out of the hole. Moreover, there is no way of determining by examining cuttings whether only one, or more than one, principal water-bearing layer is present; or if more than one is present, whether the chemical quality of the water in each is different or nearly the same.

Although the mud used in the rotary method of drilling serves the dual purpose of lining the wall of the hole (thus reducing the possibility of caving) and of transporting the cuttings to the surface, it also tends to seal off the water-bearing layers. Thus, before the water-producing potentialities of the rocks penetrated in drilling can be appraised, the hole must be flushed clear of the drilling mud. The mud also hampers the obtaining of accurate information regarding the quality of water in the well. Because the mud generally has a high pH, and may have a high content of sulfate, chloride, or bicarbonate, it is likely to contaminate the water being sampled.

EXAMINATION AND DESCRIPTION OF DRILL CUTTINGS

EQUIPMENT USED FOR EXAMINATION

A Bausch & Lomb stereoscopic wide-field microscope is used in examining the drill cuttings. Although a 10-power magnification is most convenient for general purposes, a magnification of 30 times or even 60 is advantageous if the examiner wishes to identify specific accessory minerals or is estimating the degree of roundness of fine sands. A Nicholas illuminator is used to shed light on the sample.

DESCRIPTION OF DRILL CUTTINGS

The type of rock—that is, whether the rock is a conglomerate, sandstone, siltstone, mudstone, limestone, or any other—is recorded first. Then the color of the rock is described in terms consistent with the Rock-Color Chart distributed by the National Research Council (Goddard and others, 1948). If the overall color of the rock differs from the color or colors of its component parts, both are recorded.

Except where the sample consists of silt or clay, the Wentworth grade scale [1] is used for determination of particle sizes. No attempt is made to differentiate sizes if a sample consists wholly of silt or wholly of clay. The term "mudstone" is applied to a mixture of silt and clay.

The degree of roundness is estimated by comparing a scattering of grains under the microscope with a chart that pictures well-rounded, rounded, subrounded, subangular, and angular grains.

Samples consisting of sandstone are described with respect to the degree of sorting. If 90 percent or more of the grains fall into two adjacent particle-size ranges, the sandstone is described as well sorted (Payne, 1942, p. 1707); however, if 90 percent of the grains fall into three or four adjacent ranges, it is described as fairly well sorted; and if the grains fall into five or more ranges it is described as poorly sorted. The composition of the grains is noted also. Quartz grains are described as clear, stained, frosted, or amber.

Accessory minerals are identified, if possible; but if not identifiable, their color, prevalence, and other readily observable characteristics are described. Because of their possible bearing on the quality of

[1] The U.S. Geological Survey now (1961) uses the National Research Council grade scale (National Research Council, 1947, Report of the subcommittee on sediment terminology: Am. Geophys. Union Trans., v. 28, no. 6, p. 936–938).

the ground water, sulfides, such as marcasite and pyrite, are of particular interest, as are gypsum, the halide minerals, and carbonaceous material. If ion-exchange minerals can be recognized, their presence in samples should also be recorded.

Even though fragmented and not identifiable, the occurrence of fossils in cuttings should be recorded. To date, a few fragments of bryozoa and some possible coralline material constitute the only recognizable organic remains in the cuttings from wells drilled on the Navajo Indian Reservation.

As to cementation, the rock is described as hard, firm, or weak, depending upon the extent to which the sediment has been lithified; the type of cement is recorded. Krumbein and Sloss (1951) define cement as a postdepositional chemical precipitate deposited in the interstices among grains to form a lithified sedimentary rock. However, the principal binding material in some sandstone is clay, and the sandstone is described as having an argillaceous cement. Close examination of some such clayey sandstone indicates that the argillaceous material actually is a matrix, not merely an interstitial filling. Ferruginous zones also are recorded. Such zones are of interest because they may indicate former long-time positions of the water table and, if firmly cemented, may hinder free circulation of the ground water in otherwise homogeneous rock. In places, iron-cemented zones are known to be confining layers because the water between them is under artesian pressure.

IDENTIFICATION OF STRATIGRAPHIC UNITS

The lithologic descriptions of the cuttings from successive intervals of depth constitute a log of the strata penetrated in drilling. Although such a log is similar in many respects to measured sections of exposed rocks, it differs in that the characteristics of bedding and of weathering, being less obvious, rarely are indicated in the descriptions. Once the samples have been described, the stratigraphic units represented by the cuttings are identified. If the rocks penetrated in drilling contain one or more easily recognized "marker horizons" or if the succession of strata is distinctive, the designation of the contacts between stratigraphic units is a relatively simple matter. However, if the stratigraphic units penetrated in drilling are lithologically similar, they cannot be identified definitely nor can the contacts between them be designated precisely if the features that distinguish the units are observable only at the outcrop.

COMPILATION OF LOGS

A log was prepared for each well drilled on the Navajo Indian Reservation during the course of the geologic and ground-water investigation. In the upper righthand corner of the heading of each log is the field number assigned to the well by the Bureau of Indian Affairs. Below this is recorded the office number from which the exact location of the well can be pinpointed on a map of the reservation. Also given in the heading is a description of the well in terms of distance and direction from a landmark, the dates drilling began and ended, and the names of those who described the samples and identified the stratigraphic units. The following pertinent hydrologic information is included at the end of the log: The total depth of the well, the depth to water, the water-bearing formation or formations, the depth to the water-bearing zone or zones, the results of any pumping or bailing test (such as drawdown measurements, temperature readings, and collection of water samples for chemical analysis), the depth to which the well is cased and the diameter of the casing, and the name of the driller. The importance of recording all such data before it is forgotten cannot be emphasized too strongly.

The following is a log for one of the wells on the reservation.

Well log

U.S. Geological Survey — Well No.: 13K–208
Ground Water Branch — Office No.: 48–4.25–13.85
Navajo Project
Location: 4 miles west-northwest of Bisti Trading Post
Well started: 8–8–53
Well finished: 9–4–53
Samples described by: P. R. Stevens — Date: 9–53
Stratigraphic correlation by: M. E. Cooley and P. R. Stevens — Date: 9–53

Description	Thickness (feet)	Depth (feet)
Quaternary System:		
Alluvium:		
Sandstone, yellowish orange-brown (10*YR* 6/4), coarse- to fine-grained and fairly well sorted; sand grains are subangular to subrounded and consist of clear quartz; feldspar rare; dark-red accessory mineral rare; argillaceous material common; weak argillaceous and calcareous cement	20	20
Upper Cretaceous Series:		
Kirtland Shale, lower part:		
Arenaceous mudstone, yellowish-gray (5*Y* 7/2); sand consists of medium to fine subangular to subrounded grains of clear quartz; weak calcareous cement	30	50
Arenaceous siltstone, yellowish-gray (5*Y* 7/2) and pale-brown (5*YR* 5/2); sand consists of fine to very fine subrounded to subangular grains of clear quartz; mica common; weak calcareous and argillaceous cement	10	60
Mudstone, light-gray (*N* 7) to medium-gray (*N* 5); mica common; weak calcareous cement	30	90
Argillaceous sandstone, very light gray (*N* 8); sand consists of fine to very fine subrounded grains of clear quartz; mica common; feldspar rare; argillaceous material common; weak calcareous and argillaceous cement	20	110

Description	Thickness (feet)	Depth (feet)
Upper Cretaceous Series—Continued		
Fruitland Formation:		
Mudstone, light-gray (*N* 7); mica rare; weak calcareous cement	10	120
Arenaceous siltstone, light-gray (*N* 7); sand consists of fine to very fine subrounded grains of clear quartz; mica rare; argillaceous material abundant; weak argillaceous and calcareous cement	10	130
Mudstone, medium-gray (*N* 5); weak calcareous cement	20	150
Mudstone, medium-gray (*N* 5) to black (*N* 1); carbonaceous material and coal abundant; weak calcareous cement	20	170
Arenaceous siltstone; sand consists of fine to very fine subrounded grains of clear quartz; mica rare; weak argillaceous and calcareous cement	30	200
Mudstone, medium-gray (*N* 5); carbonaceous material and coal common; weak calcareous cement	20	220
Mudstone, medium-gray (*N* 5); weak calcareous cement	30	250
Siltstone, black (*N* 1); carbonaceous material and coal abundant; weak calcareous cement	20	270
Mudstone and claystone, medium-gray (*N* 5); weak calcareous cement	15	285
Siltstone, black (*N* 1); carbonaceous material abundant and coal common; weak calcareous cement	10	295
Mudstone and claystone, medium-gray (*N* 5); coal common; weak calcareous cement	10	305
Siltstone, black (*N* 1); carbonaceous material abundant and coal common; weak calcareous cement	5	310
Mudstone, medium-gray (*N* 5); coal common; weak calcareous cement	10	320
Arenaceous siltstone, light-gray (*N* 7); sand consists of fine to very fine subrounded grains of clear quartz; argillaceous material common; mica rare; weak calcareous cement	20	340
Siltstone, black (*N* 1); carbonaceous material abundant and coal common; weak calcareous cement	10	350
Mudstone, medium-gray (*N* 5); weak calcareous cement	30	380
Pictured Cliffs Sandstone:		
Sandstone, light-gray (*N* 7), very fine grained, well-sorted; sand grains are subangular and consist of clear quartz; mica and feldspar rare; argillaceous material common; weak argillaceous and calcareous cement	15	395
Mudstone, black (*N* 1); carbonaceous material abundant and coal common; weak argillaceous and calcareous cement	10	405
Silty sandstone, very light gray (*N* 8), fairly well sorted; sand consists of fine to very fine subrounded grains of clear quartz; dark accessory mineral rare; argillaceous material rare; weak calcareous cement	55	460
Lewis Shale:		
Silty sandstone, light-gray (*N* 7), well-sorted; sand consists of very fine subrounded grains of clear quartz; mica common; dark accessory mineral rare; argillaceous material common; weak calcareous cement	20	480

Description	Thickness (feet)	Depth (feet)
Upper Cretaceous Series—Continued		
Lewis Shale—Continued		
Arenaceous siltstone, very light gray (*N* 8); sand consists of very fine subrounded grains of clear quartz; mica common; argillaceous material common; weak calcareous cement	10	490
Claystone, medium-gray (*N* 5); weak calcareous cement	30	520
Siltstone, medium-gray (*N* 5); dark accessory mineral and mica common; weak calcareous cement. Foraminifer *Lenticulina*? present at 650-ft level	140	660
Cliff House Sandstone of the Mesaverde Group:		
Sandstone, light-gray (*N* 8), coarse to very fine grained, fairly well sorted; sand consists of subangular to subrounded grains of clear quartz; mica and dark accessory minerals rare; pyrite abundant; limonite common; weak calcareous cement; pyrite also a cementing material	80	740
Arenaceous siltstone, light-gray (*N* 8); sand consists of very fine subrounded to subangular grains of clear quartz; weak calcareous cement	40	780
Arenaceous siltstone and mudstone, light-gray (*N* 8) to medium-gray (*N* 5); sand consists of very fine subrounded to subangular grains of clear quartz; weak calcareous cement	20	800

Total depth of well	800 ft
Depth to water level	280 ft
Water-bearing formation[1]	Cliff House Sandstone
Water-bearing zone	660–740 ft
Well bailed at	15.4 gpm for 2½ hr
Drawdown	160 ft
Well cased to	666 ft with 10-in. O. D. casing
Driller	Perry Bros.

[1] Water of poor quality was found in the Fruitland Formation and the Pictured Cliffs Sandstone but was sealed off by casing.

APPLICATION OF SUBSURFACE DATA TO FIELD PROBLEMS ON THE NAVAJO INDIAN RESERVATION

The subsurface information obtained by drilling on the Navajo Indian Reservation has been invaluable in helping solve numerous problems in the development of water supplies from wells. By 1953, logs of the strata penetrated in the drilling of 200 wells had been assembled. These wells, which are in all parts of the reservation, range in depth from less than 100 feet to more than 7,200 feet, the deepest being an oil test. Most of the water wells are between 300 and 1,200 feet deep, but a few are as much as 1,800 to 2,000 feet deep.

HYDROLOGIC PROBLEMS

If a water well is to be drilled, the log of a nearby well is highly valuable in that it provides information on the kind of rocks that will be penetrated and the depth to which it will be necessary to drill to obtain water. If the log also provides information on the quantity and quality of the water, it is all the more valuable. By taking into account the geologic structure of the area, it is sometimes possible, from the water-level data given in the log, to predict quite accurately the amount of water-level rise that will occur when a well is drilled into an artesian aquifer. If used in conjunction with the drilling of a well, the stratigraphic and hydrologic data contained in a log of a well drilled earlier at the same or a nearby site may also help to insure the success of the new well. For example, if the rock cuttings being brought to the surface are examined concurrently with the drilling of the well, the position of the drill in the stratigraphic section can be known at all times. Furthermore, the driller can be given advance information on the depth to, thickness, and lithology of the water-bearing beds, on the desirability of developing water from some, and on the necessity to seal off others. If the driller is forewarned of beds that are likely to cave during the drilling operations, he can take the precautions necessary to prevent their caving.

The log on page H8 is typical of those for wells drilled by a cable-tool rig into Upper Cretaceous rocks in the northern part of the San Juan Basin. Because the lithologic breaks are sharp and clear, the stratigraphic units could be identified readily. As both the Fruitland Formation and the Pictured Cliffs Sandstone yielded highly mineralized water, and the intervening Lewis Shale tended to cave, casing extending from the surface to a level about 6 feet below the top of the Cliff House Sandstone was installed to insure shutting out the water of poor quality and to prevent caving of the shale. Open-hole drilling deeper into the Cliff House Sandstone encountered water that contained 3,000 ppm (parts per million) of dissolved solids and 500 ppm of chloride. As a bailer test showed that an adequate supply of water was available and as the water was chemically suitable for stock, although not for human use, the well was developed for use as a stock-supply well.

The information obtained in drilling this well greatly assisted in the selection of a site, 15 miles due north of the well, for a second well that also would tap the Cliff House Sandstone. The sandstone dips generally northeastward from Hogback Mountain, which lies to the west and is the recharge area for the Cliff House Sandstone. Because the water in the formation must percolate in the direction of dip and the aquifer at the site for the second well was at a lower altitude than at the well already drilled, it was known that the water at the site selected for the second well would be under somewhat greater artesian pressure than at the location of the well already drilled. Also, because the site for the proposed well was only a little farther from the recharge area than the well already drilled, it could be predicted that the water would not be significantly more mineralized. Furthermore, because drilling for the proposed well would begin stratigraphically higher (in the Farmington Sandstone Member of the Kirtland

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Shale) and because all the stratigraphic units were known to thicken northward, it could be predicted that the proposed well would need to be drilled considerably deeper than the first well if it was to tap the Cliff House Sandstone. Examination of the drill cuttings during the drilling of the proposed well would provide the information needed to insure the proper sealing off of water of poor quality, such as had to be sealed off in the well already drilled.

GEOLOGIC PROBLEMS

The information contained in well logs is used in solving stratigraphic problems in much the same way that measured sections are used. By providing information on the thickness and lithologic characteristics of the stratigraphic units, the logs furnish clues, not otherwise obtainable, as to thickening, thinning, and facies changes of the different units in the subsurface. Cross sections based on logs often confirm stratigraphic relationships, such as intertonguing or truncation of units, which generally can only be surmised from the examination and correlation of outcropping rocks.

In those parts of the Navajo Indian Reservation where homogeneous crossbedded sandstone is the only outcropping rock, the geologic structure is not obvious from observations at the surface. However, where several wells have been drilled into the formation underlying the sandstone, some idea of structural conditions can be obtained by determining the altitude of the land surface at each well and computing the altitude of the top of the underlying formation. The distribution and number of wells, of course, determine whether structural conditions can be resolved in detail.

Information on the thickness of subsurface stratigraphic units, as determined by drilling, provides a check against the measurements of the thickness of the same units where they crop out. Although, ordinarily, the thicknesses are nearly the same, drilling occasionally reveals a significantly greater thickness for a stratigraphic unit than had been measured on the surface. Differences in thickness are more likely in relatively thick units composed principally of shale and in units that have been sharply folded. Where greater thicknesses characterize units along the axis of either a synclinal or an anticlinal fold, they may be reasonably explained as due to plastic flowage in incompetent strata. Where folding obviously is not an explanation for a discrepancy in thickness, as in places where beds are flat lying or dip slightly, the discrepancy may be due to an error, accounted for by concealed intervals, in the measurement made of the outcropping rocks. The possibility that faulting accounts for a difference in thickness also should not be overlooked. On the Navajo Indian Reservation, for example, the excessive thickness of the Chinle Formation, which was penetrated in drilling a well at the Iyanbite Day School, is known to be the result of faulting. In a few instances, a seemingly too great thickness measured on the surface has been verified through comparison with the subsurface thickness as determined by drilling.

In some areas, subsurface data are of great value in areal geologic mapping, especially where dipping or folded bedrock is concealed beneath unconsolidated deposits. Not only can concealed stratigraphic units generally be identified from cuttings, but their structural attitude and the approximate position of the contacts between them can often be determined.

CONSTRUCTION OF A PEG MODEL

As a means of graphically portraying the stratigraphic and hydrologic relationships of the Navajo Indian Reservation, the data obtained by drilling wells were plotted on four-sided pegs which were so arranged and mounted as to represent both the spatial arrangement and relative altitude of the wells themselves. A graphic log of the stratigraphic units penetrated in drilling is shown on one side of a peg, the water level and water-yielding beds are shown on a second side, the chemical quality of the water is shown on the third side, and miscellaneous pertinent data are shown on the fourth side. The peg model has proven highly valuable in presenting information in a three-dimensional manner, particularly to those not familiar with the more conventional modes of geologic and hydrologic illustration. Because the peg model portrays both regional and local relationships, it can be applied directly to the solution of water-supply problems on the reservation.

CONCLUSION

If, when wells are drilled in a given area, drill cuttings are sampled systematically, examined under a microscope, and described carefully, there results a library of highly valuable information on subsurface geologic and hydrologic conditions in that area. Such information not only aids the unravelling of stratigraphic and structural problems in geologic studies but also helps in the selection of sites for and the successful drilling of production wells.

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JETTING METHOD OF INSTALLING SMALL-DIAMETER WELLS

By Edward A. Moulder and Mervin L. Klug

ABSTRACT

An abundance of wells facilitates the making of detailed ground-water studies, each well serving as a "peek hole" through which subsurface hydrologic conditions can be observed. Where the water-bearing material is unconsolidated and is within about 50 feet of the land surface, wells satisfactory for the observation of water-level fluctuations or for pumping when making aquifer tests can be installed relatively cheaply and quickly by the jetting method. As described in this paper, the jetting method consists of a combination of jetting and rotary drilling.

When a water-level observation well is to be installed, a jet tube terminating in a bit is advanced into the ground as the material is loosened by the jetting action of the water and agitation of the bit. The loosened material is washed to the land surface through the annular space between the jet tube and the wall of the hole. On emerging from the hole, the jetting fluid is channeled into a pit, where the larger particles settle to the bottom, and then into a connecting reservoir pit. The muddy water from the second pit is recirculated through the jet tube and back to the land surface, thereby conserving water and at the same time plastering the sides of the hole with a mud layer that helps to prevent caving. When the desired depth is reached, the hole is flushed clean with clear water. A pipe with strainer attached is lowered inside the jet tube before the jet tube is extracted. After the resulting well has been developed by surging and pumping, the space around the pipe is filled in.

When a small-diameter production well would be satisfactory for use in making an aquifer test, one can be installed by coupling a length of pipe to a jet point and advancing it into the ground by the jetting process. When the desired depth has been reached, the resulting well is completed by surging and pumping.

The jetting equipment can be used to obtain subsurface geologic information. It also has proved to be useful for both cleaning large-diameter wells and pumping water from them.

SPECIFICATIONS FOR OBSERVATION WELLS

Drainage studies on the Buffalo Rapids irrigation project along the Yellowstone River near Glendive, Mont., and on the Crow Indian Reservation along the Little Bighorn River, also in Montana, required that a large number of observation wells be installed. Requirements governing the installation of observation wells included the following: (a) Each observation well must be of permanent construction and must be sensitive to rapid fluctuations of water level, (b) an accurate log of the general nature of the material to the depth penetrated must be obtained, and (c) installation costs must be fitted to a limited budget. A study of methods employed by several other investigators indicated that the jetting method was most suitable for installing the wells under the limitations of the project at hand.

Many pieces of equipment and various techniques were tested before adopting a procedure that best suited the available equipment and materials. Although the general procedure remained unchanged, further innovations materially reduced the labor and time involved.

The methods described should be applicable in any area of unconsolidated deposits where the depth of the wells will not exceed 50 feet, where the thickness of very coarse gravel to be penetrated does not exceed 10 feet, and where a small-diameter well will be satisfactory.

PRINCIPLES OF THE JETTING TECHNIQUE

Jetting, as described by Bowman (1911, p. 76), consists of forcing two pipes, one inside the other, into a hole which is being deepened by ejecting water, under pressure, through a combination bit and jet nozzle at the lower end of the inner pipe. The jetting action serves to loosen the material in and below the outer pipe and allows the larger pipe to be advanced into the ground. The water and the eroded material in suspension are carried to the surface through the annular space between the two pipes. When the desired depth has been reached, the inner pipe is extracted and the outer pipe remains to serve as the well casing.

A single-tube jetting method is described in this paper. In principle, the procedure is a combination of jetting and rotary drilling. The technique, illustrated in figure 1, is as follows: A pipe is advanced into the ground as the material is loosened by the jetting action of the water and the agitation of the bit. The loosened material is washed to the land surface through the annular space between the pipe and the wall of the hole. At the land surface the jetting fluid is channeled into a pit where the larger particles settle to the bottom and then is channeled into a connecting reservoir pit. To conserve water and to stabilize the sides of the hole, muddy water from the reservoir pit is recirculated through the pump.

High pressure obtained through the use of a nozzle and a high-pressure pump appears to offer no advantage. In a loose material rapid progress can be made without high pressure, and in a tight material the cutting action of the bit agitated against the bottom of the hole is more effective than high jet pressure. In fact, high pressure often impedes progress because it tends to force the bit off the bottom of the hole and thus reduces the cutting action of the bit.

When a hole is being jetted into coarse-grained material, water from the jetting cycle may be lost by seepage into the coarse material. Although the loss generally is reduced by the sealing action of the

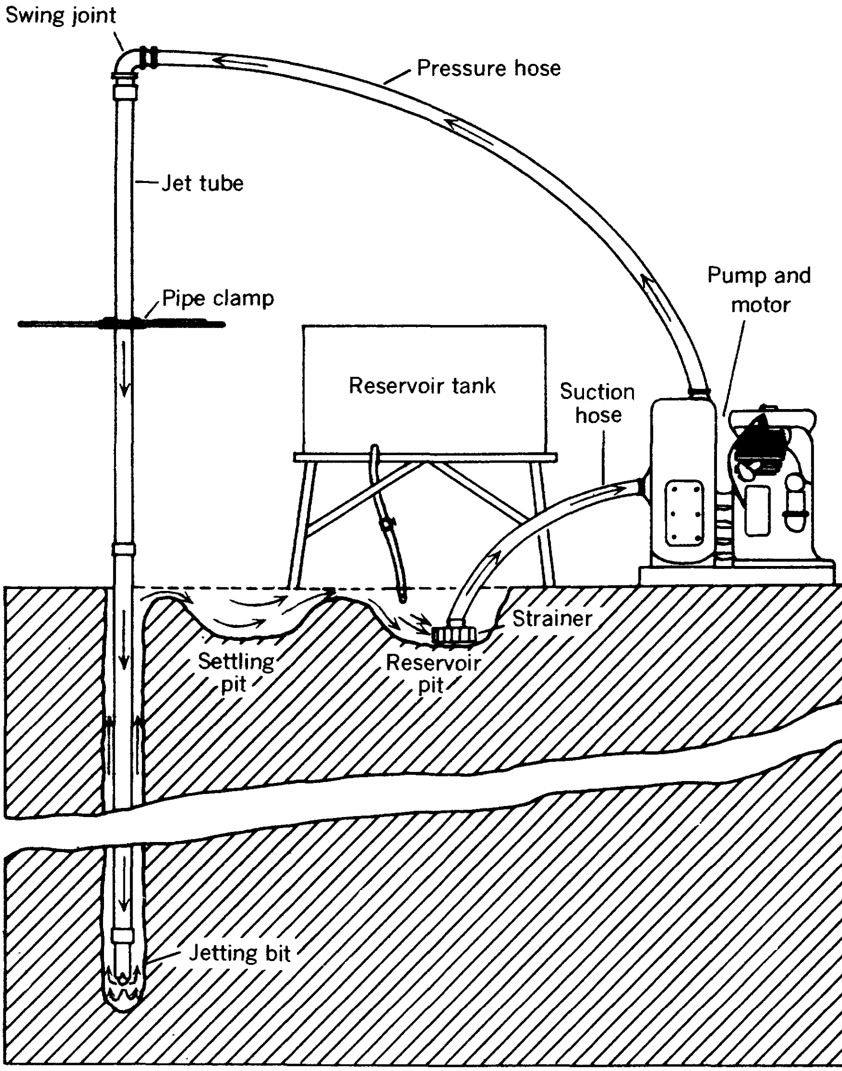

FIGURE 1.—Schematic drawing of single-pipe method of jetting small-diameter wells.

circulating mud, a source of additional water may be needed to maintain a working fluid level in the reservoir pit. In some instances the mud content of the jetting fluid may need to be increased to maintain the return flow of fluid to the surface. Progress in very coarse gravels and cobbles ordinarily can be made only if considerable fine-grained material also is present. A bit designed to loosen the gravel allows the coarser material to be pushed to one side while the fine-grained material is washed to the surface.

BASIC EQUIPMENT FOR JETTING OPERATIONS

The basic equipment needed for conducting jetting operations is as follows:

Jet tube.—Standard pipe having an inside diameter large enough to accommodate the finished well pipe and strainer is used for the jet tube. The length of pipe is determined by the expected depth of hole or convenience in handling.

Jet bits.—If materials of different hardness or texture are to be penetrated, the bits should be designed accordingly. (See fig. 2.) The bits should be interchangeable.

Hoses.—Both the pressure hose and the suction hose should be of the same diameter as the jet tube and long enough to accommodate the arrangement of the equipment. The pressure hose should be reinforced but should not be too heavy for easy handling, and the suction hose should be of the noncollapsible type and fitted with a strainer at one end to prevent passage of larger particles into the pump. Standard hose couplings to fit the pump and jet tube should be attached.

Reservoir.—A portable tank should be fitted with a gravity discharge and an opening for an air vent and for filling with water. The capacity of the tank should be as large as practicable so as to eliminate an excessive number of trips to refill it with water.

Pump.—The pump should be a self-priming centrifugal pump capable of passing sand without excessive wear of pump parts. If the diameter of the jet tube is 2 inches, the pump should be capable of discharging at least 50 gpm (gallons per minute) at a pressure of 40 psi (pounds per square inch). If smaller pipe is used, the discharge rate may be reduced slightly but the pressure rating should be increased.

Miscellaneous equipment.—Pipe wrenches and pipe clamp (fig. 3), shovel for digging circulating pits, steel brush for cleaning pipe threads, oil can, screwdriver, and pitcher pump.

EQUIPMENT ADAPTED FOR WORK IN MONTANA

Because of the large number of holes to be drilled, and to speed operations, the equipment used in Montana is more elaborate and is mounted on a 4-wheel-drive vehicle.

The jet tubes or pipes (upper fig. 4) are made of 2-inch galvanized pipe. A welded bead around the pipe at 1-foot intervals provides durable graduations that aid in the logging of the hole. Convenient lengths of jet pipe may be attached to the 2-inch pressure hose by

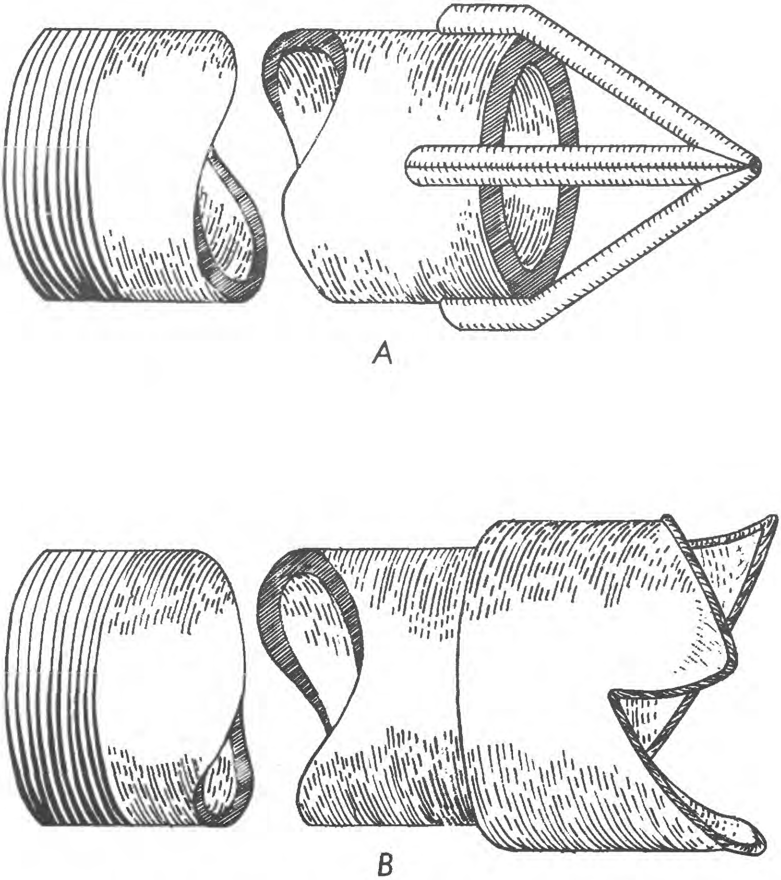

FIGURE 2.—Drilling bits used in jetting holes for observation wells. *A*, "Clay" bit used for drilling in tight fine-grained materials. Constructed by welding ¼-inch triangular tempered steel bars to threaded 2-inch nipple. Point and outer edges sharpened by grinding. *B*, "Gravel" bit used for setting strainer and for drilling in loose sandy material or gravel. Constructed by cutting 3 teeth on a 2-inch pipe and then capping cutting edges with a wear-resistant welded bead.

means of a standard brass single-swing joint (lower fig. 4) so that the pipe can be rotated about its longitudinal axis without twisting the pressure hose.

A 240-gallon tank mounted on a truck is used as a portable reservoir. The valve arrangement (figs. 5, 6) allows water to be discharged from the tank to the pump or to the reservoir pit. An opening in the top of the tank serves as an air vent as well as a place to fill the tank. By removing a plug in the bottom of the tank, it may be drained and cleaned.

The pump used is a Jaeger model 2PAFH, powered with a Wisconsin gasoline engine rated at 5.9 hp (horse power) at 3,400 rpm

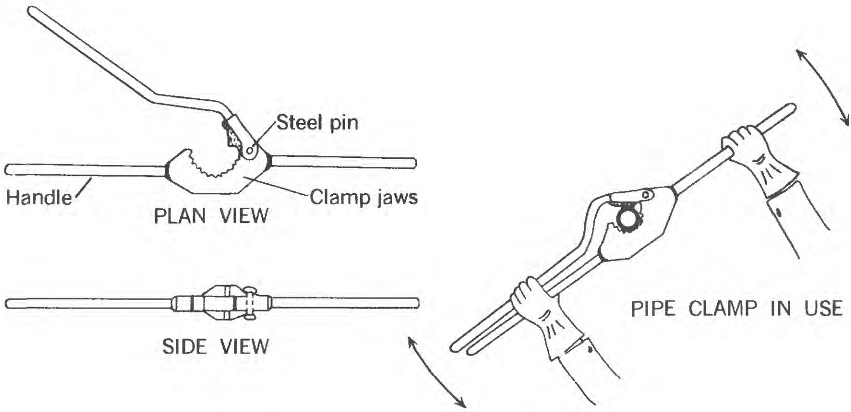

FIGURE 3.—Pipe clamp showing method of attaching it to jet tube.

(revolutions per minute). It is designed to deliver 80 gpm with a 10-foot suction lift at a discharge pressure of 40 psi. This quantity of water is sufficient to wash to the surface pebbles slightly larger than 1 inch in diameter. The pump is mounted on a 4-wheel-drive truck and attached to the tank and hoses by a convenient arrangement of valves and pipe fittings. By manipulating the lever-action gate valves, water may be pumped from the reservoir tank or from the reservoir pit. The screw-type gate valves allow water to be discharged to the reservoir tank or through the pressure hose.

Other equipment includes lightweight-alloy 24-inch pipe wrenches, smaller pipe wrenches for handling well pipe, other miscellaneous hand tools, pipe vise, pipe cutter, pipe threader and dies, pitcher pump, and pipe and hose racks mounted on the side of the truck.

PROCEDURE FOR INSTALLING A WELL

JETTING THE HOLE

Starting with a full tank of water and the jetting equipment, the truck is driven to the drilling site. There, while one man is digging the pits, the others unload and assemble the jetting equipment. The suction hose having been placed in the reservoir pit, the jet tube with the discharge hose attached is erected in a vertical position over the spot selected for the hole. (See fig. 7.) The pump is started and the valves are adjusted so that water from the reservoir tank is pumped through the jet tube. When both pits are full, the valve on the line from the reservoir pit is opened; the lever-type valves permit this to be done quickly. By gripping the pipe clamp, the jet tube is turned about its longitudinal axis with an oscillating motion. Loss of water by seepage to the ground requires that the valve on the line to the

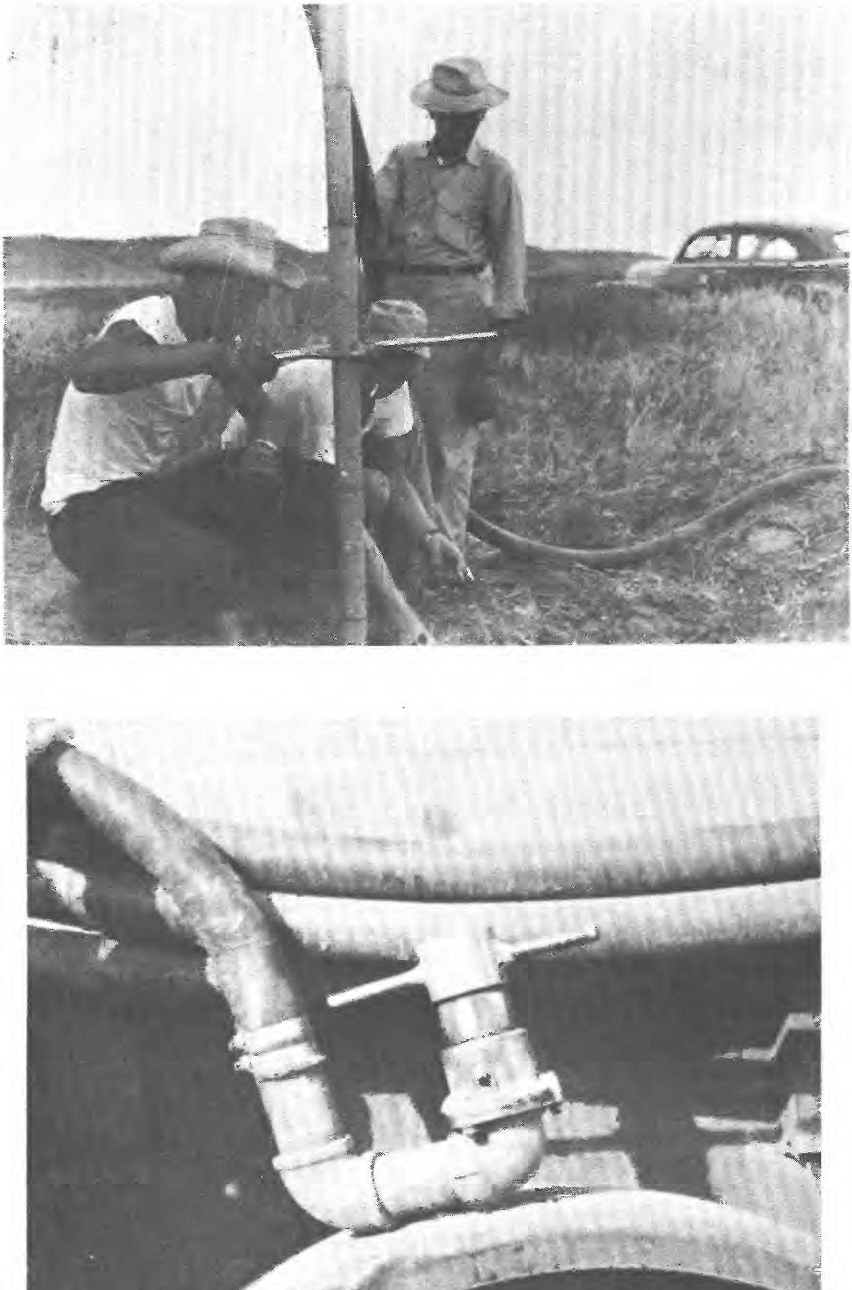

FIGURE 4.—Jet tube and single-swing swivel head used with jetting equipment in Montana. Upper, Graduated jetting tube erected in jetting position. Lower, Single-swing brass joint fitted with coupling and hand lugs.

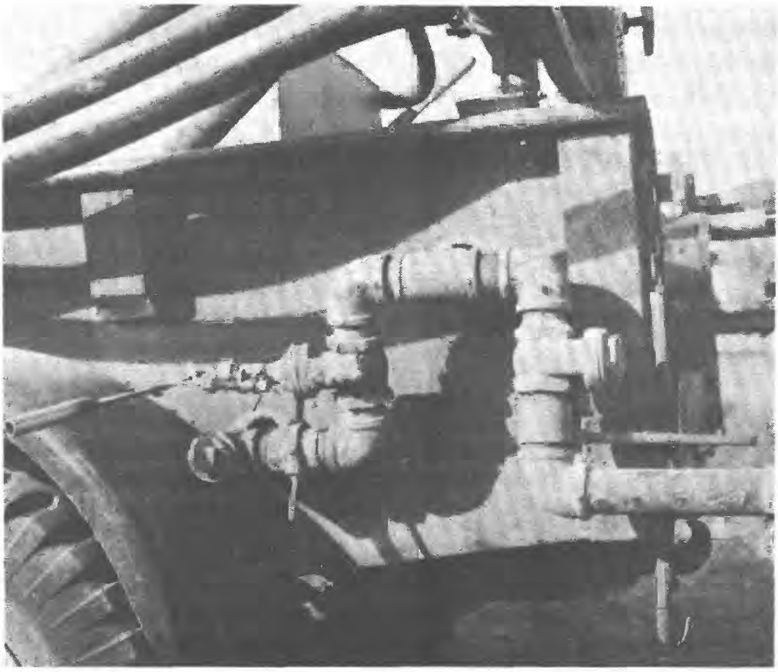

FIGURE 5.—Valves connected to suction side of truck-mounted pump. Valve on left side is attached to line from reservoir tank. Valve on right side is attached to line leading to suction hose. The valves were made from screw-type gate valves by reaming out the threads and adding the lever-handle assembly. The valves are placed in vertical parts of the line so that the gate seats will not collect sand.

reservoir tank be opened from time to time to keep the water in the pits at an operating level. When water in the reservoir tank is exhausted, the pump is shut off and the pressure hose is disconnected from the truck by loosening a pipe union fitted with hand lugs. The suction hose is placed on the hose rack, and the truck is driven to a pond or other source of water. Here the suction hose is placed in the water, the valves are adjusted, and water is pumped into the reservoir tank. Jetting then is resumed and, when needed, additional lengths of graduated pipe are coupled to the jet tube.

Two types of bits (fig. 2), each 1 foot long, are used interchangeably on the jet tube. The cutting surfaces of the bits are made of tempered steel to resist wear. The "clay" bit, which is used in tight fine-grained material, is designed to allow the cutting edges to make a hole slightly larger than the pipe, thus permitting the water to circulate freely to the surface. Although the "gravel" bit is designed primarily for use in coarse gravel, it is satisfactory for use in loose sandy material also. Its teeth are designed to loosen the gravel and to push the large cobbles to one side while the action of the jet washes the smaller particles loose.

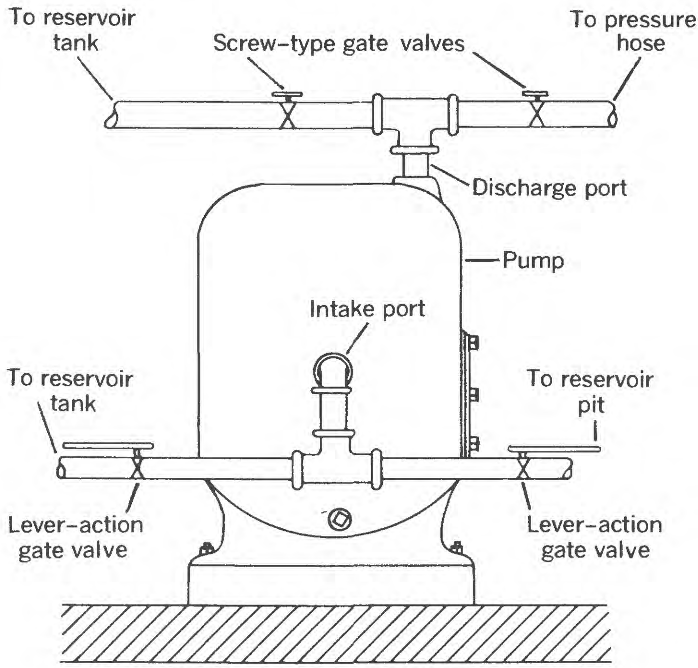

FIGURE 6.—Valve arrangement on jetting equipment.

FIGURE 7.—Graduated jetting tube in jetting position.

The teeth are made so that the leading edges tend to tighten the coupled joints of the pipe as it is turned with an oscillating motion about its longitudinal axis. The bit is constructed with an open end so that it may be left in the hole when setting an observation-well strainer in material that caves easily.

Two-inch hose is used on both the suction and discharge sides of the pump. The discharge hose is a lightweight fabric-reinforced rubber hose about 30 feet long with connections at each end adapted for standard 2-inch pipe threads. The suction hose is about 20 feet long and is made of rubber reinforced with spring steel wire to prevent its collapsing.

Jetting is started with the "clay" bit where the upper materials to be penetrated are fine grained. When coarse gravel or sand is encountered, jetting operations cease while the jet tube is withdrawn from the hole and the "clay" bit is replaced with the "gravel" bit. To expedite the work, it is more convenient to carry two jet tubes, one fitted with a "clay" bit and the other with a "gravel" bit so that changing of bits is unnecessary. After the "gravel" bit penetrates a caving material, it is unwise to change back to the "clay" bit because the hole is likely to collapse. Progress may be continued at a slower pace by continued use of the "gravel" bit in the fine-grained material.

The rate of penetration through the more resistant layers may be increased by repeatedly lifting up and forcibly lowering the jet tube. This action is used not only to penetrate dense clay, but also to break up or shove aside a boulder that is impeding progress. Added weight placed on the jet tube (for example, a man standing on the pipe clamp) also speeds progress through dense materials, but caution should be exercised to prevent plugging the bit.

Logging of the strata being penetrated is accomplished by examining the material washed to the surface, by observing the rate of penetration of the jet tube, and by judging the "feel" as the pipe is turned by the pipe clamp. This information is recorded on a mimeographed form prepared for the field record of the well (fig. 8). Jetting proceeds rapidly in a loosely packed sandy material, whereas much slower progress is made in a clay or coarse gravel. The difference in "feel" between the clay and gravel is easily detected. Although the identification of materials is less accurate than by some drilling methods, it is possible by continued practice to make reasonably accurate logs of the material penetrated. If a greater degree of accuracy is desired for the uppermost material, a hand auger may be used to bore to a level where caving prevents further progress by this method.

Field No. ______

Coordinate No. ______________. Party __________. Date ______________

Topography ____

Location (sketch)

Log of jetted hole:

Material	Thickness	Depth to bottom

Time jetting completed ________________ .

Length of pipe and strainer __________________ feet.

Development remarks ____

Height of M. P. ____ feet above L. S. D. Water level ____ feet below M. P.

Time ________ .

Remarks: ____

FIGURE 8.—Sample form for recording observation-well field data.

COMPLETION OF AN OBSERVATION WELL

When the bit has reached the depth desired for the observation well that is to be installed, clean water from the tank is used to flush from the hole the remaining loose fine-grained material. The hose then is removed from the jet tube.

The observation well is cased with a suitable length of ¾-inch pipe to which is attached a brass strainer of appropriate slot size (fig. 9A).

The appropriate slot size is determined from the grain size of the material that will surround the strainer. Inexpensive strainers of different slot sizes are available commercially. The pipe is cut so that when the installation is complete the pipe will extend 2 to 3 feet above the land surface. The pipe and attached strainer are then lowered to the bottom of the hole inside the jet tube. Then the jet tube is withdrawn from the hole, leaving the pipe and strainer in place. If caved material makes difficult the extraction of the jet tube, a pipe jack or other device may be used to lift it. A small A-frame mounted on the truck frame in front of the truck winch (fig. 10) has proved valuable for this purpose.

Withdrawal of the jet tube allows the water-bearing material to cave around the strainer. If the water level in the well is within suction lift, a pitcher pump is screwed to the top of the ¾-inch pipe and the well is pumped until the water becomes clear, indicating that

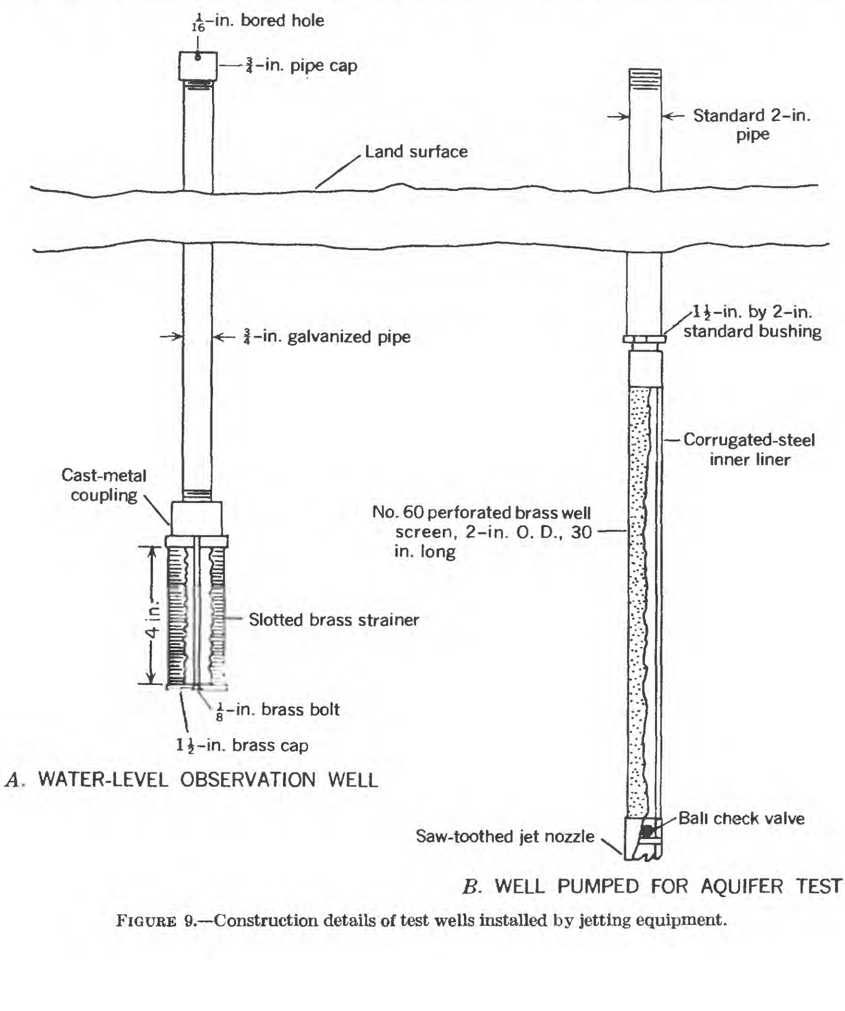

FIGURE 9.—Construction details of test wells installed by jetting equipment.

FIGURE 10.—A-frame and winch assembly used to pull jetting pipe.

the fine sand and silt around the screen have been removed and that a hydraulic connection between the well and the aquifer has been established. If the well fails to yield water, the pipe and strainer are removed and the well is flushed again with the jet tube. It is less time-consuming to do a good job of flushing initially than it is to try to develop the well thoroughly by pumping. Experience has proven that in time the well becomes plugged or partially plugged if a thorough development procedure has not been followed.

If the water level in the well is below suction lift, special care is taken to flush the hole thoroughly before installing the pipe and strainer. The finished well is tested by pouring water into the pipe and measuring the water level to make certain that it returns to its initial level rapidly.

The well is finished by filling the cavity around the pipe with dirt, by capping the pipe, and by drilling a small hole in the side of the cap near its top for an air vent. The part of the pipe extending above the land surface is painted a bright orange to facilitate detection from a distance. The pits are filled with dirt and the disturbed land is leveled while the truck is being loaded in preparation for movement to the next well site.

OTHER USES FOR JETTING EQUIPMENT

The jetting equipment is very useful for performing functions other than installing small-diameter observation wells. It is used to install wells that can be pumped for an aquifer test; to clean, develop, and pump wells having a diameter greater than that of the jet tube; and to install a special type large-diameter observation well.

Jet points (fig. 9*B*) manufactured by several well-point companies are successfully used to construct production wells. Such wells are installed by attaching the discharge hose of the jetting equipment to a suitable length of pipe coupled to a jet point and proceeding as with the jet tube. After the desired depth is reached, the equipment is used to surge, develop, and pump the well.

By using the wellhead shown in figure 11, the jetting equipment can be used to develop and pump water from large-diameter wells. Regulation of the valves permits water to be pumped from or into the well without any pipe or hose connection having to be changed. Thus, abandoned wells may be cleaned and developed for use as observation wells by lowering the jet tube inside the casing and flushing the well. Also, a well not equipped with a pump can be used as the discharging well in an aquifer test by pumping it with the jetting equipment.

The upper part of the special-type large-diameter observation well consists of a length of casing large enough to accommodate the float for a water-level recording gage. The casing is set a few feet below the water level but not into the water-bearing gravel. Hydraulic connection with the gravel is obtained by driving or jetting a well point inside and below the bottom of the casing and then uncoupling it a few feet below the expected low water level. This method of constructing wells requires an accurate knowledge of the substrata so that the well point can be positioned accurately before it is uncoupled from the pipe.

The jetting tube can be used also as a probing tool in obtaining a general knowledge of subsurface geology.

LIMITATIONS OF JETTING EQUIPMENT

The speed of installation is dependent upon the equipment used, the depth of the well, the type of materials penetrated, and the manpower used. Where the average depth of the hole is about 20 feet and about 5 feet of gravel is penetrated, a 3-man crew can complete an average of 4 to 6 wells per working day; a 5-man crew can complete 7 to 9 wells per working day. The rate of penetration varies widely in fine-grained materials, from several feet per minute in loose sandy materials to as little as 10 feet per hour in heavy clay. The construction time per well increases rapidly where greater thicknesses of coarse gravel are penetrated.

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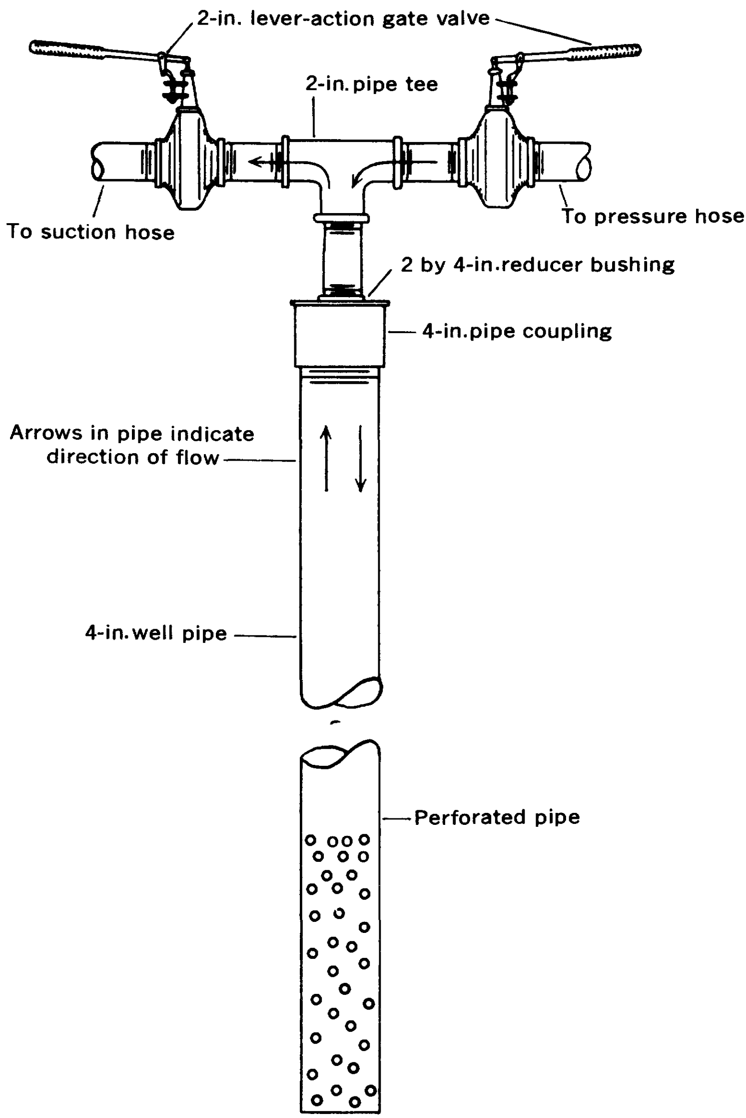

FIGURE 11.—Details of wellhead used with jetting equipment for surging and developing wells.

Use of the described equipment to drill to a depth exceeding 50 feet is impracticable because the increased weight makes the jet tube too heavy to manipulate by hand. In materials where the jetting action of the water is sufficient to make rapid progress, deeper wells could be jetted if pipe of lighter weight were used or if the jet tube were handled by mechanical means.

CONCLUSION

The single-pipe jetting method has proven to be a fast and economical means of installing permanent ¾-inch diameter shallow observation wells in unconsolidated materials. It offers the following advantages: A minimum of equipment is required; the finished well is inexpensive; the equipment may be operated by unskilled labor with a minimum of supervision; the well requires little maintenance, if it is developed properly when first installed.

The versatility of the jetting rig is evidenced by the many other jobs it will perform. Among these are the installation of shallow wells as much as 6 or 8 inches in diameter for use with float-type water-stage recorders; installation of 1¼-inch diameter jet-point wells which may be pumped for an aquifer test; development, cleaning, and pumping of drilled and jetted wells; and quick determination of the nature of shallow subsurface strata. The convenience and economy of jetting equipment make its use very desirable for many ground-water studies.

REFERENCE CITED

Bowman, Isaiah, 1911, Well-drilling methods: U.S. Geol. Survey Water-Supply Paper 257, 139 p.

REVERSE WATER-LEVEL FLUCTUATIONS

By Gordon E. Andreasen and Joseph W. Brookhart

ABSTRACT

The water level in a well that taps an aquifer 1,000 feet below the surface at Easton, Md., rises whenever water is pumped from a nearby well that taps an aquifer 100 feet below the surface. Conversely, the water level in the deeper well falls whenever the pump on the shallow well is shut off. Similar reverse water-level fluctuations have been observed at Ocean City, Md., at two places in New Jersey, and on Long Island, N.Y. One possible explanation for such water-level fluctuations is the capacity of a compacted granular material to expand in total volume when subjected to lateral pressure; another is that the fluctuations are responses to local loading and unloading of the aquifer. The need for an adequate explanation of the phenomenon and the possibility that reverse water-level fluctuations may provide data usable for computation of the hydraulic characteristics of an aquifer are pointed out.

OBSERVATION OF REVERSE WATER-LEVEL FLUCTUATIONS

Five distinct artesian aquifers underlie the city of Easton in Talbot County, Md., at depths of about 100, 300, 600, 1,000, and 1,100 feet below the land surface. Each of the 100-, 1,000-, and 1,100-foot aquifers is tapped by one or more of Easton's municipal-supply wells. In August 1950, the pump was removed, for servicing, from one of the city wells (Tal-Ce 1) that is a little more than 1,000 feet deep and taps the 1,000-foot aquifer. (See fig. 12.) A water-level recording gage was installed on this well for use during a test of the 1,000-foot aquifer. Twenty feet away from this well is another well (Tal-Ce 2), which is 110 feet deep and taps the 100-foot aquifer. The water level in the deep well was allowed to recover for several days before the aquifer test, and during this time the 110-foot well was pumped intermittently to supply water for the city.

Each time that the pump in the 110-foot well was started, the water level in the 1,000-foot well would rise at a faster rate than its recovery trend and, conversely, when the pump was shut off, the water level would decline slightly before again resuming its recovery trend.

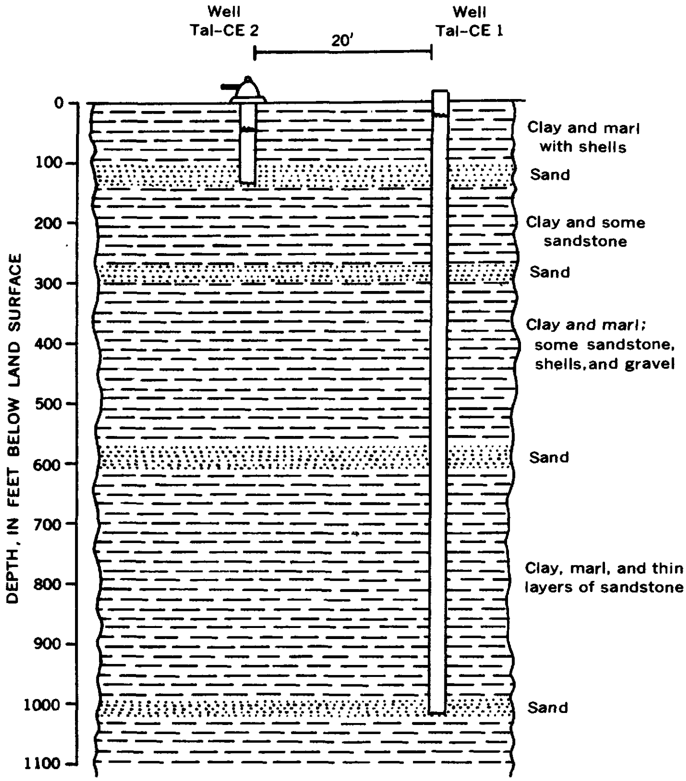

FIGURE 12.—Generalized geologic section at Easton, Talbot County, Md.

(See fig. 13.) After the aquifer test had been completed, several supplemental tests were made in an effort to obtain data that would serve as a basis for an explanation of the observed interrelation between the shallow and deep aquifers. The trace of the recording pen during one such test is reproduced in figure 14. The water level in the deep well began to rise immediately after the pump in the shallow well was turned on and began to fall as soon as the pump was turned off. Because the water-level response in the aquifer from which water was not being pumped was opposite to that in the aquifer from which water was being pumped, it is referred to as a reverse fluctuation.

When measured in September 1950, the temperature of the water in the 100-foot aquifer was 59°F, whereas that in the 1,000-foot aquifer was 72°F. Because it was thought possible that the reverse water-level fluctuations were related to the wide difference in water temperatures, a thermistor was lowered into well Tal-Ce 1 to a depth of 200 feet and the temperature at various depths was read by means of a Wheatstone bridge. The temperature data, shown in figure 15, pro-

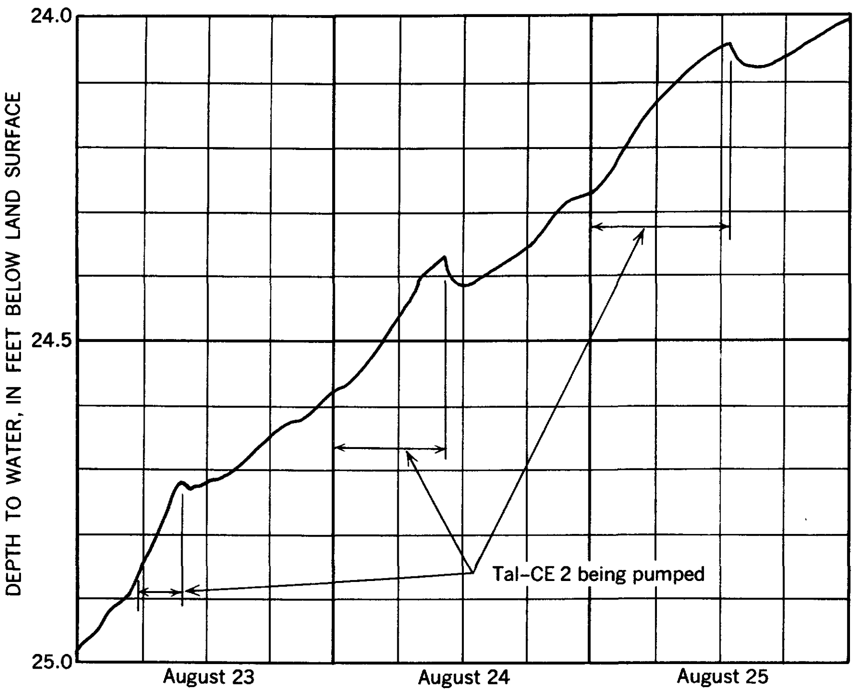

FIGURE 13.—Hydrograph showing reverse water-level fluctuations in well Tal-Ce 1, Aug. 23–25, 1950.

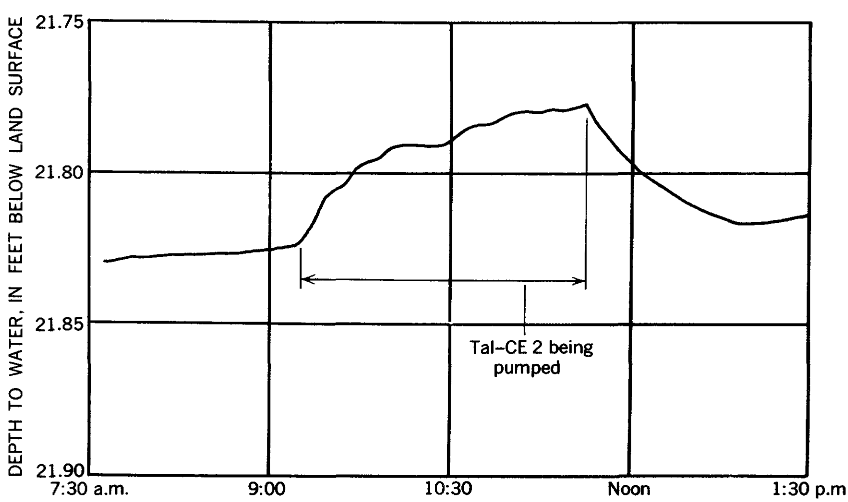

FIGURE 14.—Hydrograph showing reverse water-level fluctuations in well Tal-Ce 1 on Sept. 15, 1950.

vided no obvious explanation for the reverse-fluctuation phenomenon. Furthermore, the rapidity of the water-level response in well Tal-Ce 1 to the pumping of well Tal-Ce 2 indicates a mechanical force rather than a temperature phenomenon.

As the magnitude of the fluctuation was only 0.05 foot, it appeared conceivable that the measuring point might be moving because of compression of sediments resulting from loading stresses due to pumping. An engineer's level was placed at a distance of 300 feet from the observation well, and a rod was placed on the well casing. An additional rod was set approximately in the same line at a distance of 300 feet beyond the level. However, the elevation of neither rod changed perceptibly when pumping from the 110-foot well began or ended.

Similar reverse water-level fluctuations have been observed at Ocean City, Worcester County, Md. There, when a well 185 feet deep is pumped, the water level rises in a well that is 285 feet deep and 160 feet away; both aquifers are artesian. Figure 16 shows the observed effect on the water level in the deeper well when the shallow well was pumped December 12–13, 1951. Before the pump was started, the water level in the deep well was rising in response to the increasing load caused by a rising tide. When the pump was turned on, the observed water level rose sharply, leveled off somewhat, and continued to rise in response to the tide. When the pump was turned off, the water level declined rapidly before resuming the tidal fluctuations.

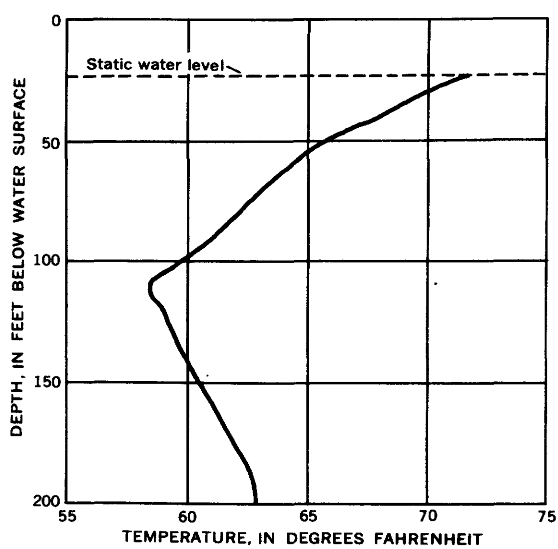

FIGURE 15.—Graph of temperature vs. depth in well Tal-Ce 1 on Sept. 14, 1950.

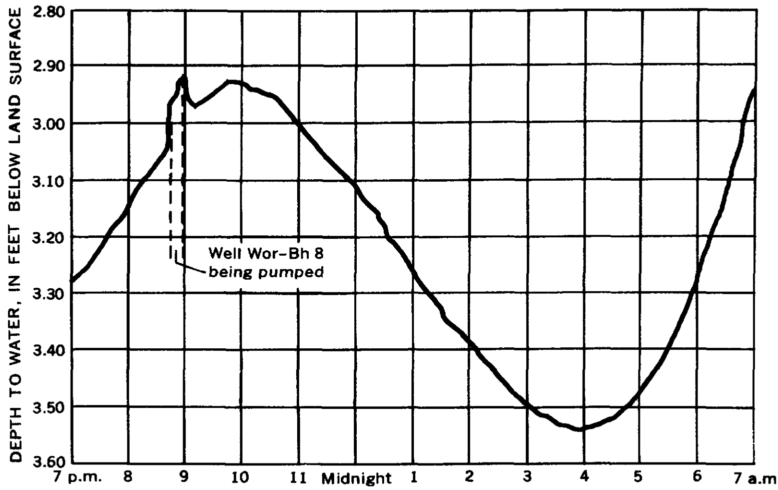

FIGURE 16.—Hydrograph showing reverse and tidal water-level fluctuations in well Wor-Bh 2, Ocean City, Worcester County, Md., Dec. 12–13, 1951.

This phenomenon has been observed also at the Atlantic City Water Works, N.J., at the Whitesville plant of the Monmouth Consolidated Water Co., near Asbury Park, N.J., and also on Long Island, N.Y. (Barksdale and others, 1936, p. 87).

Because the reverse water-level fluctuation is similar to the curve of the water-level drawdown that results from the pumping of a well and to the curve of water-level recovery after pumping is stopped, it is possible that formulas for determination of the coefficients of transmissibility and storage could be derived from the relationship. It appears to be a reasonable assumption that the magnitude of fluctuation is influenced by the amount of water discharged, the thickness and character of sediments, and the distance from the pumped well.

POSSIBLE EXPLANATIONS FOR REVERSE WATER-LEVEL FLUCTUATIONS

Two tentative but different hypotheses to explain the phenomenon of reverse water-level fluctuations have been offered (Barksdale and others, 1936, p. 88–91). One, proposed by the late D. G. Thompson, of the U.S. Geological Survey, is based on the principal of dilatancy, which was first described by Reynolds (1886). Dilatancy is the capacity of a compacted granular material to expand in total volume when subjected to an increase in lateral pressure and, conversely, to contract in total volume when subjected to a decrease in lateral pressure. If pumping of water from a shallow aquifer results in a decrease in pressure on the deeper aquifers, the particles constituting the deeper aquifers presumably would rearrange in such a way that the porosity is reduced—that is, the aquifer would be compressed, thereby forcing the water level in the wells tapping them to rise. On cessation of pumping, the pressure on the deeper aquifers likewise would increase. The increase in pressure then would cause the deeper aquifers to dilate, thus increasing their porosity and resulting in a lowering of the water level in wells tapping them.

The other explanation, suggested by Barksdale, is that the reverse water-level fluctuation results from loading and unloading in the vicinity of the wells. When pumping from a well tapping a shallow aquifer is started, a sudden load is placed on the pump foundation. This load is transmitted to the aquifers below, causing the water level in wells tapping them to rise. Then when the pump is stopped, the load on the pump foundation is removed and the water level in the deeper wells falls. This is in accord with Newton's third law of motion—that every action always has an equal and opposite reaction.

CONCLUSION

Although reverse water-level fluctuations are of small magnitude and therefore of little economic importance, a study of fluctuations of this type holds promise of permitting computation of hydraulic characteristics of aquifers with fewer data than are ordinarily required. The authors suggest that as many cases as possible should be noted and an adequate explanation sought.

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COMPUTATION OF GROUND-WATER VELOCITY FROM TEMPERATURE DATA

By Robert W. Stallman

ABSTRACT

The analytical methods now in use for calculating the hydraulic constants of aquifers require measurement of the distribution of head in space and time and of the discharge from or recharge to the aquifer. Because of these requirements, determination of the desired constants is limited to those areas where adequate testing facilities are available. Indirect methods of measuring ground-water velocity may serve to reduce this limitation.

The simultaneous transfer of heat and flow of water underground results in head and temperature distributions which can be expressed by differential equations. A sample equation is derived for saturated permeable material that is both isotropic and homogeneous insofar as the flow of heat and water is concerned. A sample computation shows that the velocity of ground water has an appreciable influence on the distribution of underground temperatures. Thus, it appears feasible that temperature measurements can be used for calculating flow velocity and that a combination of head and temperature measurements can be used for calculating aquifer permeability.

SCOPE AND PURPOSE OF PAPER

The theoretical solutions to problems in hydrodynamics, heat flow, electricity and magnetism, and other fields have given the ground-water hydrologist several analytical equations that he may use in estimating the hydraulic constants of an aquifer. These equations relate head to discharge, time, space, and hydrologic properties and are applicable to the conditions under which ground water commonly occurs and under which water may be recharged to or discharged from an aquifer (Ferris, 1949; Jacob, 1950; and others). All these equations have been derived through application of Darcy's law to the continuity equation. Thus, determination of the hydraulic constants of an aquifer requires not only measurements of the head distribution in space and time but also measurements of discharge from or recharge to the aquifer at some location where the shape of the flow-field boundary is known.

At most locations in an aquifer, it is altogether impractical to obtain, by direct measurement, the data needed for application of the available analytical equations. Therefore, the hydraulic constants of an aquifer as a function of space generally are determined by interpolating between the results obtained from geologic investigations at a few selected test sites. In some cases, particularly those for which geologic data are few, a satisfactory interpolation can be obtained by numerical methods. Thus far, however, the application of numerical methods to ground-water hydrology has been based wholly on equations for the flow of a homogeneous fluid and does not provide for a direct measurement of permeability except through the use of velocity observations made outside the aquifer.

If some indirect method for measuring ground-water velocity can be found, the utility of field tests to determine the hydraulic constants of aquifers can be greatly extended. The obvious approach is to include, in the testing and analysis, observations of variables (other than the distribution of head) that are directly dependent on the direction and velocity of flow. The purpose of this paper is to call attention to the possibility of utilizing measurements of the distribution of underground temperatures as an indirect manifestation of ground-water velocity.

SIGNIFICANCE OF CONVECTION IN GROUND-WATER FLOW

Detailed information on the spatial distribution of temperatures in aquifers is scarce, and such data as are available seem insufficient for a conclusive determination of the feasibility of estimating ground-water velocity from measurements of underground temperatures. However, a qualitative measure of such feasibility can be gained by a study of the manner in which heat moves through an aquifer.

Aside from geologic considerations, the distribution of temperatures in an aquifer is determined by the manner in which heat moves from one point to another. In the case of fluid flow through a permeable material, the movement of heat occurs principally in two ways. One is by conduction in response to temperature gradients within the saturated material. The other is by convection, such as occurs when the heat contained in the fluid is moved along with, and in the direction of, fluid flow.

An analytical equation relating conduction and convection in terms of ground-water velocity and temperature is required if the relative significance of ground-water flow to the spatial distribution of temperatures is to be determined. Although Schild (1957) and others have published equations that relate these factors, they have emphasized those problems in which temperature variations cause significant changes in the properties of the flowing fluid. A differential equation expressing the flow of heat through a saturated permeable material is derived first so that the assumed conditions will be understood fully.

Shown in figure 17 is an element of volume, $dx\,dy\,dz$, of permeable material, which is assumed to be isotropic, homogeneous, and fully

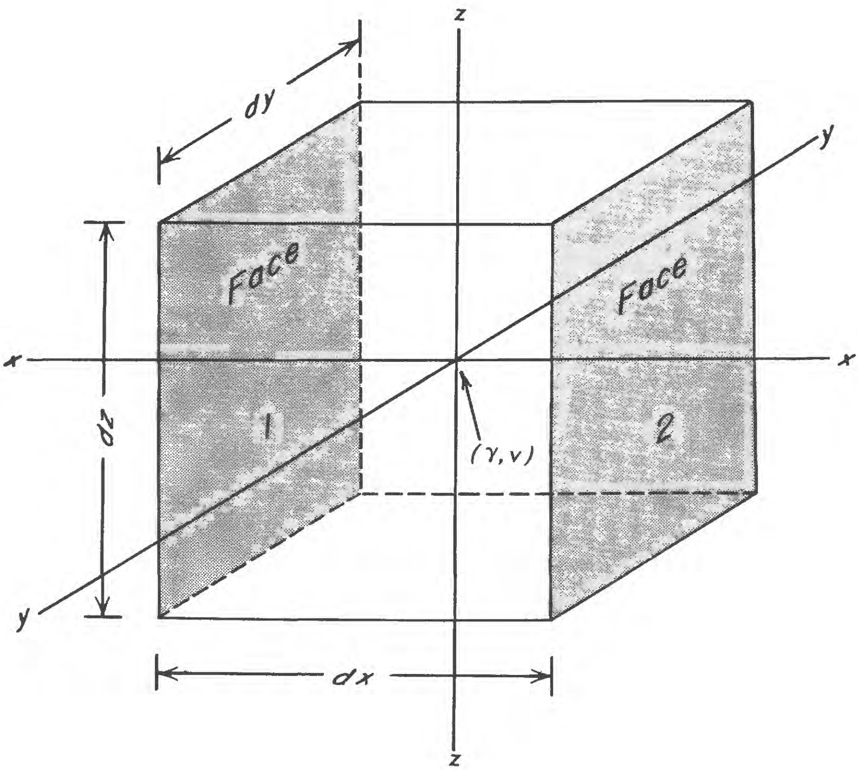

FIGURE 17.—An element of volume of saturated permeable material in which heat flow and fluid flow are simultaneous.

saturated. The distribution of temperatures is assumed to be smoothly continuous through space, irrespective of the fluid-solid distribution; the magnitude of the distribution approximately correlates with the dimensions of the pores. For the very low ground-water velocities occurring under natural conditions, this assumption is believed to be a valid approximation. The finite gross water velocity, v, which occurs through the interstitial passages, is defined by Darcy's law as

$$v = -P \frac{dh}{dl},$$

where

v = the velocity along the direction l,

P = the permeability of the material to the flow of water,

and

h = the head of water above an arbitrary horizontal reference plane.

The components of the velocity in the x-, y-, and z-directions are v_x, v_y, and v_z, respectively. At point (x, y, z) in the center of the element of volume, let the temperature be γ. The temperature at face 1, parallel to the yz plane, can be written

$$\gamma_1=\gamma-\frac{1}{2}\frac{\partial\gamma}{\partial x}\,dx, \tag{1}$$

and the temperature at face 2, also parallel to the yz plane, is

$$\gamma_2=\gamma+\frac{1}{2}\frac{\partial\gamma}{\partial x}\,dx. \tag{2}$$

Similarly, the velocity at face 1 is

$$v_1=v_x-\frac{1}{2}\frac{\partial v_x}{\partial x}\,dx, \tag{3}$$

and at face 2 is

$$v_2=v_x+\frac{1}{2}\frac{\partial v_x}{\partial x}\,dx. \tag{4}$$

From the law of heat conduction and equations 1 and 2, the rates, q_{c1} and q_{c2}, at which heat is conducted through faces 1 and 2, respectively, can be written as follows:

$$q_{c1}=-k_{ws}\frac{\partial\gamma_1}{\partial x}\,dydz=-k_{ws}\left(\frac{\partial\gamma}{\partial x}-\frac{1}{2}\frac{\partial^2\gamma}{\partial x^2}\,dx\right)dydz \tag{5}$$

and

$$q_{c2}=-k_{ws}\frac{\partial\gamma_2}{\partial x}\,dydz=-k_{ws}\left(\frac{\partial\gamma}{\partial x}+\frac{1}{2}\frac{\partial^2\gamma}{\partial x^2}\,dx\right)dydz, \tag{6}$$

where

k_{ws} = the thermal conductivity of the saturated material in the volume $dx\,dy\,dz$.

The net rate at which heat is added to the volume by conduction through faces 1 and 2 is given by

$$q_{c1}-q_{c2}=k_{ws}\frac{\partial^2\gamma}{\partial x^2}\,dx\,dy\,dz. \tag{7}$$

Likewise, equations similar to equation 7 can be derived for the net rate at which heat is added by conduction in the y- and z-directions, that is, through the remaining faces of the cube. Thus the total rate, q_c, at which heat enters the element of volume by conduction is found to be

$$q_c=k_{ws}\left(\frac{\partial^2\gamma}{\partial x^2}+\frac{\partial^2\gamma}{\partial y^2}+\frac{\partial^2\gamma}{\partial z^2}\right)dx\,dy\,dz. \tag{8}$$

The rate, q_{w1}, at which heat contained within the moving liquid enters face 1 along the x-axis is

$$q_{w1}=(c_{pw}\rho_w v_1\gamma_1)dydz, \tag{9}$$

where

c_{pw}=the specific heat of the water entering face 1

and

ρ_w=the density of the water entering face 1.

Substitution of equations 1 and 3 for γ_1 and v_1 in equation 9 gives

$$q_{w1}=c_{pw}\rho_w\left(v_x-\frac{1}{2}\frac{\partial v_x}{\partial x}dx\right)\left(\gamma-\frac{1}{2}\frac{\partial\gamma}{\partial x}dx\right)dy\,dz$$

$$=c_{pw}\rho_w\left(v_x\gamma-\frac{1}{2}v_x\frac{\partial\gamma}{\partial x}dx-\frac{1}{2}\gamma\frac{\partial v_x}{\partial x}dx+\frac{1}{4}\frac{\partial v_x}{\partial x}\frac{\partial\gamma}{\partial x}\overline{dx^2}\right)dy\,dz. \tag{10}$$

Similarly, if the water density throughout the element of volume is assumed to be virtually constant, the rate at which heat contained in the water leaves through face 2 is

$$q_{w2}=c_{pw}\rho_w\left(v_x\gamma+\frac{1}{2}v_x\frac{\partial\gamma}{\partial x}dx+\frac{1}{2}\gamma\frac{\partial v_x}{\partial x}dx+\frac{1}{4}\frac{\partial v_x}{\partial x}\frac{\partial\gamma}{\partial x}\overline{dx^2}\right)dy\,dz \tag{11}$$

The difference between equations 10 and 11 is the net rate at which heat contained in the fluid enters the volume in the x-direction; hence,

$$q_{w1}-q_{w2}=-c_{pw}\rho_w\frac{\partial(v_x\gamma)}{\partial x}dx\,dy\,dz. \tag{12}$$

The net rate, q_w, at which heat enters the element of volume with the fluid flow through all faces is obtained by summing expressions similar to equation 12 for the x-, y-, and z-directions. In this way it is shown that

$$q_w=-c_{pw}\rho_w\left[\frac{\partial(v_x\gamma)}{\partial x}+\frac{\partial(v_y\gamma)}{\partial y}+\frac{\partial(v_z\gamma)}{\partial z}\right]dx\,dy\,dz. \tag{13}$$

If, for the present, it is assumed that no heat is consumed or generated within the element of volume, the total rate at which heat enters the volume equals the sum of the heat which enters by convection and that which enters by conduction, that is, q_c+q_w, or the sum of equations 8 and 13. If $q_c+q_w=0$, the temperature varies as a function of the time, as follows:

$$q_c+q_w=c_{ws}\rho_{ws}\frac{\partial\gamma}{\partial t}dx\,dy\,dz, \tag{14}$$

where

ρ_{ws}=the density (weight per unit gross volume) of the saturated material,

c_{ws}=the specific heat of the saturated material, and

t=the time.

If equations 8 and 13 are substituted in equation 14 and the terms are rearranged, then

$$\frac{\partial^2\gamma}{\partial x^2}+\frac{\partial^2\gamma}{\partial y^2}+\frac{\partial^2\gamma}{\partial z^2}=\frac{c_{pw}\rho_w}{k_{ws}}\left[\frac{\partial(v_x\gamma)}{\partial x}+\frac{\partial(v_y\gamma)}{\partial y}+\frac{\partial(v_z\gamma)}{\partial z}\right]+\frac{c_{ws}\rho_{ws}}{k_{ws}}\frac{\partial\gamma}{\partial t}. \tag{15}$$

Equation 15 provides a convenient means for evaluating the temperature effects created by the flowing ground water. To simplify the equation, assume that steady-state conditions prevail in both the velocity and thermal fields, that the velocity components are important only in the x-direction, and that the temperature field is of significance only in the z-direction, except for a small gradient in the x-direction. These conditions correspond to those encountered in field sites inasmuch as the ground-water flow is linear along a horizontal axis and the heat flow is predominantly vertical. With these simplifications, equation 15 becomes

$$\frac{\partial^2\gamma}{\partial z^2}=\frac{c_{pw}\rho_w v_x}{k_{ws}}\frac{\partial\gamma}{\partial x}. \tag{16}$$

According to Birch (1942, p. 258), k_{ws} equals about 36 Btu per day-foot-degree F, and $c_{pw}\rho_w$ is 62.4 Btu per cubic foot-degree F. Therefore, from equation 16,

$$\frac{\partial^2\gamma}{\partial z^2}=1.73\ v_x\frac{\partial\gamma}{\partial x}. \tag{17}$$

Aquifers at depth are subject to the natural temperature gradients in the earth's crust. For convenience, assume that the natural temperature gradient is 1°F per 100 feet. If the dip of the aquifer is 1° (0.02 ft per ft), then $\frac{\partial\gamma}{\partial x}$ is about 2×10^{-4} °F per foot, provided, of course, that the dip and the direction of flow are parallel. A conservative value of v_x is about 1 foot per day. For these assumed conditions,

$$\frac{\partial^2\gamma}{\partial z^2}=3.5\times10^{-4}\ \text{approximately}. \tag{18}$$

The latter relation can be used to gain some idea of the temperature effects under the assumptions thus far employed. For this purpose a finite-difference approximation can be used, that is

$$\frac{\partial^2\gamma}{\partial z^2}\sim\frac{4(\gamma_T-2\gamma_C+\gamma_B)}{m^2}\sim3.5\times10^{-4}, \tag{19}$$

where

γ_T = the temperature change at the top of the aquifer,
γ_C = the temperature change at the center of the aquifer,
γ_B = the temperature change at the bottom of the aquifer,

and

m = the thickness of the aquifer.

γ_T, γ_C, and γ_B are all due to the assumed ground-water velocity being superimposed on the thermally conductive system. If, for example, $m=100$ feet and $\gamma_C=\gamma_B=0$, then the change in temperature at the top of the aquifer, due to the influence of the ground-water velocity, is about 1°F.

Thus, for the conditions assumed in developing equation 19, ground-water flow is seen to be an important governing factor in the distribution of underground temperatures. The effect ordinarily is great enough that it can be measured with standard well-logging equipment. Because both temperature gradients and ground-water velocities are highly variable from place to place, the relative effect of fluid velocity on temperature distribution varies over wide limits and in some places the two are not measurably interdependent.

PERMEABILITY CALCULATED FROM HEAD AND TEMPERATURE MEASUREMENTS

Although the gross velocity of the water is of interest in some phases of ground-water studies, the permeability of the water-bearing material generally is of greater interest. Equation 15 includes temperature and velocity as dependent variables and time as an independent variable. If an adequate number and distribution of temperature measurements are obtained throughout a given area, the temperature differentials can be estimated and the individual velocity components can be computed by applying a finite-difference form of equation 15. Then, if the ground-water gradients are known from the measurements of head, Darcy's law can be used to compute the permeability. This procedure would necessitate not only the collection of many data but also much computation. For flow through homogeneous and isotropic aquifers, the velocity components can be written in terms of head, thereby providing a more direct approach for the calculation of the permeability.

The bracketed term in equation 15 is equivalent to the following expanded form:

$$v_x \frac{\partial \gamma}{\partial x}+v_y \frac{\partial \gamma}{\partial y}+v_z \frac{\partial \gamma}{\partial z}+\gamma \frac{\partial v_x}{\partial x}+\gamma \frac{\partial v_y}{\partial y}+\gamma \frac{\partial v_z}{\partial z}. \tag{20}$$

If the density of the fluid is assumed to be uniform in space, application of the continuity equation to the nonsteady flow of incompressible fluids gives

$$\frac{\partial v_x}{\partial x}+\frac{\partial v_y}{\partial y}+\frac{\partial v_z}{\partial z}=-S'\frac{\partial h}{\partial t}, \tag{21}$$

where

S'=the unit storage coefficient of the saturated permeable material,

and

h=the head at point (x, y, z) at the center of the element of volume.

If the fluid flow is assumed to be steady, $S'\frac{\partial h}{\partial t}$ is small compared to the terms of equation 15 and the expanded term 20 reduces to

$$v_x\frac{\partial \gamma}{\partial x}+v_y\frac{\partial \gamma}{\partial y}+v_z\frac{\partial \gamma}{\partial z}. \tag{22}$$

Then equation 15 can be written

$$\frac{\partial^2\gamma}{\partial x^2}+\frac{\partial^2\gamma}{\partial y^2}+\frac{\partial^2\gamma}{\partial z^2}=\frac{c_{pw}\rho_w}{k_{ws}}\left(v_x\frac{\partial \gamma}{\partial x}+v_y\frac{\partial \gamma}{\partial y}+v_z\frac{\partial \gamma}{\partial z}\right)+\frac{c_{ws}\rho_{ws}}{k_{ws}}\frac{\partial \gamma}{\partial t}. \tag{23}$$

If, for the moment, it is assumed that the temperature differentials in equation 23 can be estimated from field data, there would remain the problem of reducing the velocity components v_x, v_y, and v_z to a single unknown so that the velocity could be computed from a minimum amount of data. For this purpose, Darcy's law yields the following for homogeneous and isotropic media:

$$v_x=-P\frac{\partial h}{\partial x},\ v_y=-P\frac{\partial h}{\partial y},\ \text{and}\ v_z=-P\frac{\partial h}{\partial z}. \tag{24}$$

The substitution of these equations in equation 23 gives

$$\frac{\partial^2\gamma}{\partial x^2}+\frac{\partial^2\gamma}{\partial y^2}+\frac{\partial^2\gamma}{\partial z^2}=-\frac{c_{pw}\rho_w P}{k_{ws}}\left(\frac{\partial h}{\partial x}\frac{\partial \gamma}{\partial x}+\frac{\partial h}{\partial y}\frac{\partial \gamma}{\partial y}+\frac{\partial h}{\partial z}\frac{\partial \gamma}{\partial z}\right)+\frac{c_{ws}\rho_{ws}}{k_{ws}}\frac{\partial \gamma}{\partial t}. \tag{25}$$

The conventional approach to data analysis generally involves the use of an analytical equation subject to the boundary conditions of the flow field. The complexity of equation 25 and the boundary conditions normally met with in field studies preclude the conventional analytical approach, except for those cases in which both heat and water flow are along one and the same direction. In a written communication (May 10, 1956) to the author, R. E. Glover, of the U.S. Geological Survey, suggested a solution to the latter case.

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From inspection of equation 23 it is apparent that velocity determinations cannot be made from temperature data unless a temperature gradient is measurable along the direction of at least one significant velocity component. Generally, the term

$$v_x \frac{\partial \gamma}{\partial x} + v_y \frac{\partial \gamma}{\partial y} + v_z \frac{\partial \gamma}{\partial z}$$

must have a value other than zero to permit the desired analysis. Provided this condition is met, estimates of P can be made from head and temperature measurements from a minimum of five wells through the application of a finite-difference approximation of equation 25. Fundamentally, such an analysis is relatively independent of the boundaries of the flow field and requires that the assumed conditions are satisfied over only a comparatively small segment of the flow field.

The assumptions leading to equation 25 may be summarized as follows: (a) The aquifer system is homogeneous and isotropic to the flow of both heat and water; (b) water flow occurs under steady-state conditions and heat flow occurs under nonsteady conditions; (c) ground-water velocity components are defined by Darcy's law; and (d) heat is neither generated nor consumed within the aquifer. Although some field conditions will meet these specifications, others obviously will not meet them all. Therefore, equation 25 is to be considered more as a symbolic form than a panacea. The conditions governing the flow of heat and water at each field site, where it is proposed to make a velocity or permeability determination by measurements of temperature and head, must be known. Knowing these conditions permits making assumptions similar to those listed above and thus permits the derivation of the appropriate differential equation relating temperatures, velocities, and head. In each case, finite-difference approximations of the differential terms and field observations of head and temperature can be employed for estimating permeability and(or) velocity.

Use of equation 25 as a basis for estimating P is predicated on the assumption that field observations of head and temperature can be made with sufficient accuracy. Many commercial well-logging devices appear to yield sufficiently accurate data for estimating the temperature differentials along the well axis. However, cursory evidence leads to the belief that instrumental drift may be too great in most or all units to provide the controlled stability needed for relative temperature measurement in the plane normal to the well axis. Furthermore, the accuracy of measurements of head in wells of shallow to moderate depths is also thought to be a minor problem. However, from the qualitative information now available, analysis of the underground distribution of temperatures and head, as outlined above, would seem to provide estimates of aquifer permeability at many locations without the need for a direct measurement of water velocity.

Such an approach will not be successful at some locations because the attainable accuracy and sensitivity of measurements will be less than the change in variables from point to point in the aquifer. Detailed studies are needed to determine the instrumental and data accuracy required for specific field situations. Perhaps restudy of data already collected and available on known field sites and instruments would shed some quantitative light on the feasibility of this approach.

CONCLUSION

Most field methods for determining the hydraulic constants of an aquifer require measurement not only of the distribution of head in space and time but also of ground-water discharge. Because suitable facilities for making the required measurements are not widely or conveniently distributed in most aquifers, studies of this nature are restricted in areal scope. A method whereby ground-water velocities could be determined by means of indirect measurements would increase the scope and usefulness of the quantitative phases of ground-water investigations.

The simultaneous conduction and convection of heat in aquifers is affected by the velocity of ground-water flow. Conversely, the distribution of temperatures in an aquifer is an indication of the magnitude of the ground-water velocity. For example, an approximately horizontal flow velocity of 1 foot per day and a coincident temperature gradient of about 2×10^{-4} °F would cause the temperature at the top of an aquifer that is 100 feet thick to differ by 1 °F from what it would be if the ground water were static. A greater ground-water velocity or a greater aquifer thickness would make the effect more pronounced.

If the distribution of head and temperature in an aquifer is known, finite-difference approximations of the differential equation relating the two could be used in calculating the permeability of that aquifer. Such approximations could be used for differential equations developed to describe the flow in virtually any known hydraulic system. Evidently temperature data provide a means whereby determinations of the velocity of the ground water or the permeability of an aquifer can be made for places where the testing facilities needed in other methods of determining hydraulic constants are not available.

At those locations where the temperature gradient is zero along the direction of ground-water flow, the proposed method of analysis would not be feasible. However, at locations where the temperature gradient is measurable, the method seems promising. Additional work is required to assess the probability of successful application in the field.

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STREAMBED PERCOLATION IN DEVELOPMENT OF WATER SUPPLIES

By Matthew I. Robabaugh

ABSTRACT

During and since World War II, municipal and industrial water supplies obtained by inducing percolation through a streambed have been extensively developed in the Ohio River valley. Such supplies have been developed by placing tubular wells or horizontal-type collector wells (such as Ranney collectors) near a surface stream which flows on permeable glacial outwash or other permeable valley-fill deposits. When pumping lowers the ground-water level below that of stream level, stream water percolates downward through the streambed, thereby furnishing a large supply of water to the ground-water installation. The design of an installation to be supplied by streambed percolation requires a knowledge or hydrologic and geologic factors determined by test drilling and from aquifer tests.

The principal factors to be considered are the permeability, thickness, storage capacity, and storage coefficient of the aquifer, possibility of dewatering the aquifer, the available head, the head loss associated with the installation, the interference resulting from other installations, and the viscosity changes due to changes in the temperature of the water in the stream.

Performance data collected during the period 1945–50 for a horizontal-type collector located along the Ohio River demonstrate the following: An increase in specific capacity during floods because of a gain in storage and an increase in the thickness of the saturated material; a decrease in specific capacity after floods because of removal of water from storage and a reduction in the thickness of saturated material; and a substantial decrease in yield during the winter because low temperature causes an increase in the viscosity of the river water. The temperature of the river ranged from 32° to 85°F and of the pumped water from 47° to 64°F. The temperature cycle of the pumped water lagged about 10 weeks behind that of the river water. The water entering the collector from the horizontal screens that extend riverward had a wider range in temperature and less time lag than the water from the landward-extending horizontal screens. Silting of the riverbed did not cause a permanent reduction in the yield of the collector. The mineral content of the pumped water was intermediate between that of the water in the river and that of the water in the aquifer. The pumped water contained no bacteria, was clear, and was free of the chemical wastes that made difficult the treatment of the river water itself.

SCOPE OF THE INVESTIGATION

The discussion in this paper will be limited to the downward percolation of surface water through a saturated streambed, as related to the practical problems of developing water supplies that take advantage of the natural conditions in many stream valleys. This particular phase of the subject was selected for detailed discussion because of its increasing economic importance in water-supply development and because of the technical advances made in theory and practical application during and since World War II. Although it had been known for many years that wells located near streams might derive a substantial part of their yield from the streams themselves, the formulation of methods for making the quantitative evaluations necessary to the design of water-supply installations had progressed very slowly. The need for very large supplies of water for industrial use during and since the war led to improvement and refinement of quantitative theory, to confirmation of theory by field testing and by collection and analysis of statistical data on existing installations, and to better efficiency through improved methods of design and construction. This discussion is based almost wholly on data from the Ohio River valley, also the glaciated area north of the valley, where extensive developments based on induced infiltration of river water have been made.

ACKNOWLEDGMENTS

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GEOLOGIC ORIGIN OF VALLEY-FILL DEPOSITS IN AND NORTH OF THE OHIO RIVER VALLEY

Before the Pleistocene epoch, the streams in Ohio, Indiana, and Illinois flowed to the north and northwest. The advance of the ice sheets blocked drainage in those directions, and the dammed streams in the part of the area south of the ice margin found escape by breaching the divides between the preglacial valleys. The water from the obstructed valleys, augmented by melt water from the ice, cut a new river valley approximately along the southern limit of the ice sheet. This valley, now occupied by the Ohio River, was cut into the consolidated rocks to a width of 1 to 6 miles and to a depth of as much as 150 feet below the present flood plain. As the volume of water from the receding ice sheet diminished, the valley was partly filled with glacial outwash and river deposits. The meandering Ohio River, ranging in width from about 1,000 to about 5,000 feet, flows on the surface of these valley-fill deposits. In most places, the riverbed is the upper surface of a deposit of sand and gravel which is as much as 110 feet thick. On both sides of the river, the valley-fill deposits are mantled by flood-plain deposits that consist principally of clay and silt and range in thickness from 10 to 40 feet. Although in many places the valley-fill deposits consist of highly permeable deposits of sand and gravel and thus constitute an ideal aquifer, in some places they contain so many lenses of silt and clay that suitable sites for wells are difficult to find.

The preglacial valleys north of the newly formed Ohio River valley also were filled with glacial deposits. A new drainage pattern was formed as the ice sheet melted, the streams draining southward to the Ohio River. Where these new streams cross or follow filled preglacial valleys, conditions commonly are suitable for the development of water supplies by inducing stream water to percolate into the glacial materials.

REQUIREMENTS FOR INDUSTRIAL OR MUNICIPAL WATER SUPPLIES

A water supply for an industry or a municipality must meet certain requirements as to minimum yield, temperature, turbidity, and chemical and bacterial quality. Almost nowhere can all requirements be met by developing only a surface-water source or only a groundwater source.

Inasmuch as the initial source of all water supplies is precipitation, the size of the catchment area together with natural or artificial storage capacity will determine the dependable yield. For surface water, the controlling factors are the size of the drainage area and the amount of precipitation on that area; for ground water, the controlling factor is either the relatively small zone of influence of the well or the small area of the outcrop of the aquifer. The Ohio River drainage basin, which receives an average annual precipitation of 40 to 50 inches over a very large area, provides surface water greatly in excess of needs. However, the temperature of the water exceeds 80°F in the summer, which makes it unsuitable for such industrial uses as air conditioning, chemical processing, and distilling. Moreover, in recent years the surface supplies have been seriously contaminated by municipal and industrial wastes, the removal of which has added substantially to the cost of treatment. In some places this cost has become so high or the odor and taste of the treated water have become so bad that surface water has had to be abandoned as a source of supply.

Ground-water supplies normally have an almost uniformly cool temperature, are free of turbidity, have a chemical quality not subject to significant changes, and can be developed more cheaply than surface-water supplies. In the Ohio River drainage basin, except where streambed percolation can be induced, the dependable yield of a well tapping highly permeable valley-fill deposits is at best only moderately large because, under the prevailing water-table conditions, the size of the area throughout which water can be diverted to the well is relatively small. The yield of wells tapping the bedrock aquifers is small, even though artesian conditions prevail, because these aquifers are not highly permeable.

Where geologic and hydrologic conditions are favorable, it is possible to combine the advantages of both types of supply—to use the larger catchment area of the stream and at the same time to obtain water of satisfactory temperature and quality. This can be done by inducing percolation from the stream through its bed into a highly permeable aquifer.

The rate of ground-water flow (Q) is governed by the permeability of the water-bearing material (P), by the hydraulic gradient (I), and by the cross-sectional area perpendicular to the direction of flow (A). When a well is pumped or is allowed to flow, the water table or piezometric surface in the immediate vicinity of the well assumes the shape of an inverted cone so that Darcy's relationship, $Q=PIA$, is satisfied at all points. If a well is so situated that, in expanding, the inverted cone reaches a stream from which infiltration can be induced, the inverted cone develops asymmetrically, the hydraulic gradient between the stream and the well becoming steep in comparison to that on the side away from the stream. All other factors being equal, the flow in the distorted cone will follow the Darcy relation; that is, the flow toward the well will be greatest on the side nearest the stream because there the hydraulic gradient is the steepest. When the inverted cone first reaches the stream, only a small part of the discharge from the well consists of induced percolation through the streambed. If pumping is continued long enough, a condition is reached whereby virtually all the water being pumped is derived from the stream. The theory for this problem has been discussed by Muskat (1937, p. 175–181) and Jacob (1950, p. 351–354), and applications to practical problems have been demonstrated by Kazmann (1948a, b) and Rorabaugh (1948, 1956).

If the water being discharged from a well is derived almost wholly from a stream, then the dependable yield of the well is related directly to the low-water flow of the stream. Because even the minimum flow of the Ohio River exceeds foreseeable needs, the dependable yields of well installations along the main stem of the river obviously will not be limited by a lack of supply. However, along a small stream the dependable yield definitely will be limited to the low-water flow of the stream unless a large quantity of ground water is in storage. Only if a large quantity of ground water is in storage can the dependable yield be substantially larger than the low flow of the stream (Kazmann, 1949).

FACTORS IN THE PRACTICAL DEVELOPMENT OF A WATER SUPPLY

The planning of a water supply that is to be dependent on induced percolation through a streambed requires extensive knowledge of not only the hydrology of the basin, but also the geologic and ground-water conditions in the vicinity of the proposed installation. Important facts that need to be known are (a) the low flow of the stream, (b) the range in stage of the stream, (c) the range in chemical quality and the range in temperature of the water in the stream, (d) the vertical permeability of the streambed, (e) the horizontal permeability of the aquifer, (f) the thickness and lateral extent of the aquifer, (g) the water level and rate of flow in the aquifer, (h) the quality and temperature of the ground water, (i) the available head, (j) the distance from the point of withdrawal to the area of effective streambed percolation, (k) the geologic and hydraulic boundaries of the aquifer, (l) the extent of the interference from nearby installations, (m) the available quantity of ground water in storage, (n) the head losses in the installation (well, gallery, or horizontal-type collector), (o) the turbulence of the flow, (p) the amount of distortion in the flow lines because of screen location, and (q) the reduction in saturated thickness of the aquifer as dewatering occurs.

It has become general practice to make detailed field investigations before the design and construction of installations for development of water supplies based on the induced percolation of stream water to an aquifer. Test drilling is done to determine the nature of the water-bearing material, its depth, the lateral extent of the aquifer, the available drawdown or head below the surface stream, and the geologic boundaries that may also be hydraulic boundaries. From the test drilling a favorable site is selected for making a detailed aquifer test. Such a test determines (a) whether the stream and the aquifer are hydraulically connected, (b) the distance from the effective area of percolation to the pumped well, (c) the permeability of the aquifer, (d) the storage coefficient, and (e) the location and effect of hydraulic boundaries, such as a valley wall or a major change in lateral permeability in the aquifer. From the hydrologic constants determined from the test it is then possible to compute the expected yield of any type of installation placed at any distance from the stream (Rorabaugh, 1956). Neither the test drilling nor the making of aquifer tests will provide complete information on the effect of low temperature on the rate of discharge from the installation, on the percolation rate through the streambed, or on the chemical quality and temperature characteristics of the water produced from the installation. Detailed discussion of these items follows.

TEMPERATURE OF THE WATER

The temperature of the water discharged from an installation that induces percolation through a streambed follows a cycle governed by the seasonal fluctuations in the temperature of the stream water (Burdick, 1942; Jeffords, 1945; Kazmann, 1947, 1948b; Rorabaugh, 1956). The range in the temperature of the discharged water, however, is less than that of the stream water, and the highs and lows in the temperature of the discharged water occur later than the corresponding highs and lows in the temperature of the stream. Both the range and time lag in the temperature of the discharged water depend on a large number of variables, the more important of which are (a) the temperature of the stream water, (b) the distance of the installation from the stream, (c) the spacing of the installation, (d) the discharge rate, (e) the volume and porosity of the aquifer, (f) the amount and the temperature of the ground water entering the installation from the landside, and (g) the specific heat of the material in the aquifer. At any given time, the water percolating from the stream to the installation is following various paths and is flowing at rates governed by the hydraulic gradient and the transmissibility of the aquifer along the paths of flow; thus, the stream water that infiltrates the aquifer near the installation, where the gradient is steepest, travels to the installation in a very short time compared to that of water entering the aquifer some distance upstream or downstream. In other words, the water being discharged at any given time is a mixture of ground water of almost uniform temperature with stream water that entered the aquifer at different points, at different times, and at different temperatures. As a result of the mixing, the range in the temperature of the water being discharged from the installation is narrower than that of the stream water. The narrower range is due also to an exchange of heat between the water and the material composing the aquifer, as water of one temperature flows into the aquifer having a different temperature. An additional factor may be the radiation of heat not only within the aquifer but also to or from the underlying bedrock or the overlying unsaturated material.

Further complications are introduced by changes in viscosity that are associated with changes in temperature; changes in viscosity alter the rate of flow, either damping or accentuating all the other effects in various parts of the aquifer. The viscosity of water varies about 1.5 percent per degree Fahrenheit throughout the temperature range ordinarily encountered in practical problems. The rate of flow varies inversely as the viscosity; a drop of 1° in temperature will decrease the flow rate by about 1.5 percent. An installation with a yield of 5 mgd (million gallons per day) at a temperature of 70°F will yield only about 3.2 mgd when the temperature is reduced to 40°F. It is evident, therefore, that temperature is one of the most important variables to be considered in the design of a water-supply installation that induces percolation of stream water into the aquifer.

PERCOLATION RATES

Special consideration should be given to the possibility that stream water will percolate through only a part of the streambed and that the critical element in the problem may be the vertical permeability of the material composing the streambed in that part where percolation can occur. Although an aquifer test takes into account the water-level drawdown between the stream and the well, it does not permit separation of the head loss into separate values attributable to vertical percolation and to horizontal flow. Moreover, the rate of pumping during an aquifer test generally is only a fraction of the pumping rate of the final installation. Where the area through which streambed percolation may occur is small or the permeability in the vertical direction is low, an aquifer test made at a low pumping rate could indicate a hydraulic connection between the stream and the aquifer whereas the final installation having a higher pumping rate would withdraw water at a rate in excess of the ability of the streambed to transmit it.

Although the maximum, or limiting, percolation rate of the streambed generally cannot be determined precisely, it ordinarily is possible to determine whether the percolation rate will be a critical element in the design of a water-supply installation. Records of water-level fluctuations in observation wells may be revealing. The degree of correlation between fluctuations of stream level and fluctuations of ground-water level furnishes a clue as to the freeness of the connection between the stream and the aquifer. Study of the water-table profile along a line perpendicular to the stream at the side of a proposed installation provides additional clues. If the water table is continuout with the stream surface, both uniform horizontal flow and free flow through the streambed are indicated; but if an extension of the water-table profile passes above or below the stream surface, either a zone of low horizontal permeability or restricted vertical flow in the streambed is indicated. The location and areal extent of the part of the streambed through which percolation can be induced generally can be determined by test drilling and geologic study.

The effective distance between a well that has been pumped in making an aquifer test and the source of recharge from a stream can be determined graphically from a profile based on the water-level position, during the test, in observation wells between the pumped well and the stream, or it can be computed from the water-level position in nearby observation wells Kazmann, 1948a, p. 88; Rorabaugh, 1956, p. 144–145). If a small stream is the source, the distance determined from the test should be equal, or nearly so, to the physical distance to the center of the stream. However, if the effective distance determined from the test is unreasonably great compared to the known distance, the permeability of the streambed is indicated to be low enough to become a critical factor in the problem. For a very wide stream, such as the Ohio River, the physical distance to the source of recharge cannot be determined precisely, and the effective distance determined from the test should not be considered unreasonable unless it places the source beyond the far bank of the stream. Use of the effective distance to the source when such distance is unreasonably great may be justified, to some extent, on the basis that use of the larger figure will compensate, in part, for a low rate of percolation through the streambed. Such analysis must be given thorough study inasmuch as the percolation rate is a direct function of head, whereas the distance to source enters the computation as a logarithm.

Where test drilling and the results of an aquifer test indicate that the critical factor in the design of an installation is the percolation rate of the streambed, the design of the installation should be checked against the design of successful installations under similar geologic and hydraulic conditions elsewhere. Very few data have been published on this phase of hydrology.

In the United States, perhaps the best known installation that induces percolation through a streambed is the infiltration gallery along the Raccoon River at Des Moines, Iowa. This installation, which has been in operation since 1908, has a streambed percolation rate of about 0.25 mgd per acre (Burdick, 1942, p. 1611), which is the same as 9 inches per day.

Studies of the Middle Branch of Nimishillen Creek in Ohio were made in 1947 (Youngquist, 1948). Water levels in the glacial material in the valley had been lowered below stream level at some points by pumpage from wells, which averaged about 8 mgd. Current-meter measurements at various points on the stream demonstrated a loss of stream water to the underlying glacial material. The percolation rate was computed to be 3.6 mgd per acre, or 11.0 feet per day.

Determination of percolation rates for large streams in terms of rate per unit area is difficult. The rate of percolation is a function of the permeability of the material composing the streambed, but it also varies with the head or drawdown under the stream and with temperature changes. The effective area of streambed percolation cannot be determined accurately. When a well near a large river is pumped, the cone of depression extends beneath the river until sufficient head and area are developed to satisfy the needs of the installation. In a highly permeable bed the cone may extend only part way beneath the river. Where low vertical permeability exists, the come may expand to include the full width of the river and then extend upstream and downstream. Since the head distribution is logarithmic, percolation rates in the area near the installation will be several times larger than the average over the effective area of percolation.

The largest infiltration development along the Ohio River is at Charleston, Ind. Seven horizontal-type (Ranney) collectors having a combined dependable yield of about 65 mgd are located along a 2-mile reach of the river. If the full width of the river is regarded as effective, the average percolation rate during periods of most intensive pumping is computed to be 0.15 mgd per acre.

In downtown Louisville, Ky., about 1 mile from the Ohio River, the combined discharge of a large number of vertical wells is about 10 mgd. It is estimated that this withdrawal induces percolation through the streambed of the river at an average rate of 0.01 mgd per acre. Withdrawals from a collector southwest of Louisville induces streambed percolation of about 0.05 mgd per acre. These rates are for existing installations, no estimate having been made of the maximum possible. Most of the head between the river level and the pumping level in downtown Louisville is used in horizontal flow from the river to the wells. Considerably higher percolation rates could be developed by placing wells nearer the river, thereby increasing the hydraulic gradient. Detailed investigations of a 6-mile reach along the river northeast of downtown Louisville indicate that a dependable supply of about 280 mgd could be developed by induced infiltration (Rorabaugh, 1956, p. 159).

QUALITY OF WATER

A water supply developed through streambed percolation is more nearly uniform in chemical quality than a supply directly from the stream. Because water that leaves the stream at any given time is mixed, before it reaches the well, with water that left the stream at other times, sudden changes in the quality of the stream water are not reflected in the water pumped from the water-supply installation.

Most objectionable odors and tastes, which have been a major problem in the treating of surface water, apparently are removed or diluted as the water percolates through the streambed and toward the water-supply installation. Although definite data to prove this are lacking, evidence that users of such supplies have not been troubled by odors and tastes has been cited by both Jeffords (1945, p. 151) and Kazmann (1948b, p. 419).[2]

PERFORMANCE OF A HORIZONTAL-TYPE COLLECTOR SOUTHWEST OF LOUISVILLE, KY.

Performance data for a horizontal-type collector at the National Carbide Co. plant southwest of Louisville, Ky. (fig. 18), are used to illustrate the effects of various factors involved in a supply system that is designed to induce streambed percolation.

At this location the Ohio River is controlled by navigation dams; it has a minimum water level of 45 feet above bedrock and a minimum flow of several thousand cubic feet per second. Water-bearing glacial outwash consisting of sand and gravel underlies both the river and the flood plain. However, except where the river is deepest, this coarse-grained deposit is mantled everywhere by relatively impervious clay. This clay blanket, which extends under the river for about 160 feet, not only restricts the aquifer to a thickness of about 20 feet in the area through which river water must percolate to reach the installation but also prevents percolation of river water in the area near the installation. Furthermore, the position of the underside of the clay layer is such that the ground water is artesian, or confined, whenever the pumping rate is low or the river is in flood and that water-table conditions prevail during periods of heavy pumping. Consideration of the storage changes and the changes in the transmission rate associated with partial dewatering of the aquifer is necessary.

The collector is of the horizontal type and was placed in operation in the fall of 1945 (Silitch, 1948). It consists of a caisson, 13 feet in diameter, sunk to bedrock at the low-water edge of the river. Screens projecting radially from near the bottom of the caisson extend about 175 feet in a riverward direction and a little more than 300 feet in the upstream, downstream, and landward directions.

Comparison of the river level (graph A, fig. 18) with the water level in the collector (graph *C*) during the period of nearly constant discharge rate (graph *D*) shows that the river and the collector are hydraulically connected. However, a time lag of a few days and a damping effect are noticeable. As shown by graph *B*, ground-water levels at a point 1,500 feet landward from the river show a recovery

[2] The great increase in the use of synthetic detergents since the preparation of this paper probably invalidates these statements, because synthetic detergents are not entirely removed by natural filtration.

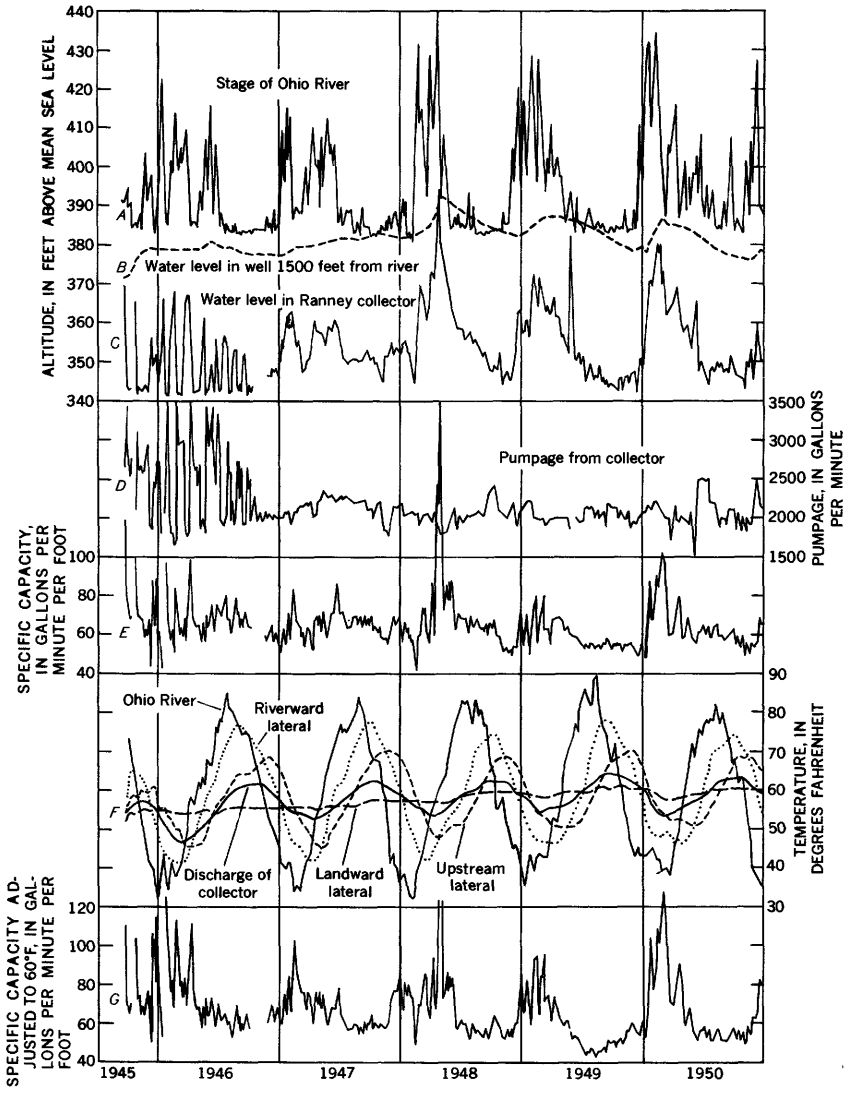

FIGURE 18.—Performance graphs for collector southwest of Louisville, Ky.: *A*, stage of Ohio River; *B*, water level in well 1,500 feet from the Ohio River; *C*, water level in collector; *D*, discharge from collector, *E*, specific capacity; *F*, thermographs for river, collector discharge, and flow in selected laterals; *G*, specific capacity corrected to 60°F.

in 1945–46 following a reduction of pumpage in the industrial area, a rise in 1948 reflecting the effects of the 1948 flood, and a decline in 1949–50 resulting from an increase in withdrawals for industrial use farther from the river.

The specific capacity, or yield in gallons per minute per foot of drawdown, for the collector is shown by graph *E*. It was obtained by dividing the discharge by the average head, which was determined by computing the difference between the level in the collector (graph *C*) and the average of river level (graph *A*) and the water level in a well 1,500 feet from the river (graph *B*). This graph shows that the yield rarely dropped below 50 gpm per ft (gallons per minute per foot), which is equal to 2,000 gpm for a normal pumping head of 40 feet. It shows also that the specific capacity increases when the water level in the well is higher, as during periods of flood. Such increases result partly from resaturation of the dewatered part of the aquifer, which increases the transmissibility, and partly from the gain in storage during the flood.

Graph *F* shows the temperature of the river water; the temperature of the water entering the collector from the laterals that extend riverward, upstream, and landward; and the temperature of the water discharged from the collector. The time lag in the individual laterals and the magnitude of the cycle differs according to the nearness of the laterals to the river. The discharge from the installation is a mixture of water of different temperature entering from the different laterals. The pronounced cycle of high specific capacity in the summer and low specific capacity in the winter, as shown by graph *E*, is related directly to the changes in the viscosity of the water, which, in turn, are related directly to changes in the water temperature.

Graph *G* was obtained by adjusting the specific capacity, as shown by graph *E*, to a constant temperature of 60°F. Although this graph shows a nearly constant value for specific capacity during periods of low water in the river, it shows, as does graph *E*, that high values are associated with floods. The temperature correction was based on the average temperature of both the river water and the discharge from the collector. That this simplification of a very complex variable produces usable results has been confirmed by statistical analyses of performance data. Graph G would seem to indicate that the minimum specific capacity had declined from about 58 to 51 gpm per ft during the 5-year period, or about 2 percent per year. Although, on first thought, the decline might be attributed to gradual silting of the riverbed and consequent lowered percolation rates, variation in specific yield with time during a long period of pumping also must be considered as a possible factor.

The discharge capacity of the collector was tested monthly during the first year. Each test consisted of first increasing the discharge until the water level was lowered to the minimum allowable and then gradually reducing the discharge so as to maintain that level. The discharge at the end of 10 days was used as representative of the yield for the conditions of river level and temperature prevailing for that test. The low points during the first year on graph *G* are for pumping periods of 10 days. If the tests had been run for a longer time, the specific capacity would have declined even more because, at the end of each test, water still was being removed from storage and the rate at which the aquifer could transmit water was being reduced correspondingly. An analysis of the 12 monthly tests produced a rating for the collector for a wide variety of both river levels and river temperatures for the condition of maximum drawdown after pumping for 10 days. For a water temperature of 60°F and the minimum (controlled by navigation dams) pool level of the river, the collector had a rated capacity of 2,200 gpm, or 55 gpm per ft of drawdown.

A theoretical analysis of the data obtained during the preliminary test at the site and of the data from the first test of the capacity of the collector produces values for all the hydrologic factors that need to be considered in the drawing of a rating curve which shows the variation of specific capacity with time. This curve includes a series of parameters for conditions following floods of different heights. Under conditions of maximum drawdown and a water temperature of 60°F, the 100-day specific capacity is 52 gpm per ft, the 200-day specific capacity is 50 gpm per ft, and the long-term specific capacity is 48 gpm per ft. The collector would need to be pumped continuously for nearly 2 years for the long-term specific capacity to be reached.

Thus, if the well had been pumped continuously throughout 1946, the specific capacity, adjusted to a water temperature of 60°F, would have dropped to values no lower than those of 1948 and 1950. From this analysis it is concluded that silting of the riverbed, at least through 1950, had not caused any permanent decline in the yield of the collector. In 1947, the water levels were not lowered sufficiently to dewater the aquifer as extensively as in the other years and for that reason the specific capacity at 60°F was not so low as in 1948 and 1950.

The low specific capacity in 1949 does not conform to the analysis. Although the condition was only temporary, its exact cause has not been established definitely. Possibly, the driving of piles for a loading dock just downstream from the collector disturbed the arrangement of the particles composing the aquifer and several months may have been required for redevelopment of the aquifer. That the discharge from the collector contained sand at times after the piles had been driven tends to lend credence to this hypothesis. Another possible explanation is based on the fact that considerable riverdrift was lodged among and upstream from the piles during the flood period in the spring of 1949. The resulting reduction in the velocity of the muddy river water may have caused deposition of silt and mud on the streambed in the vicinity of the collector and, after the flood period, removal of the debris may have permitted a return to the normal distribution of velocities and a removal of the silt and mud. If either

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possible explanation was the real cause of the lowered specific capacity, it is surprising that the temperature of the water entering the caisson from the lateral nearest the loading dock did not deviate from its normal cycle. The specific capacity at 60°F returned to a normal level during the period August to October 1949, even though the river remained at pool stage and the rate of discharge from the collector was increased somewhat.

Practically speaking, the specific capacity, adjusted to 60°F, probably never will be reduced to 48 gpm per ft for any appreciable length of time because, every winter or spring in this part of the Ohio River valley, floods of at least medium stages result in a refilling of the aquifer. However, the specific capacity at 60°F could be reduced temporarily to somewhat less than that value if unusually adverse conditions were to prevail. For example, if the river were to remain at pool level throughout the cold months, the correction for changes in temperature would result in a specific capacity of 40 gpm per ft, or a discharge rate of 1,600 gpm. Such conditions are known to have occurred during the drought of 1930–31 when the river was at pool level for a 7-month period—May 1930 to January 1931—and the average temperature during December 1930 was considerably below normal. However, they have not occurred at any other time in the 75-year period of record, 1875–1950.

In general, the effects of low head during periods of low river level, such as occur during the summer and fall, are offset by the increase in flow rate due to the high temperature; conversely, during flood periods the added head offsets the reduction in flow rates due to low temperature. For practical purposes, therefore, the long-term dependable yield of the collector may be considered to be about 50 gpm per ft, or 2,000 gpm.

Performance data for the horizontal-type collector at the National Carbide Co. plant southwest of Louisville, Ky., show that the specific capacity of the installation varies with river level, with temperature, and with time. Correlation of the data shows the efficiency of this installation did not decrease during the first 5 years of operation and that silting of the riverbed did not cause a permanent reduction in the yield. Although, in 1949, the specific capacity fell below that computed by theory the condition was temporary, as shown by the increase in specific capacity during the late summer. The rated dependable specific capacity of this collector under conditions of low river level, winter temperature, and maximum drawdown for a period of long duration is 40 gpm per ft, or a discharge rate of 1,600 gpm. Study of the river and temperature records show that the conditions that would have caused the specific capacity of the collector to drop to this value occurred only once (1930–31) in the 75-year period 1875–

1950. The hydrology of the Ohio River drainage basin is such that low water usually occurs in the late summer and that floods occur in the winter and spring. During periods of low water, the low head is offset by the lower viscosity of the warm water, and during the winter, the increased head and storage offset the higher viscosity of the cold water. From a practical standpoint, the dependable specific capacity of the collector may be considered to be about 50 gpm per ft, or a discharge rate of 2,000 gpm.

CONCLUSION

During and since World War II, large supplies of water have been developed in the Ohio River drainage basin by means of inducing percolation through a streambed. Supplies based on this type of development have characteristics of both ground water and surface water and combine the advantages of both. The dependable yield of such a development is limited by the low flow of the stream rather than by the limited zone of influence of the well. Because ground-water storage can be used during periods of low flow, the combined sources produce a higher safe limit than either surface water or ground water alone. Not only the mixing of stream water with ground water but also the mixing of water that leaves the stream during different seasons of the year produces a water having a temperature range less than that of the stream. Furthermore, the water infiltrating from the river is generally free of bacterial contamination, turbidity, taste, and odor by the time it reaches the well.

Water supplies developed by this method are suitable for industrial processes, many of which cannot use stream water because of its high summer temperature. A more uniform chemical content and freedom from turbidity also make this type of water supply attractive to certain industries. Test drilling, geologic study, and aquifer tests will provide adequate data for a sound design using galleries, tubular wells, or horizontal-type collectors.

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A WATER BUDGET FOR THE ARTESIAN AQUIFER IN OGDEN VALLEY, WEBER COUNTY, UTAH

By Harold E. Thomas

ABSTRACT

In addition to fluctuating in response to changes in storage, the water level in the Tower well in Ogden Valley, Weber County, Utah, fluctuates in response to the following pressure effects: Changes in atmospheric pressure, changes in the contents of Pine View Reservoir, and changes in the discharge rate of the Ogden municipal-supply wells. Adjustment of the water-level measurements for these pressure effects results in a record that reflects storage changes in the aquifer tapped by the Tower well. An analysis of the fluctuations attributed to changes in storage shows that a little less than two-thirds of the average annual recharge to the aquifer is due to infiltration of precipitation and local runoff and that the remainder is due to seepage from the principal streams crossing the valley floor. During the period 1935–51, the annual discharge from the artesian aquifer averaged about 13,350 acre-feet and the annual recharge averaged about 13,540 acre-feet.

SCOPE AND PURPOSE OF PAPER

Records of water-level fluctuations in wells are worth the cost and trouble of collecting only if they are used as a basis for hydrologic interpretations. Although water-level records have been vital to the reaching of conclusions regarding the occurrence and development of ground water in specific areas, many such records still await interpretation. Similarly, a wealth of climatologic and other hydrologic data is in need of analysis.

The water level in a well fluctuates in response to the addition of water to, or the subtraction of water from, some part of the aquifer tapped by the well, and also, if the water in the aquifer is confined, in response to an increase or decrease of pressure upon the water somewhere in the aquifer. If the fluctuations of water level in a single well can be correlated quantitatively with the various factors that cause changes in storage or changes in pressure, a record of the water-level fluctuations in that well is an index to the quantities of water recharged to or discharged from the aquifer in given periods.

The Tower well [3] in Ogden Valley, Utah, has proven to be an especially good index well. A float-type recording gage was installed on

[3] So called because the casing extends 16 feet above the land surface and must be climbed when the recording gage mounted upon it is serviced. In reports by Leggette and Taylor (1937) and Thomas (1945), the well is designated "No. 82," and in the annual reports on water levels and artesian pressures in wells, published by the Geological Survey in its series of water-supply papers, it is called well (A–6–1) 12aad–1, in accordance with the coordinate well-numbering system that is standard for Utah. This coordinate number is based upon the location of the well in the SE¼NE¼NE¼ sec. 12, T. 6 N., R. 1 E., Salt Lake base line and meridian.

the Tower well when it was drilled in September 1932. The record of water-level fluctuations in this well is the longest of any in Utah and probably is among the dozen longest in the country. An analysis of the water-level record of this well in the light of other pertinent data, as described in this paper, made possible the formulation of a water budget for the artesian aquifer in Ogden Valley.

GEOLOGIC AND HYDROLOGIC FEATURES OF OGDEN VALLEY

Ogden Valley, an area of about 23 square miles, is in the eastern part of Weber County and is about 12 miles east of the city of Ogden. The altitude of the valley floor is about 5,000 feet. The South, Middle, and North Forks of the Ogden River enter the valley from the east, northeast, and north, respectively, and join in the lower part of the valley to form the Ogden River, which flows westward out of the valley by way of Ogden Canyon. The Ogden River is a tributary of the Weber River, which empties into Great Salt Lake.

Ogden Valley is believed to be unique in its water-storage facilities in that it contains a surface reservoir (Pine View Reservoir) which overlies an artesian aquifer from which large quantities of water are withdrawn. The surface reservoir, created when Pine View Dam in the Ogden Canyon was completed by the U.S. Bureau of Reclamation in 1936, occupies the lower part of Ogden Valley and has a capacity of 43,600 acre-feet.[4] The reservoir covers only a part of the area underlain by the artesian aquifer. Both are of great economic importance: The artesian aquifer provides all but a small part of the municipal water supply for the city of Ogden, and Pine View Reservoir provides water for irrigation of about 16,000 acres of farmland in Weber and Box Elder Counties.

As described by Blackwelder (1910, p. 520–526), Gilbert (1928, p. 57–62), and other geologists, Ogden Valley lies in a graben, or structural trough. The graben is separated from the Great Basin farther west by the horst that has formed a range of mountains which, at the latitude of Ogden Valley, is 6 to 8 miles wide. These mountains, commonly referred to as the Wasatch Mountains, are a part of the Wasatch Range. Bordering the graben along its east side is the Bear River Range, which by some is also included as part of the Wasatch Range. The mountain crests on both sides of Ogden Valley are about 9,000 feet above sea level.

Ogden Valley is separated from Morgan Valley, to the southeast, by rolling lands that stand as much as 1,000 feet higher than the floor of Ogden Valley. In large part, these rolling lands are underlain by

[4] All statements in this report pertain to conditions existing before or in 1952, the date of the writing of this paper. In 1957, the storage capacity of Pine View Reservoir was increased to 110,000 acre-feet.

the Norwood Tuff of Oligocene age (Eardley, 1944). Ogden Valley is separated from Cache Valley, to the north, by low hills of volcanic debris.

Compared to other agricultural areas in northern Utah, Ogden Valley stands out as especially favored with respect to water supply. The annual precipitation, averaging more than 20 inches during a 30-year period of record at Huntsville, is 15 to 25 percent more than at Salt Lake City, Ogden, or Brigham. The water requirement for irrigation in Ogden Valley is appreciably less than that near Ogden and elsewhere west of the Wasatch Range because its 95-day growing season is 60 days shorter and the summer temperature commonly is 4° to 6°F lower. The average annual inflow from the South Fork of the Ogden River, which contributes a little less than half of the total inflow to the valley, is enough to cover the entire valley area to a depth of 60 inches. Although, on an annual basis, the tributary streams contribute an abundance of water to the valley, water for irrigation in late summer may be in short supply because the inflow comes chiefly from snowmelt in the spring.

It was inevitable that these abundant water supplies would be developed for use by the communities west of the Wasatch Range. The city of Ogden has obtained its municipal supplies from the artesian aquifer since 1914, and as the city has grown, its withdrawals from the aquifer have increased from less than 10,000 acre-feet per year in the 1920's to 16,700 acre-feet in 1951. Pine View Reservoir also is basic to the water economy of the communities west of the Wasatch Range. It stores only a minor fraction of the total inflow to Ogden Valley, its capacity being equivalent to 60 percent of the average annual inflow from the South Fork alone. Without doubt, these facilities for storage of water constitute the principal economic asset of Ogden Valley. The valley itself has a population of about 1,000, chiefly in the villages of Huntsville, Eden, and Liberty. By contrast, the water from Ogden Valley serves a population of 60,000 and supplies water to about 16,000 acres of irrigated farmland west of the Wasatch Range.

DATA AVAILABLE FOR A HYDROLOGIC STUDY OF OGDEN VALLEY

In Ogden Valley and in the areas that drain into it, too few data have been collected to make a quantitative inventory of the water in each of the various phases of the hydrologic cycle. However, sufficient data are available for a qualitative evaluation of the principal factors that affect the water supply of the valley and for the computation of a tentative water budget for the artesian aquifer. The data consist of records of precipitation, atmospheric pressure, stream discharge, storage in Pine View Reservoir, withdrawals from the artesian aquifer, and water-level fluctuations in two wells tapping that aquifer.

PRECIPITATION

Precipitation was recorded at Huntsville in the southeastern part of Ogden Valley during the period 1895–1930 and at Pine View Dam during the period 1935–51. (See table 1.) The average annual precipitation during the period of record at Huntsville was 20.4 inches and at Pine View Dam, 29.2 inches. Absence of overlap in the two periods of record makes correlation impossible, but the precipitation at Pine View Dam appears to be considerably more than at Huntsville, presumably because of orographic influences. The record of precipitation at the dam includes data on the amount that fell as snow and, for some winters, daily measurements of the depth of snow on the ground. From these records some inferences can be drawn as to the times when precipitation accumulated as snow and when that snow melted. However, because the frost conditions in the soil were not recorded, the periods when infiltration resulted from snowmelt cannot be differentiated from the periods when snow disappeared by runoff or evaporation.

TABLE 1.—*Monthly and annual precipitation, in inches, at Pine View Dam*

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1935	0.78	1.54	2.38	5.30	3.18	Tr.	0.00	0.62	0.90	1.63	2.45	2.25	21.03
1936	8.78	8.34	3.39	1.45	1.42	1.39	1.57	1.16	.22	1.85	1.67	3.63	34.87
1937	5.57	4.50	2.88	3.69	2.19	.22	.96	.21	.37	2.79	2.41	3.10	28.89
1938	2.70	3.00	6.87	2.88	4.01	.72	.85	.88	.13	2.88	3.34	2.53	30.79
1939	2.71	3.46	1.89	1.80	1.65	2.16	.30	.25	2.43	1.97	Tr.	1.60	20.22
1940	5.01	5.49	3.12	3.18	.05	.95	1.18	.10	3.03	2.34	1.14	4.88	30.47
1941	3.23	4.37	2.91	5.92	1.46	1.84	1.65	1.34	1.17	3.92	3.77	5.80	37.38
1942	3.28	3.19	2.06	3.28	.66	.81	.41	.61	1.43	1.13	4.05	5.62	26.53
1943	2.81	2.38	3.05	2.20	2.52	3.95	.73	2.02	.46	4.52	.85	1.59	27.08
1944	1.93	.93	4.09	3.92	1.82	4.75	.35	.00	1.05	.37	3.06	1.74	24.01
1945	.72	5.73	4.93	2.83	2.15	6.02	.48	4.45	.95	1.98	4.28	4.81	39.33
1946	2.03	1.42	2.97	2.28	2.54	.50	.43	.72	.75	5.95	2.90	3.03	25.52
1947	1.23	.71	3.76	3.00	2.08	4.29	Tr.	3.83	2.63	2.65	3.65	2.06	29.89
1948	.83	2.80	4.94	4.94	3.31	1.97	Tr.	1.30	1.23	3.44	2.81	3.28	30.85
1949	2.64	1.46	4.27	1.12	4.15	2.44	.39	.71	.52	5.66	2.12	3.18	28.66
1950	4.06	1.88	4.46	2.12	3.25	1.27	.80	.01	1.39	1.86	7.15	3.52	31.77
1951	4.31	2.39	1.13	3.46	2.41	.18	1.24	2.94	.56	2.91	4.31	2.78	28.62

ATMOSPHERIC PRESSURE

Salt Lake City, 35 miles south of Ogden Valley, is the nearest point for which a long-term record of barometric pressure is available. This record has been used in relating changes in atmospheric pressure to water-level fluctuations in the Tower well, although it is realized that local cyclonic disturbances, particularly in the summer, may occur in Ogden Valley and not at Salt Lake City, or vice versa. In recent years fluctuations of atmospheric pressure have been recorded at the Ogden airport, 10 miles west of Ogden Valley.

STREAM DISCHARGE

The discharge of the South Fork of the Ogden River has been measured since March 1921 at a gaging station (South Fork of Ogden River near Huntsville, Utah) in the South Fork Canyon about a mile upstream from the margin of Ogden Valley. The monthly and annual totals for calendar years 1931–51 are given in table 2, and the monthly totals for the same period are shown graphically in figure 19. The drainage basin above the gaging station has an area of about 148 square miles.

The inflow to Ogden Valley from the Middle and North Forks and from minor tributaries is not measured.

The discharge of the Ogden River has been measured since October 1931 at a gaging station (Ogden River near Ogden, Utah, 1931–37; Ogden River below Pine View Dam, near Ogden, Utah, 1938–) about one-fourth of a mile downstream from Pine View Dam. Until 1936, when storage in Pine View Reservoir began, the measurements represented the total outflow from Ogden Valley. Diversion into the Pine View pipeline at a point upstream from the gaging station began in 1937. The annual discharge of the Ogden River until 1937 and the annual combined discharge of the Ogden River and the pipeline from 1937 to 1951 are given in table 3, together with the annual changes in contents of Pine View Reservoir and the adjusted outflow from Ogden Valley.

There appears to be a rather close relationship between the annual outflow from Ogden Valley and the annual inflow from the South Fork of the Ogden River. (See fig. 20.) If the discharge for 1934, which was the year of the least runoff on record, is omitted from the computations, the inflow from the South Fork during the water years 1932–50 ranged from 37 to 53 percent of the outflow from the valley and averaged about 45 percent. (The area drained by the South Fork above the gaging station is 46 percent of the area that is drained through Ogden Canyon.)

STORAGE IN PINE VIEW RESERVOIR

The altitude of the water surface in Pine View Reservoir has been recorded daily at 8 a.m. since the gates were first closed in November 1936. The readings made on the first day of each month are given in table 4. These measurements and a capacity table supplied by the Bureau of Reclamation were used in computing the contents of the reservoir on the first of each month. (See table 5.) The water-level measurements and the computations of water in storage are used in analyzing the effects of the changing load on the artesian aquifer: the changes in the level of Pine View Reservoir are proportional to

TABLE 2.—*Monthly and annual discharge, in acre-feet, of the South Fork of the Ogden River*

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1931	2,360	2,180	2,660	4,800	6,150	2,310	1,750	1,680	1,670	1,890	1,880	1,940	31,270
1932	1,970	2,270	5,610	23,200	47,300	11,800	4,030	2,520	2,290	2,310	2,240	2,150	107,700
1933	2,210	1,980	3,490	11,700	28,700	14,800	3,180	2,340	2,090	2,440	2,280	2,330	77,540
1934	2,340	2,030	2,920	3,970	2,320	1,690	1,460	1,420	1,440	1,800	1,900	2,110	25,400
1935	2,290	2,640	3,680	12,300	20,580	7,640	2,530	1,880	1,670	1,880	1,930	1,980	61,000
1936	1,980	2,140	5,150	41,770	50,300	8,670	3,730	2,680	2,320	2,380	2,250	2,220	125,600
1937	2,300	2,190	4,370	13,130	34,150	7,580	3,510	2,450	2,130	2,460	2,440	2,550	79,260
1938	2,550	2,160	6,030	21,010	24,210	7,070	3,450	2,610	2,320	2,320	2,330	2,300	78,360
1939	2,210	2,000	6,630	16,700	9,990	3,480	2,310	1,990	1,940	2,070	1,930	1,970	53,220
1940	2,010	2,200	5,140	10,920	9,340	2,600	1,830	1,650	1,700	1,890	1,900	1,830	43,010
1941	1,870	2,080	3,510	7,850	13,260	3,670	2,120	1,860	1,750	2,010	1,990	2,150	44,120
1942	1,950	1,900	3,300	20,570	15,890	6,340	2,680	2,000	1,900	2,030	2,020	2,100	62,680
1943	2,280	2,950	6,450	30,490	19,800	9,760	3,860	2,680	2,280	2,400	2,270	2,230	87,450
1944	2,220	2,140	2,680	7,200	22,640	10,540	3,480	2,460	2,250	2,350	2,320	2,170	62,450
1945	2,170	2,310	4,050	10,060	27,070	16,380	4,540	3,130	2,530	2,600	2,800	3,180	80,820
1946	3,250	2,850	8,720	39,620	21,420	7,710	3,610	2,770	2,490	2,810	2,750	2,880	100,900
1947	2,340	2,430	5,200	12,270	20,880	6,850	3,730	2,930	2,560	2,580	2,490	2,560	66,820
1948	2,690	2,420	2,930	17,460	38,790	9,060	3,860	2,710	2,390	2,500	2,500	2,600	89,910
1949	2,460	2,400	6,630	27,380	30,530	9,400	4,250	3,040	2,650	3,030	2,700	2,640	97,110
1950	3,450	3,990	7,160	26,950	40,500	16,940	5,520	3,640	3,030	2,980	3,320	3,820	121,300
1951	3,370	5,040	6,630	32,300	41,110	10,760	4,570	3,510	2,870	3,030	2,860	3,050	119,100

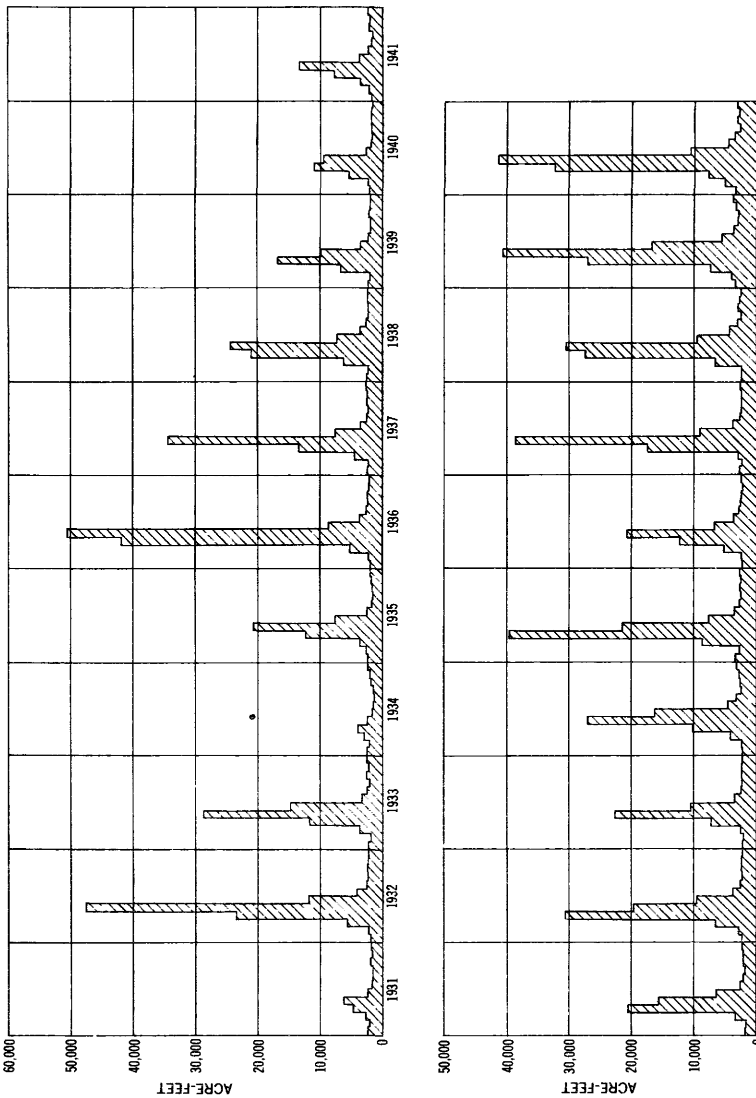

FIGURE 19.—Graph of monthly discharge of the South Fork of the Ogden River.

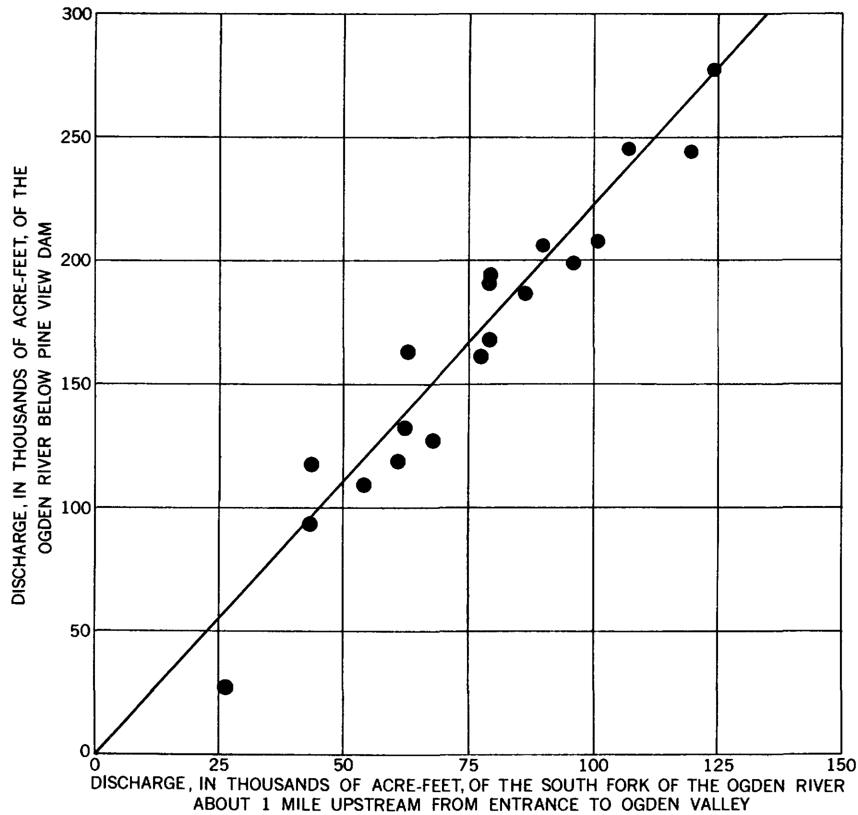

FIGURE 20.—Relation of outflow from Ogden Valley to inflow from the South Fork of the Ogden River. Slope of line indicates that inflow from South Fork of Ogden River is 45 percent of outflow from Ogden Valley.

the changes in load per unit of area, and the changes in contents of Pine View Reservoir are proportional to the changes in total load upon the artesian aquifer.

WITHDRAWALS FROM THE ARTESIAN AQUIFER

Since 1916 the artesian aquifer has discharged principally through the wells that supply the city of Ogden. For years these wells were the center of attraction at a small picnic ground called Artesian Park, located near the junction of the Middle and North Forks of the Ogden River. Before the completion of Pine View Dam, 48 of the wells flowed into a collecting system and the total discharge was regulated to fit the city's need by closing or opening valves on 19 of the wells, by varying the height of discharge at 22 wells, or by pumping as many as 28 wells with compressed air. A short while before

TABLE 3.—*Annual outflow, in acre-feet, from Ogden Valley, Utah*

Calendar year	Combined discharge of Ogden River and pipeline	Increase (+) or decrease (−) in contents of Pine View Reservoir	Adjusted outflow from Ogden Valley [1]
1932	248, 000		248, 000
1933	160, 000		160, 000
1934	25, 720		25, 720
1935	121, 100		121, 100
1936	277, 200	+4, 570	281, 800
1937	186, 600	+6, 140	192, 700
1938	169, 100	−680	168, 400
1939	105, 500	+8, 730	114, 200
1940	110, 400	−15, 910	94, 490
1941	110, 900	+12, 670	123, 600
1942	163, 800	−2, 910	160, 900
1943	193, 200	−1, 510	191, 700
1944	135, 200	−10, 370	124, 900
1945	200, 400	+1, 960	202, 400
1946	203, 100	+1, 510	204, 600
1947	125, 800	−1, 350	124, 400
1948	202, 400	+5, 330	207, 700
1949	200, 500	+980	201, 500
1950	242, 900	+11, 950	254, 800
1951	259, 000	−12, 710	246, 300

[1] Does not include discharge from pipeline which spills at No. 7 tunnel near mouth of Ogden Canyon; this discharge is estimated to have been 1 to 2 cubic feet per second (724 to 1,448 acre-ft per year) since 1945 and much higher before that year. Outflow from Ogden Valley is affected by diversions for irrigation and public supply above Pine View Reservoir and by evaporation and seepage from the reservoir.

Artesian Park was inundated by the filling of Pine View Reservoir, the casings of 46 of the wells were cut down as much as 10 feet and connected to a subterranean collecting system. By thus lowering the points of discharge, the maximum discharge of all wells flowing free was increased 20 percent above the previous maximum which was attained with air lift. Since 1922, a venturimeter has provided a continuous record of discharge from these wells into the municipal pipeline. The monthly discharge from the wells during the period 1931–51 is given in table 6.

Altogether, the city of Ogden drilled 51 wells in Artesian Park. However, as five of the wells were poor producers, they were plugged and abandoned. Of the 46 wells in use in 1951, 43 range in depth from 85 to 218 feet and the other 3 are 246, 475, and 600 feet deep. According to Leggette and Taylor (1937, p. 148–149), the shut-in pressure of the three deepest wells was greater than the shut-in pressure of the other wells. Whether these differences in pressure were caused entirely by the greater draft from shallow strata or were due to an initial difference in head between deep and shallow strata is not known. In any event, they indicate that the artesian aquifer includes several permeable beds which are separated from each other, at least in places, by less permeable material. Because practically all the

TABLE 4.—*Altitude, in feet above mean sea level, of the water surface in Pine View Reservoir on the first day of the month*

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1936	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	4, 829. 4
1937	4, 836. 6	4, 833. 1	4, 825. 4	4, 831. 5	4, 847. 3	4, 859. 8	4, 859. 6	4, 856. 3	4, 850. 3	4, 845. 2	4, 846. 2	4, 848. 0
1938	4, 846. 0	4, 849. 9	4, 851. 8	4, 860. 5	4, 865. 7	4, 871. 0	4, 869. 5	4, 866. 8	4, 862. 4	4, 859. 6	4, 858. 2	4, 852. 1
1939	4, 844. 8	4, 833. 5	4, 833. 0	4, 845. 9	4, 870. 0	4, 870. 3	4, 867. 8	4, 862. 7	4, 856. 7	4, 853. 2	4, 853. 4	4, 854. 0
1940	4, 854. 4	4, 849. 7	4, 848. 8	4, 854. 8	4, 869. 0	4, 870. 2	4, 864. 4	4, 856. 1	4, 843. 7	4, 841. 1	4, 838. 7	4, 836. 5
1941	4, 832. 9	4, 829. 5	4, 832. 9	4, 840. 5	4, 863. 8	4, 872. 0	4, 869. 8	4, 865. 4	4, 860. 4	4, 857. 2	4, 855. 4	4, 854. 4
1942	4, 851. 2	4, 845. 6	4, 841. 0	4, 840. 3	4, 870. 3	4, 872. 0	4, 869. 8	4, 864. 6	4, 857. 7	4, 853. 0	4, 851. 9	4, 852. 7
1943	4, 848. 4	4, 846. 5	4, 845. 6	4, 858. 6	4, 868. 9	4, 872. 1	4, 870. 8	4, 864. 7	4, 857. 2	4, 850. 9	4, 850. 3	4, 851. 1
1944	4, 846. 4	4, 845. 5	4, 845. 2	4, 844. 3	4, 856. 4	4, 871. 9	4, 870. 8	4, 863. 6	4, 854. 1	4, 845. 2	4, 838. 7	4, 825. 5
1945	4, 826. 2	4, 826. 6	4, 831. 5	4, 842. 8	4, 863. 9	4, 872. 0	4, 871. 7	4, 865. 7	4, 860. 3	4, 851. 0	4, 825. 8	4, 824. 7
1946	4, 833. 6	4, 831. 8	4, 828. 2	4, 849. 7	4, 871. 4	4, 872. 0	4, 867. 8	4, 859. 9	4, 850. 4	4, 842. 5	4, 842. 6	4, 844. 3
1947	4, 835. 4	4, 833. 5	4, 835. 2	4, 850. 8	4, 866. 0	4, 871. 7	4, 870. 1	4, 861. 4	4, 854. 4	4, 848. 6	4, 842. 9	4, 826. 0
1948	4, 833. 1	4, 834. 1	4, 829. 2	4, 829. 2	4, 861. 5	4, 872. 0	4, 870. 5	4, 862. 3	4, 853. 0	4, 844. 9	4, 844. 2	4, 845. 3
1949	4, 842. 5	4, 833. 7	4, 829. 2	4, 836. 7	4, 864. 6	4, 872. 0	4, 870. 5	4, 863. 3	4, 854. 1	4, 846. 8	4, 846. 6	4, 847. 4
1950	4, 844. 1	4, 843. 6	4, 846. 5	4, 839. 5	4, 856. 8	4, 870. 9	4, 871. 4	4, 866. 1	4, 858. 3	4, 851. 1	4, 850. 0	4, 853. 7
1951	4, 856. 5	4, 853. 6	4, 852. 8	4, 845. 6	4, 861. 6	4, 871. 9	4, 869. 6	4, 862. 2	4, 856. 5	4, 849. 3	4, 848. 0	4, 849. 4
1952	4, 843. 0	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------

TABLE 5.—*Contents, in thousands of acre-feet, of Pine View Reservoir on the first day of the month*

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1936												1.5
1937	4.6	2.9	.6	2.3	11.8	25.1	24.9	20.8	14.5	10.1	10.9	12.4
1938	10.8	14.1	16.0	26.1	33.4	41.8	39.3	35.0	28.7	24.9	23.1	16.3
1939	9.8	3.1	2.9	10.6	40.2	40.6	36.6	29.1	21.3	17.4	17.6	18.4
1940	18.8	14.0	13.1	19.1	38.5	40.5	31.4	20.6	9.0	7.2	5.8	4.5
1941	2.8	1.6	2.8	6.9	30.6	43.6	39.9	33.0	26.0	21.8	19.8	18.9
1942	15.4	10.4	7.1	6.7	40.7	43.6	39.7	31.8	22.5	17.3	16.1	17.0
1943	12.7	11.1	10.4	23.7	38.3	43.7	41.4	32.0	21.9	15.1	14.5	15.3
1944	11.0	10.3	10.1	9.4	20.9	43.4	41.5	30.3	18.4	10.1	5.7	.6
1945	.8	.8	2.3	8.4	30.7	43.6	43.0	33.4	25.8	15.2	.7	.5
1946	3.1	2.4	1.2	13.9	42.5	43.6	36.6	25.2	14.6	8.2	8.2	9.4
1947	4.0	3.1	3.9	15.0	33.8	43.0	40.3	27.3	18.7	12.9	8.4	.7
1948	2.9	3.4	1.5	1.5	27.4	43.6	41.0	28.6	17.2	9.9	9.4	10.2
1949	8.1	3.2	1.5	4.6	31.7	43.6	41.0	30.0	18.4	11.3	11.2	11.9
1950	9.3	8.9	11.1	6.2	21.4	41.6	42.6	34.0	23.2	15 3	14.2	18.0
1951	21.1	17.9	17.0	10.4	27.6	43.3	39.6	28.4	21.1	13.4	12.2	13.5
1952	8.2											

water is yielded from a zone less than 140 feet thick, these differentials are ignored in this paper and the producing strata are regarded as a single aquifer.

Possibly a small quantity of water is discharged from the artesian aquifer other than through the municipal-supply wells. Leggette and Taylor (1937, p. 137–141) estimated that in 1934, before the construction of Pine View Dam, the discharge from wells not owned by the city of Ogden totaled 1,700 acre-feet and that seepage from the artesian aquifer into Ogden Canyon amounted to about 2,100 acre-feet. They estimated that in the same year about 1,600 acre-feet of ground water was consumed by evapotranspiration and that 6,600 acre-feet of ground water was discharged to streams in the area that is underlain by the artesian aquifer. Probably most of this water was derived from the shallow water-table aquifer that overlies the clay layer that confines the water in the artesian aquifer. The amount of water lost from the artesian aquifer by upward movement through the clay layer was considered to have been small.

As construction of Pine View Dam practically eliminated seepage from the artesian aquifer into Ogden Canyon and as all flowing wells not owned by the city of Ogden were plugged before the initial filling of Pine View Reservoir, the discharge from the artesian aquifer has been limited since 1936 to the quantity withdrawn for the Ogden municipal supply. Upward movement through the confining clay layer undoubtedly is less now than the small amount inferred by Leggette and Taylor (1937, p. 137), because of the downward pressure of the water in Pine View Reservoir and, perhaps to a small extent, the compaction of sediments resulting from that loading.

TABLE 6.—*Monthly discharge in acre-feet, of Ogden municipal-supply wells*

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1931	[1] 780	[1] 760	[1] 790	[1] 830	[1] 880	[1] 1,300	[1] 1,230	[1] 1,120	[1] 930	[1] 830	[1] 800	[1] 800	11,100
1932	[1] 740	[1] 650	[1] 680	[1] 650	[1] 650	[1] 930	[1] 1,190	[1] 1,180	[1] 910	[1] 750	610	680	9,600
1933	870	790	870	875	915	1,000	1,115	1,155	1,100	910	835	860	11,300
1934	860	775	910	965	970	1,010	1,160	1,200	1,090	900	860	920	11,600
1935	920	800	870	840	875	915	1,005	1,130	1,095	[2] 1,000	[2] 900	[2] 930	11,300
1936	1,000	920	1,005	1,015	1,000	1,050	1,340	1,265	1,190	1,160	895	940	12,800
1937	1,000	930	985	965	1,125	985	1,245	1,390	1,295	1,195	845	750	12,700
1938	755	685	730	665	695	890	1,300	1,215	1,065	945	755	730	10,400
1939	750	670	735	620	910	1,005	1,385	1,340	970	785	855	820	10,800
1940	790	665	755	695	1,095	1,265	1,445	1,395	875	920	775	795	11,500
1941	790	680	630	550	910	1,000	980	1,070	1,090	790	690	710	9,900
1942	770	730	790	840	1,030	1,070	1,130	1,380	1,250	1,170	860	890	11,900
1943	900	810	860	1,040	1,250	1,020	1,280	1,480	1,380	1,180	900	900	13,000
1944	960	930	930	780	990	960	1,460	1,590	1,300	1,350	1,120	1,350	13,700
1945	1,350	1,020	1,030	870	1,030	900	1,310	1,380	1,370	1,330	1,200	1,260	14,100
1946	1,270	1,050	990	860	1,300	1,300	1,650	1,700	1,360	1,270	1,210	1,210	15,200
1947	1,280	1,060	1,150	1,070	1,250	1,180	1,580	1,470	1,370	1,260	1,160	1,270	15,100
1948	1,140	1,110	1,170	1,120	1,350	1,560	1,600	1,410	1,300	1,220	1,160	1,210	15,400
1949	1,310	1,170	1,220	1,210	1,250	1,410	1,560	1,560	1,560	1,250	1,240	1,240	16,000
1950	1,100	1,100	1,350	1,050	1,360	1,480	1,740	1,540	1,730	1,260	1,400	1,400	16,500
1951	1,300	1,060	1,270	1,390	1,430	1,660	1,680	1,490	1,460	1,400	1,300	1,280	16,700

[1] Measured in city and so does not include waste at well field.
[2] Estimated.

WATER-LEVEL FLUCTUATIONS IN THE TOWER WELL

The strata penetrated in the drilling of the Tower well and the occurrence of water in those strata are described in the log given below.

Log of the Tower well (A–6–1) 12aad–1

Type of material	Thickness (feet)	Depth (feet)	Type of aquifer	Remarks
Sand and gravel; pebbles as large as 1½ in. across.	10	10	Unconfined	Water level in a nearby sump 4 ft deep ranged from 0 to 1½ ft below land surface during the period September 1932 to October 1934.
Clay and silt; some sand	28	38	Not an aquifer	
Sand and gravel	9	47	Confined	Water level in a nearby well 40 ft deep was 4 ft lower than in the Tower well throughout the period October 1932 to November 1934. Fluctuations paralleled those in Tower well.
Sand, fine to coarse	4	51		
Sand, coarse, and gravel	4	55		
Sand, fine to medium	10	65		
Sand, coarse, and gravel	3	68		
Clay, laminated	6	74	Not an aquifer	
Sand and gravel	34	108	Confined	Tower well, 108 ft deep, is open to this aquifer only.

The Ogden municipal-supply wells are 9,700 to 10,700 feet from the Tower well in directions ranging from S. 63° W. to S. 76° W. The "center of discharge" from these wells, as determined by weighting the wells according to the cross-sectional area of their casings and computing a center of gravity based on the well location, is about 10,200 feet S. 70° W. of the Tower well.

A water-level recording gage has been operated at the Tower well since September 1932. Except for a few short periods when the recorder failed to operate properly or snow made the well inaccessible, the record of water-level fluctuations is continuous. The altitude of the water level on the first day of each month during the period October 1932 to January 1952 is given in table 7.

WATER-LEVEL FLUCTUATIONS IN THE CEMETERY WELL

As part of the ground-water studies made by Leggette and Taylor (1937), two wells were drilled within the area that later was flooded by the Pine View Reservoir. One of these, well 101, was 68 feet deep and the other, well 102, 90 feet deep, and both were equipped with water-level recording gages. The water levels were found to fluctuate in response to changes in the rate of withdrawal from the Ogden municipal-supply wells. During the summer, when withdrawals were greater, the water levels in wells 101 and 102 were at about the same altitude. The water level in both wells rose gradually from September to May, but as the rate of rise in well 102 was slightly greater, by May the water level in this well was about 1 foot higher than the water level in well 101.

In October 1935 the Bureau of Reclamation drilled the Cemetery well as a replacement for these two wells. The site of the Cemetery

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TABLE 7.—*Altitude, in feet above mean sea level, of the water level in the Tower well on the first day of the month*

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1932	--------	--------	--------	--------	--------	--------	--------	--------	--------	4, 872. 6	4, 873. 7	4, 873. 9
1933	4, 872. 7	4, 871. 0	4, 869. 8	4, 870. 8	4, 874. 4	4, 874. 9	4, 875. 1	4, 873. 9	4, 873. 0	4, 872. 6	4, 873. 2	4, 873. 2
1934	4, 872. 8	4, 871. 7	4, 871. 4	4, 873. 1	4, 874. 6	4, 873. 8	4, 872. 4	4, 870. 3	4, 867. 8	4, 865. 9	4, 866. 9	4, 869. 3
1935	4, 869. 4	4, 870. 1	4, 872. 4	4, 874. 0	4, 874. 8	4, 875. 0	4, 874. 9	4, 873. 6	4, 872. 3	4, 871. 1	4, 871. 7	4, 871. 0
1936	4, 869. 8	4, 868. 6	4, 868. 9	4, 873. 6	4, 874. 8	4, 875. 3	4, 874. 6	4, 873. 8	4, 873. 6	4, 874. 8	4, 875. 9	4, 875. 8
1937	4, 875. 4	4, 873. 0	4, 872. 0	4, 875. 0	4, 879. 0	4, 882. 4	4, 882. 3	4, 880. 4	4, 877. 8	4, 876. 0	4, 877. 4	4, 879. 9
1938	4, 879. 6	4, 879. 4	4, 879. 6	4, 884. 4	4, 886. 7	4, 889. 6	4, 888. 1	4, 885. 8	4, 883. 5	4, 882. 3	4, 883. 1	4, 880. 1
1939	4, 878. 8	4, 876. 7	4, 875. 4	4, 878. 3	4, 888. 4	4, 888. 6	4, 886. 7	4, 883. 5	4, 880. 1	4, 879. 1	4, 880. 9	4, 880. 5
1940	4, 879. 6	4, 877. 3	4, 876. 8	4, 880. 7	4, 887. 5	4, 887. 8	4, 884. 0	4, 878. 5	4, 874. 8	4, 873. 6	4, 876. 1	4, 876. 9
1941	4, 874. 9	4, 873. 0	4, 874. 2	4, 878. 5	4, 884. 1	4, 889. 3	4, 888. 2	4, 884. 9	4, 880. 8	4, 877. 8	4, 878. 8	4, 879. 1
1942	4, 878. 8	4, 878. 0	4, 878. 4	4, 879. 5	4, 888. 3	4, 889. 1	4, 888. 0	4, 883. 5	4, 879. 2	4, 875. 8	4, 876. 6	4, 877. 7
1943	4, 877. 1	4, 877. 7	4, 878. 7	4, 882. 8	4, 887. 2	4, 888. 5	4, 887. 5	4, 883. 4	4, 879. 8	4, 877. 0	4, 878. 1	4, 877. 5
1944	4, 876. 0	4, 874. 4	4, 873. 5	4, 875. 1	4, 879. 6	4, 888. 2	4, 887. 7	4, 882. 1	4, 876. 7	4, 874. 5	4, 874. 7	4, 874. 3
1945	4, 872. 5	4, 871. 5	4, 874. 0	4, 876. 7	4, 884. 2	4, 888. 7	4, 888. 6	4, 883. 6	4, 881. 1	4, 878. 4	4, 876. 6	4, 875. 8
1946	4, 878. 0	4, 878. 0	4, 877. 0	4, 880. 5	4, 888. 0	4, 889. 8	4, 886. 2	4, 881. 2	4, 876. 6	4, 875. 4	4, 877. 9	4, 877. 7
1947	4, 877. 6	4, 876. 2	4, 876. 2	4, 879. 9	4, 884. 3	4, 888. 3	4, 887. 0	4, 881. 4	4, 878. 7	4, 877. 1	4, 877. 4	4, 875. 3
1948	4, 875. 5	4, 876. 3	4, 875. 9	4, 876. 2	4, 882. 4	4, 888. 0	4, 886. 8	4, 882. 2	4, 877. 8	4, 876. 6	4, 876. 5	4, 875. 3
1949	4, 874. 6	4, 874. 2	4, 874. 5	4, 877. 5	4, 883. 4	4, 888. 7	4, 887. 1	4, 882. 3	4, 877. 9	4, 876. 7	4, 878. 2	4, 878. 5
1950	4, 877. 9	4, 878. 9	4, 879. 7	4, 879. 4	4, 882. 1	4, 887. 6	4, 887. 3	4, 884. 0	4, 880. 0	4, 878. 1	4, 877. 5	4, 879. 4
1951	4, 881. 5	4, 880. 2	4, 881. 1	4, 880. 2	4, 884. 0	4, 888. 1	4, 886. 3	4, 882. 2	4, 880. 4	4, 878. 3	4, 878. 4	4, 878. 3
1952	4, 877. 6	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------

well, which is about 50 feet higher and about 1,300 feet south of wells 101 and 102, is about 7,300 feet S. 59° W. of the Tower well and about 3,300 feet east of the "center of discharge" from the municipal-supply wells. The strata penetrated in drilling the Cemetery well and the occurrence of water in those strata are described in the log given below.

Log of the Cemetery well (A–6–1) 11dcd–1

Type of material	Thickness (feet)	Depth (feet)	Type of aquifer	Remarks
Sand	37	37	Not saturated	
Clay	68	105	Not an aquifer	
Sand, fine to coarse	15	120	Confined	
Clay, sandy	5	125	Not an aquifer	
Gravel and sand	5	130	Confined	Cemetery well, 152 ft deep, is open to this aquifer only.
Sand, fine to coarse	20	150		
Gravel	2	152		

The clay layer between the depths of 37 and 105 feet in the Cemetery well probably is equivalent, at least in part, to that between the depths of 14 and 56 feet in well 101 and between the depths of 14 and 55 feet in well 102. The Cemetery well and wells 101 and 102 were drilled 47, 12, and 35 feet, respectively, into the artesian aquifer confined by the clay layer.

As a replacement for the wells that were to be flooded, the Cemetery well was very disappointing. The water-level response to changes in atmospheric pressure proved to be almost negligible. In 1936, while well 102 was still equipped with a recording gage, the Cemetery well was far less sensitive than well 102 to changes in the rate of discharge from the municipal-supply wells. Similarly, until mid-1946, it was far inferior to the Tower well as an indicator of changes in discharge from the municipal-supply wells or of changes in storage in Pine View Reservoir. It is not known why in mid-1946 the water-level fluctuations in the Cemetery well began to reflect, as faithfully as the fluctuations in the Tower well, the various pressure effects upon the artesian water. No water had been pumped from the well nor had any attempt been made to develop the well. Only the record of water-level fluctuations after mid-1946 is regarded to be of value.

FACTORS PRODUCING WATER-LEVEL FLUCTUATIONS IN THE TOWER WELL

The fluctuations of water level in the Tower well are attributed to many causes, most of which have already been discussed in published reports by Leggette and Taylor (1937, p. 122–131) and Thomas (1945, p. 15–17, 21–37). In general, the fluctuations reflect changes in pressure upon the confined water and changes in the amount of water stored in the artesian aquifer.

CHANGES IN PRESSURE UPON THE WATER IN THE ARTESIAN AQUIFER

Changes in the pressure upon the water confined in the artesian aquifer are attributable to several different causes, the most important of which are changes in atmospheric pressure, variations in withdrawal from the municipal-supply wells, and changes in the quantity of water stored in Pine View Reservoir. Leggette and Taylor (1937, p. 128) show that earthquakes caused water-level fluctuations in several wells in Ogden Valley; such fluctuations are caused by compressional waves.

ATMOSPHERIC PRESSURE

Fluctuations of water level in response to changing atmospheric pressure have been noted in the Tower well and other artesian wells in Ogden Valley (Leggette and Taylor, 1937, p. 126; Thomas, 1945, p. 22–23). Such fluctuations are common in wells tapping confined water, because the full change in atmospheric pressure is transmitted directly to the water surface in the well, but elsewhere in the aquifer the change in atmospheric pressure is divided between the water and the aquifer material. The ratio of water-level change to barometric change (both expressed in feet of water) is the barometric efficiency of the well and is a measure of the relative compressibilities of the water and the aquifer material.

Comparison of hydrographs with barographs indicates that the barometric efficiency varies with the rate of change in atmospheric pressure; during a rapid rise or decline in atmospheric pressure, the barometric efficiency of the Tower well may be as great as 35 percent, whereas a change of equal magnitude applied gradually over a period of several days has far less effect upon the water level. Thus, time is an important factor.

A comparison of the daily noon atmospheric pressure at Salt Lake City with the daily noon artesian pressure in the Tower well during November 1933, when water-level fluctuations due to other forces were at a minimum, showed the average barometric efficiency of the Tower well to have been about 22 percent (Thomas, 1945, p. 22). A similar comparison for February 1938 showed the average barometric efficiency to have been equally high, and comparisons for several other selected periods showed barometric efficiencies ranging from 8 to 15 percent. However, no positive correlation could be made for some periods.

During the period 1943–51 measurements of the atmospheric pressure at the same hour of the first day of each month in Salt Lake City have ranged from 25.3 to 26.0 inches of mercury and have averaged 25.7 inches. If the barometric efficiency of the Tower well is assumed to be 25 percent, a change of atmospheric pressure of 0.8 inch of mercury would change the water level in the well by 0.2 foot. As the water level in the well has fluctuated through a range of more than 24 feet, the fluctuations due to changes in atmospheric pressure obviously are small in comparison to the changes due to other causes.

In constructing the hydrograph for the Tower well (fig. 21), adjustments for changes in atmospheric pressure were made by adding 0.1 foot when the contemporaneous atmospheric pressure was 25.9 inches or higher and subtracting 0.1 foot when that pressure was 25.5 inches or lower. Commonly, no adjustments were necessary.

RATE OF WITHDRAWAL FROM OGDEN MUNICIPAL-SUPPLY WELLS

Certain water-level fluctuations in the Tower well can be correlated directly with changes in the rate of withdrawal from the municipal-supply wells. Ordinarily the first detectable water-level response to a change in the rate of withdrawal is 6 to 12 hours later than the change actually occurred. Although the maximum observed effect occurs within 48 hours, the lag may be as much as 4 days.

Before the construction of Pine View Dam, the water level in the Tower well declined about 0.1 foot when the rate of withdrawal from the municipal-supply wells increased 1 cfs (cubic foot per second) (Thomas, 1945, p. 21). Similarly, when the loading effect of the filled reservoir remained approximately constant for periods of 5 to 36 days, the water level in the Tower well fluctuated about 0.1 foot for each change of 1 cfs in discharge through a range of 14 to 28 cfs. (See fig. 22.) In deriving the hypothetical position of the water level for an assumed constant discharge of 20 cfs from the municipal-supply wells, the measured water level on the first day of the month was corrected according to that ratio. Because of the lag in effect, the average discharge on the last day of the preceding month was used in computing the correction; in more than 75 percent of the months during the period 1931–51 the discharge was constant during the last 3 days of the month. The corrections ranged from −1.1 feet (April 1941) to +1.1 feet (July 1948). (See table 8.)

CONTENTS OF PINE VIEW RESERVOIR

Beginning in November 1936, when water was first impounded behind Pine View Dam, the major fluctuations of the water level in the Tower well have been related to changes in storage in Pine View Reservoir. (See fig. 21.) The water level in the well was highest (about 4,889 ft above sea level) each time the reservoir was filled to capacity. The maximum levels were 14 to 15 feet higher than the annual highest levels during the period 1932–36. The minimum water level in the period 1937–51 (4,871 ft above sea level) was recorded

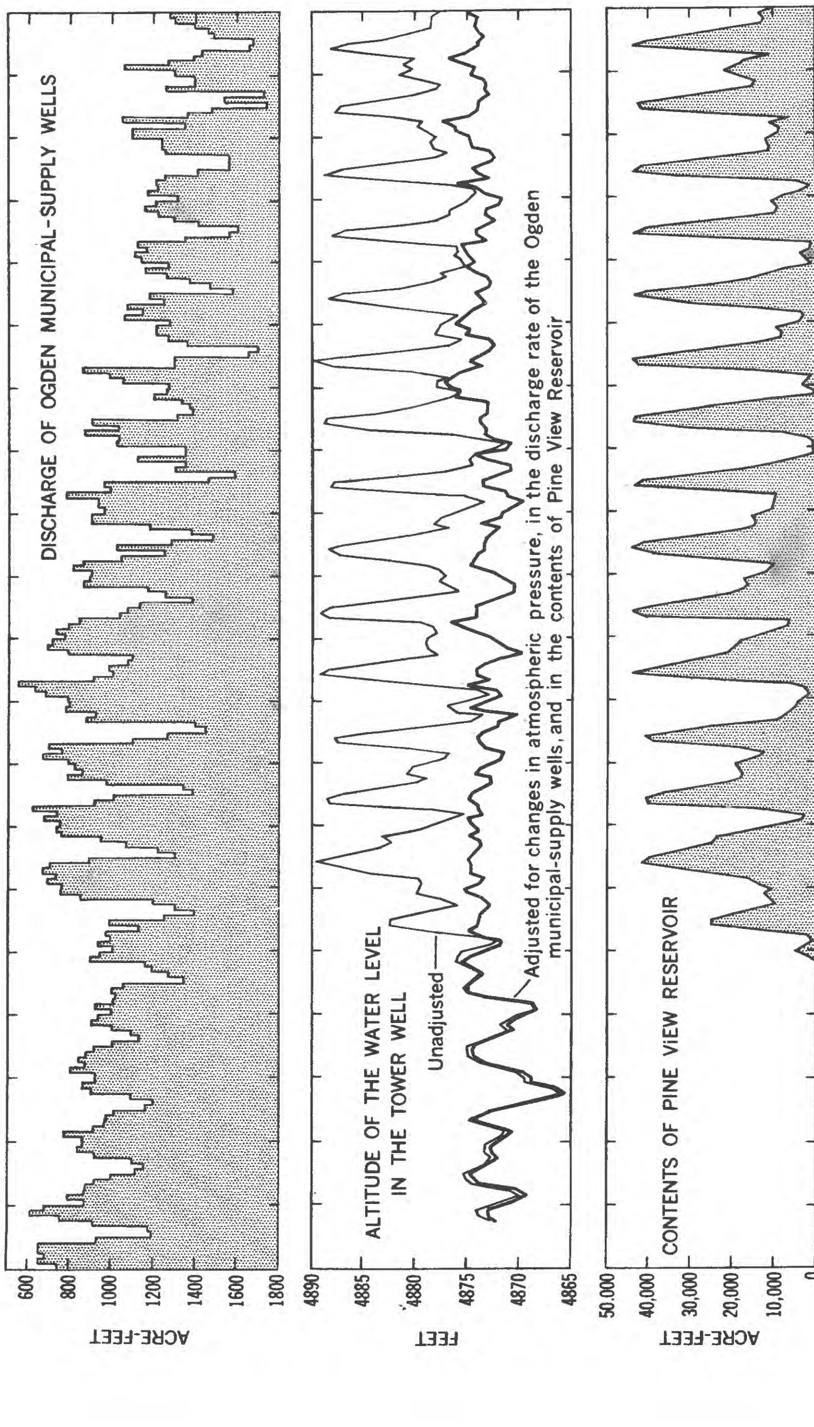

FIGURE 21.—Graph of monthly discharge from the Ogden municipal-supply wells, unadjusted and adjusted hydrographs for the Tower well, and graph of monthly contents of Pine View Reservoir.

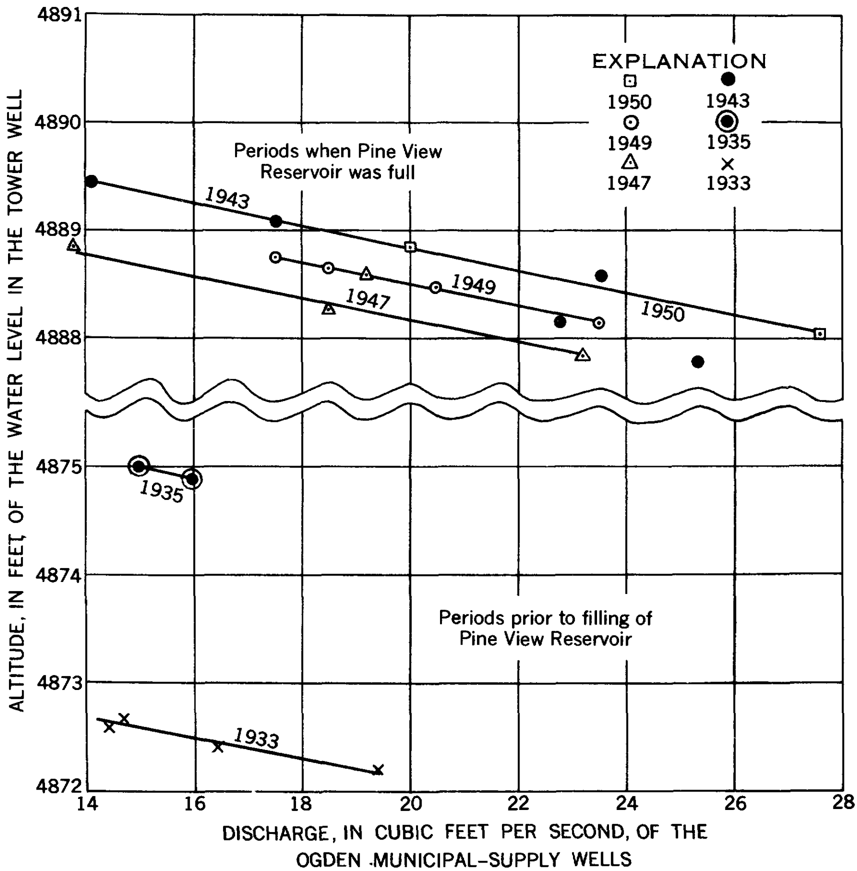

FIGURE 22.—Relation of the water level in the Tower well to the rate of withdrawal from the Ogden municipal-supply wells. All lines slope at rate of 0.1-foot change in water level to 1-cfs change in rate of discharge from wells.

on February 2, 1945, after Pine View Reservoir was drained for the first time. This level was about as low as the minimum recorded in the winter of 1934, but it was not so low as the minimum recorded in the winters of 1933, 1935, and 1936. The lowest known water level in the Tower well (4,865.8 ft above sea level) was recorded on October 6 of the drought year 1934.

As changes of water level in the Tower well invariably are less than the changes in reservoir level, it is concluded that part of the increase or decrease in pressure is transmitted to the water within the aquifer. The ratio of water-level change in the well to water-level change in the reservoir is a measure of the relative compressibilities of the water in the aquifer and of the aquifer material and thus is

TABLE 8.—*Corrections, in feet, applied to the measured water levels in the Tower well. for changes in the discharge rate of the Ogden municipal-supply wells*

Year	Jan.	Feb.	Mar.	Apr.	May.	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1932	------	------	------	------	------	------	------	------	------	−0.5	−0.8	−1.0
1933	−0.9	−0.6	−0.6	−0.6	−0.5	−0.5	−0.3	0.0	0.0	−.6	−.6	−.6
1934	−.6	−.6	−.6	−.6	−.4	−.3	−.1	.0	.0	−.5	−.7	−.5
1935	−.5	−.6	−.6	−.6	−.6	−.5	−.5	−.1	−.1	−.5	−.5	−.5
1936	−.5	−.4	−.4	−.4	−.1	−.4	+.1	+.2	.0	.0	−.5	−.5
1937	−.5	−.2	−.3	−.4	−.3	−.1	−.1	+.2	+.3	+.1	−.2	−.7
1938	−.8	−.8	−.8	−.9	−.9	−.8	−.2	+.2	−.1	− 2	−.6	−.8
1939	−.9	−.8	−.8	−.8	−.9	−.3	+.1	−.4	−.2	−.4	−.7	−.7
1940	−.8	−.7	−.8	−.9	−.8	−.2	.0	+.6	+.3	−.8	−.8	−.7
1941	−.8	−.7	−.9	−1.1	−1.0	−.6	−.7	−.5	−.1	−.7	−1.0	−.8
1942	−.9	−.7	−.7	−.7	−.6	−.6	−.5	+.3	+.2	+.5	−.6	−.6
1943	−.6	−.6	−.6	−.7	−.4	−.3	−.1	+.7	+.1	+.1	+.3	−.6
1944	−.6	−.3	−.4	−.6	−1.0	−.1	−.3	+.5	+.3	.0	+.2	+.2
1945	−.9	−.2	−.4	−.4	−.7	−.4	−.5	+.7	+.7	−.4	−.3	+.2
1946	−.3	−.1	−.1	−.5	−.1	−.6	−.1	+.2	+.7	+.3	.0	+.1
1947	−.1	+.1	.0	−.6	+.3	−.2	+.4	+.9	+.2	+.2	− 3	+.1
1948	−.2	−.2	−.2	−.2	−.1	+.7	+1.1	+.5	+.4	.0	−.2	+.1
1949	− 1	+.1	.0	−.1	.0	−.2	+1.0	+.6	+.6	−.2	.0	.0
1950	.0	.0	.0	.0	−.2	+.3	+.9	+1.0	+.6	+.4	+.3	.0
1951	+.1	.0	−.1	.0	+.1	+.5	+.9	+.7	+.5	+.4	+.1	+.1

analogous to the tidal efficiency of artesian wells in coastal areas. As demonstrated by Jacob (1940, p. 583), the sum of the tidal efficiency and the barometric efficiency equals unity, or 100 percent.

The ratio of the water-level change in the Tower well to the water-level change in Pine View Reservoir is referred to as "load" efficiency and has been computed for 27 periods of constant rate of discharge from the municipal-supply wells. Although these periods represent nearly all stages of the reservoir from empty to full (that is, 4,823 to 4,872 ft above sea level), in no one of them did the level of Pine View Reservoir rise or fall more than 11 feet. As shown by table 9, the "load" efficiencies ranged from 45 to 65 percent when the reservoir level was more than 4,860 feet above sea level, from 30 to 50 percent when the level was between 4,850 and 4,860 feet above sea level, and 5 to 30 percent at lower levels. The shoreline of the reservoir is less than 1,000 feet from the Tower well when the reservoir is full and more than 2 miles away when the reservoir level is down to 4,825 feet. As the maximum "load" efficiency is about 65 percent and the maximum barometric efficiency is about 35 percent, a combination of circumstances could result in 100 percent efficiency.

The loading effect of the reservoir also was determined by graphically plotting the reservoir level on the first day of each month against the water level in the Tower well on the same day but adjusted for effects of the atmospheric pressure and discharge from the municipal-supply wells. For each reservoir level above 4,860 feet the dispersion of the plotted points was within a 2- to 3-foot range, and for reservoir levels below 4,850 feet the dispersion commonly was 5 to 7 feet. The

TABLE 9.—*"Load" efficiency of the Tower well during periods of constant rate of discharge from the Ogden municipal-supply wells*

Period	Altitude of the water surface in Pine View Reservoir: Beginning of period (feet above sea level)	End of period (feet above sea level)	Rise (+) or decline (−) during period (feet)	"Load" efficiency (percent)
Distance from well to nearest shoreline of reservoir 1,000 to 2,100 feet				
August 9–25, 1938	4,866	4,863	−3	65
August 26–31, 1938	4,863	4,862	−1	50
April 9–17, 1939	4,857	4,863	+6	45
April 18–25, 1939	4,863	4,868	+5	55
April 25–May 1, 1939	4,868	4,870	+2	65
April 19–28, 1940	4,863	4,868	+5	55
April 26–May 7, 1947	4,863	4,870	+7	45
July 17–29, 1949	4,869	4,864	−5	55
May 25–31, 1950	4,869	4,871	+2	65
Distance from well to nearest shoreline of reservoir 2,100 to 3,000 feet				
July 24–August 9, 1937	4,858	4,855	−3	50
August 10–24, 1937	4,855	4,852	−3	40
November 14–30, 1938	4,858	4,852	−6	45
April 4–7, 1939	4,850	4,857	+7	40
April 1–12, 1940	4,854	4,858	+4	50
April 17–26, 1941	4,853	4,858	+5	40
April 1–24, 1947	4,851	4,862	+11	30
May 14–18, 1950	4,855	4,859	+4	30
Distance from well to nearest shoreline of reservoir 3,000 to 12,000 feet				
April 9–25, 1937	4,832	4,843	+11	15
December 16–30, 1938	4,849	4,845	−4	10
March 29–April 12, 1941	4,840	4,850	+10	30
February 1–28, 1946	4,831	4,826	−5	15
November 18–24, 1947	4,828	4,823	−5	10
December 5–31, 1947	4,831	4,833	+2	10
January 6–23, 1948	4,832	4,837	+5	15
February 24–March 7, 1950	4,845	4,850	+5	10
March 14–21, 1950	4,840	4,845	+5	5
April 1–20, 1950	4,840	4,850	+10	5

graph indicated the following progressive increase in "load" efficiency as the reservoir contents increased:

Reservoir level (feet above sea level)	*"Load" efficiency (percent)*
Below 4,840	10
4,840 to 4,850	20
4,850 to 4,860	40
Above 4,860	60

Although progressive compaction of sediments underlying the reservoir might have been expected, no progressive change is indicated for the first 14 years of reservoir life.

Unlike the relationship between the adjusted water level in the Tower well and the reservoir level, the relationship between the adjusted water levels in the well and the total load superimposed upon the artesian aquifer is nearly a straight line. (See fig. 23.) Although the points representing low volumes in the reservoir are somewhat

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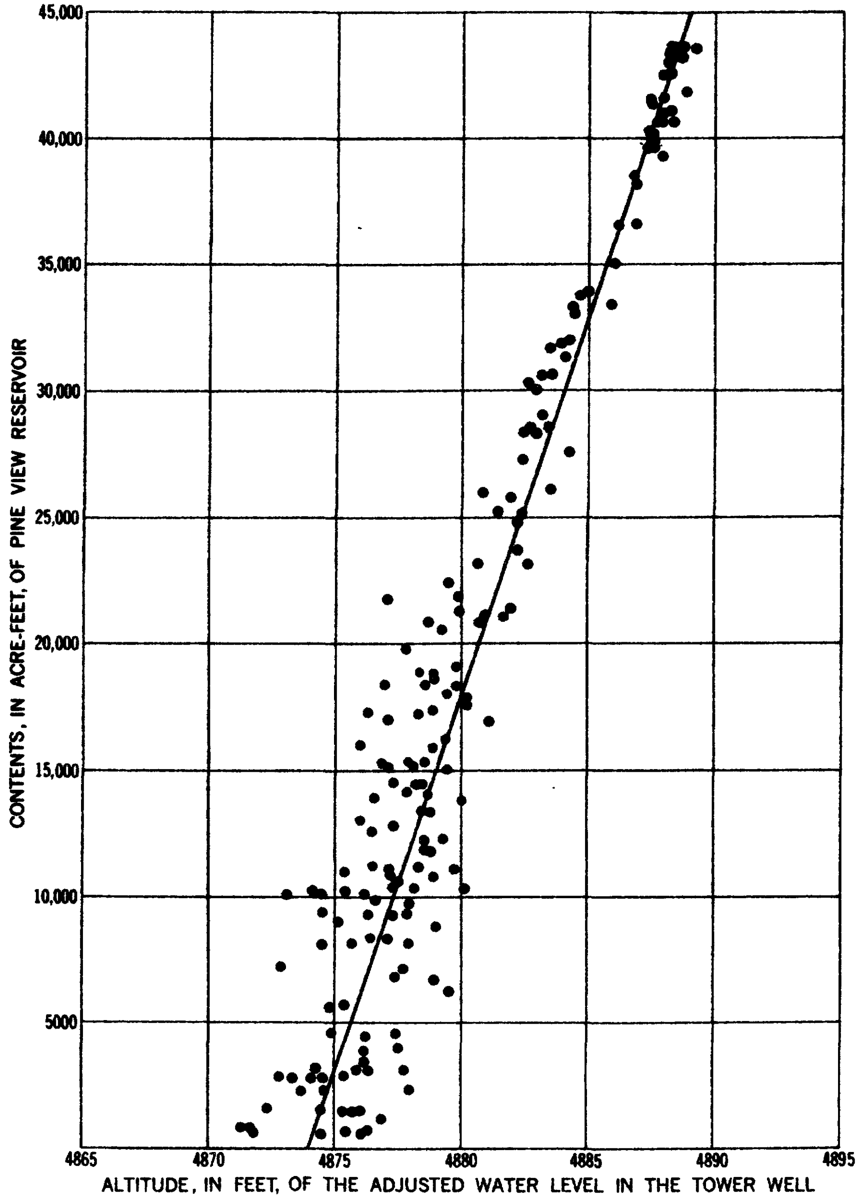

FIGURE 23.—Relation of the water level in the Tower well to the contents of Pine View Reservoir. Slope of line indicates that a change in storage of 3,000 acre-feet causes the water level in the Tower well to change 1 foot.

dispersed, the grouping of the points indicates that, on the average, an increase of 3,000 acre-feet in reservoir contents causes the water level in the Tower well to rise 1 foot. This ratio was used in adjusting the monthly water levels to eliminate the pressure effects of the surface storage. (See table 10.) An adjustment of −14.6 feet was made when Pine View Reservoir was filled to the spillway level, which is 4,872 feet above sea level.

TABLE 10.—*Corrections, in feet, applied to the measured water levels in the Tower well for changes in the contents of Pine View Reservoir*

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1936												−0.5
1937	−1.5	−1.0	−0.2	−0.8	−3.9	−8.4	−8.3	−6.9	−4.8	−3.4	−3.6	−4.1
1938	−3.6	−4.7	−5.3	−8.7	−11.1	−13.9	−13.1	−11.7	−9.6	−8.3	−7.7	−5.4
1939	−3.3	−1.0	−1.0	−3.5	−13.4	−13.5	−12.2	−9.7	−7.1	−5.8	−5.9	−6.1
1940	−6.3	−4.7	−4.4	−6.4	−12.8	−13.5	−10.5	−6.9	−3.0	−2.4	−1.9	−1.5
1941	−.9	−.5	−.9	−2.3	−10.2	−14.5	−13.3	−11.0	−8.7	−7.3	−6.6	−6.3
1942	−5.1	−3.5	−2.4	−2.2	−13.6	−14.5	−13.2	−10.6	−7.5	−5.8	−5.4	−5.7
1943	−4.2	−3.7	−3.5	−7.9	−12.8	−14.6	−13.8	−10.7	−7.3	−5.0	−4.8	−5.1
1944	−3.7	−3.4	−3.4	−3.1	−7.0	−14.5	−13.8	−10.1	−6.1	−3.4	−1.9	−.2
1945	−.3	−.3	−.8	−2.8	−10.2	−14.5	−14.3	−11.1	−8.6	−5.1	−.2	−.2
1946	−1.0	−.8	−.4	−4.6	−14.2	−14.5	−12.2	−8.4	−4.9	−2.7	−2.7	−3.1
1947	−1.3	−1.0	−1.3	−5.0	−11.3	−14.3	−13.4	−9.1	−6.2	−4.3	−2.8	−.2
1948	−1.0	−1.1	−.5	−.5	−9.1	−14.5	−13.7	−9.5	−5.8	−3.3	−3.1	−3.4
1949	−2.7	−1.1	−.5	−1.5	−10.6	−14.5	−13.7	−10.0	−6.1	−3.8	−3.7	−4.0
1950	−3.1	−3.0	−3.7	−2.1	−7.1	−13.9	−14.2	−11.3	−7.7	−5.1	−4.7	−6.0
1951	−7.0	−6.0	−5.7	−3.5	−9.2	−14.5	−13.2	−9.5	−7.0	−4.5	−4.1	−4.5
1952	−2.7											

WATER-LEVEL ADJUSTMENTS FOR PRESSURE EFFECTS

Fluctuations of the water level in the Tower well are shown by the two hydrographs in figure 21. One, the light line, is a record of the actual position of the water level on the first day of each month (table 7); the other, the heavy line, is a record of the position of the water level adjusted for the pressure effects of pumpage from the municipal-supply wells, storage in the reservoir, and atmospheric pressure (table 11). Although, at first glance, the adjusted hydrograph appears less impressive than the original, it is believed to be much more nearly indicative of the changes in ground-water storage.

CHANGES IN GROUND-WATER STORAGE

The artesian aquifer in Ogden Valley is recharged largely, if not wholly, in the higher parts of the valley. The principal sources of recharge are seepage from the streams that enter the valley, local run-off, and precipitation. Withdrawals through the Ogden municipal-supply wells constitute the only significant discharge from the artesian aquifer. If the adjusted hydrograph for the Tower well is to serve as an index to the quantity of water in storage, it must show the net effect of these subtractions from and additions to the artesian aquifer. In the following paragraphs an effort is made to segregate the effects of discharge from the municipal-supply wells and recharge from each of the several sources.

TABLE 11.—*Altitude, in feet, of the water level in the Tower well on the first day of the month*

[Data adjusted for changes in atmospheric pressure, changes in the discharge rate of the Ogden municipal-supply wells, and changes in the contents of Pine View Reservoir]

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1932	------	------	------	------	------	------	------	------	------	4, 872. 1	4, 872. 9	4, 872. 9
1933	4, 871. 8	4, 870. 4	4, 869. 2	4, 870. 2	4, 873. 9	4, 874. 4	4, 874. 8	4, 873. 9	4, 873. 0	4, 872. 0	4, 872. 6	4, 872. 6
1934	4, 872. 2	4, 871. 1	4, 870. 8	4, 872. 5	4, 874. 2	4, 873. 5	4, 872. 3	4, 870. 3	4, 867. 8	4, 865. 4	4, 866. 2	4, 868. 8
1935	4, 868. 9	4, 869. 5	4, 871. 8	4, 873. 4	4, 874. 2	4, 874. 5	4, 874. 4	4, 873. 5	4, 872. 1	4, 870. 6	4, 871. 2	4, 870. 5
1936	4, 869. 3	4, 868. 2	4, 868. 5	4, 873. 2	4, 874. 7	4, 874. 9	4, 874. 7	4, 874. 0	4, 873. 6	4, 874. 8	4, 875. 4	4, 874. 8
1937	4, 873. 4	4, 871. 8	4, 871. 5	4, 873. 8	4, 874. 8	4, 873. 9	4, 873. 9	4, 873. 7	4, 873. 3	4, 872. 7	4, 873. 6	4, 875. 1
1938	4, 875. 2	4, 873. 9	4, 873. 5	4, 874. 8	4, 874. 7	4, 874. 9	4, 874. 8	4, 874. 3	4, 873. 8	4, 873. 8	4, 874. 8	4, 873. 9
1939	4, 874. 6	4, 874. 9	4, 873. 6	4, 874. 0	4, 874. 1	4, 874. 8	4, 874. 6	4, 873. 5	4, 872. 8	4, 872. 9	4, 874. 3	4, 873. 7
1940	4, 872. 5	4, 871. 9	4, 871. 6	4, 873. 4	4, 873. 9	4, 874. 1	4, 873. 5	4, 872. 2	4, 872. 1	4, 870. 4	4, 873. 4	4, 874. 7
1941	4, 873. 2	4, 871. 8	4, 872. 4	4, 875. 1	4, 872. 9	4, 874. 2	4, 874. 2	4, 873. 4	4, 872. 0	4, 869. 8	4, 871. 2	4, 872. 0
1942	4, 872. 7	4, 873. 8	4, 875. 3	4, 876. 6	4, 874. 1	4, 874. 0	4, 874. 3	4, 873. 2	4, 871. 9	4, 870. 5	4, 870. 4	4, 871. 4
1943	4, 872. 3	4, 873. 4	4, 874. 7	4, 874. 2	4, 874. 0	4, 873. 5	4, 873. 5	4, 873. 3	4, 872. 6	4, 872. 1	4, 873. 7	4, 871. 8
1944	4, 871. 7	4, 870. 7	4, 869. 7	4, 871. 3	4, 871. 6	4, 873. 5	4, 873. 6	4, 872. 4	4, 870. 8	4, 871. 1	4, 873. 0	4, 874. 3
1945	4, 871. 4	4, 871. 0	4, 872. 7	4, 873. 4	4, 873. 2	4, 873. 8	4, 873. 9	4, 873. 2	4, 873. 2	4, 873. 0	4, 876. 1	9, 875. 9
1946	4, 876. 7	4, 877. 1	4, 876. 5	4, 875. 5	4, 873. 7	4, 874. 7	4, 873. 9	4, 873. 0	4, 872. 4	4, 872. 9	4, 875. 1	4, 874. 7
1947	4, 876. 2	4, 875. 4	4, 874. 9	4, 874. 2	4, 873. 4	4, 873. 7	4, 874. 1	4, 873. 1	4, 872. 8	4, 873. 0	4, 874. 3	4, 875. 1
1948	4, 874. 3	4, 874. 9	4, 875. 2	4, 875. 5	4, 873. 1	4, 874. 2	4, 874. 1	4, 873. 2	4, 872. 5	4, 873. 3	4, 873. 2	4, 872. 0
1949	4, 871. 7	4, 873. 2	4, 874. 0	4, 875. 8	4, 872. 7	4, 874. 0	4, 874. 4	4, 872. 9	4, 872. 4	4, 872. 7	4, 874. 5	4, 874. 6
1950	4, 874. 7	4, 875. 9	4, 876. 1	4, 877. 3	4, 874. 7	4, 874. 0	4, 874. 0	4, 873. 7	4, 872. 9	4, 873. 3	4, 873. 1	4, 873. 4
1951	4, 874. 6	4, 874. 2	4, 875. 3	4, 876. 7	4, 874. 9	4, 874. 1	4, 874. 0	4, 873. 4	4, 873. 9	4, 874. 2	4, 874. 1	4, 873. 9
1952	4, 874. 8	------	------	------	------	------	------	------	------	------	------	------

DISCHARGE FROM THE ARTESIAN AQUIFER

Although unceasing, the discharge from the municipal-supply wells has fluctuated within rather wide limits from season to season and year to year. If it is assumed that very little if any water is discharged from the artesian aquifer other than that withdrawn through the municipal-supply wells, the quantity of withdrawal can be computed for any month or other desired period.

It is reasonable to assume that the discharge from the municipal-supply wells exceeded recharge to the aquifer during each month for which the adjusted hydrograph (fig. 21) shows a net decline in water level. The monthly net changes in water level, computed from the values in table 11, are shown in table 12. The amount of the monthly net decline, of course, did not correlate perfectly with the quantity withdrawn from the municipal-supply wells. During some months of heavy withdrawal there was either very little change in the adjusted water level in the Tower well or the change was upward, probably because recharge to the aquifer nearly equalled or exceeded the discharge. Presumably, the decline in water level was greatest per unit of volume withdrawn in those months when the rate of recharge was minimum.

The relation between monthly discharge from the municipal-supply wells and monthly net decline in adjusted water level in the Tower well is shown in figure 24. In the great majority of months the water level declined at a rate of 1.0 foot or less per 450 acre-feet withdrawn from the municipal-supply wells. This rate was exceeded only in the month of April in each of the years 1941, 1942, 1949, and 1950. Each of these months of extraordinary decline followed a month when there was much recharge to the artesian aquifer by infiltration from precipitation.

TABLE 12.—*Monthly rise (+) or decline (−), in feet, of the adjusted water level in the Tower well*

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1933	−1.4	−1.2	+1.0	+3.7	+0.5	+0.4	−0.9	−0.9	−1.0	+0.6	0.0	−0.4
1934	−1.1	−.3	+1.7	+1.7	−.7	−1.2	−2.0	−2.5	−2.4	+.8	+2.6	+.1
1935	−.4	+2.3	+1.6	+.8	+.3	−.1	−.9	−1.4	−.5	+.6	−.7	−1.2
1936	−1.1	+.3	+4.7	+1.5	+.2	−.2	−.7	−.4	+1.2	+.6	−.6	−1.4
1937	−1.6	−.3	+2.3	+1.0	−.9	.0	−.2	−.4	−.6	+.9	+1.5	+.1
1938	−1.3	−.4	+1.3	−.1	+.2	−.1	−.5	−.5	.0	+1.0	−.9	+.7
1939	+.3	−1.3	+.4	+.1	+.7	−.2	−1.1	−.7	+.1	+1.4	−.6	−1.2
1940	−.6	−.3	+1.8	+.5	+.2	−.6	−1.3	−.1	−.7	+3.0	+1.3	−1.5
1941	−1.4	+.6	+2.7	−2.2	+1.3	.0	−.8	−1.4	−2.2	+1.4	+.8	+.7
1942	+1.1	+1.5	+1.3	−2.5	−.1	+.3	−1.1	−1.3	−1.4	−.1	+1.0	+.9
1943	+1.1	+1.3	−.5	−.2	−.5	.0	−.2	−.7	−.5	+1.6	−1.9	−.1
1944	−1.0	−1.0	+1.6	+.3	+1.9	+.1	−1.2	−1.6	+.3	+1.9	+1.3	−2.9
1945	−.4	+1.7	+.7	−.2	+.6	+.1	−.7	.0	−.2	+3.1	−.2	+.8
1946	+.4	−.6	−1.0	−1.8	+1.0	−.8	−.9	−.6	+.5	+2.2	−.4	+1.5
1947	−.8	−.5	−.7	−.8	+.3	+.4	−1.0	−.3	+.2	+1.3	+.8	−.8
1948	+.6	+.3	+.3	−2.4	+1.1	−.1	−.9	−.7	+.8	−.1	−1.2	−.3
1949	+1.5	+.8	+1.8	−3.1	+1.3	+.4	−1.5	−.5	+.3	+1.8	+.1	+.1
1950	+1.2	+.2	+1.2	−2.6	−.7	.0	−.3	−.8	+.4	−.2	+.3	+1.2
1951	−.2	+1.1	+1.4	−1.8	−.8	−.1	−.6	+.5	+.3	−.1	−.2	+.9

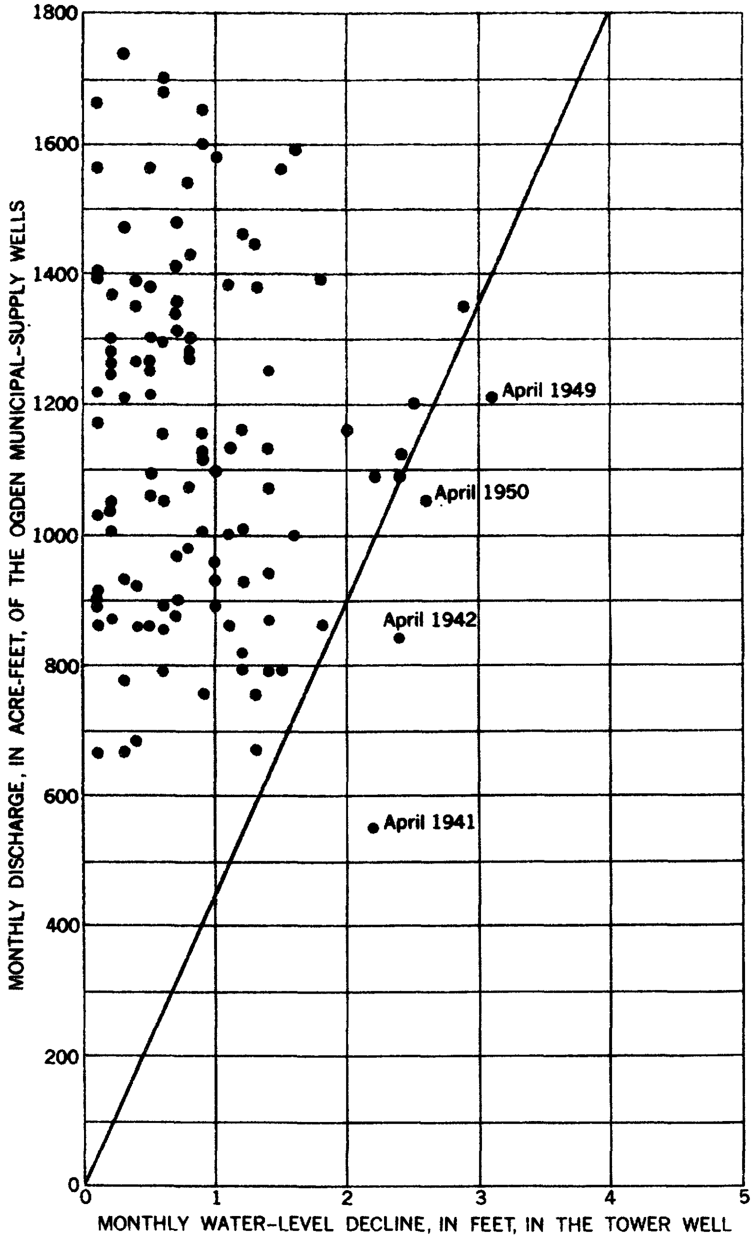

FIGURE 24.—Relation of water-level decline in the Tower well to discharge from the Ogden municipal-supply wells. Slope of line indicates that a withdrawal of 450 acre-feet from the Ogden municipal-supply wells causes the water level in the Tower well to decline a maximum of 1 foot.

The ratio of 1 foot of water-level decline in the Tower well to each withdrawal of 450 acre-feet from the artesian aquifer appears to be confirmed to some extent by the results of an earlier study of the Ogden Valley records by Thomas (1945, p. 28–31). To show the relation between the water level in the Tower well and the inflow of the South Fork of the Ogden River, Thomas divided the years 1932 to 1936 into 30 periods which omitted the months of the spring runoff. These periods ranged from 24 to 36 days in length and during each the withdrawal from the municipal-supply wells totaled 1,000 acre-feet. Thomas (1945, fig. 5) graphically plotted, for each period, the water-level change in the Tower well against the corresponding discharge of the South Fork, and he summarized the relationship between recharge and discharge as follows:

> * * * [Eight of the nine] points representing periods in the season 1934–35 * * * define a fairly straight line that would give the following relationship between recharge and discharge: The recharge is sufficient to offset discharge and maintain a constant water level in well 82 [the Tower well] when the runoff from the South Fork is about twice as great as the discharge from Artesian Park [the Ogden municipal-supply wells]—or in the periods representing withdrawals of 1,000 acre-feet from Artesian Park, if the runoff [discharge] of the South Fork is about 2,000 acre-feet. The trend of the line indicates that, for each 400 or 500 acre-foot increase in runoff during the period, the water level in well 82 would rise about a foot, and conversely for each 400 or 500 acre-foot decrease in runoff the water level would decline 1 foot. Eight points representing periods during the 1933–34 season define a line approximately parallel to that drawn for 1934–35, but farther to the right, so that a runoff of about 2,700 acre-feet from the South Fork is shown to be required to offset a withdrawal of 1,000 acre-feet from Artesian Park and hold the water level constant in the well.

As pointed out by Leggette and Taylor (1937, p. 132), the channel of the South Fork of the Ogden River was dry in several places below the gaging station throughout the winter of 1933–34. Probably this was also true in the winters of the other years. Thus the measured increases and decreases in streamflow became increases or decreases in seepage to the artesian aquifer. It is not known, however, what proportion of the seepage from the South Fork entered the artesian aquifer or what proportion of the total recharge in those months came from that stream.

The water level in the Tower well declined at the rate of 1 foot for each 450 acre-feet of withdrawal from the municipal-supply wells only when recharge was at a minimum. In other months, the effect of withdrawals from the municipal-supply wells would have been at a comparable rate but would have been partly or wholly offset by the effects of the recharge. The discharge component in the monthly changes of the adjusted water level in the Tower well—that is, the amount the water level in the Tower well would have been lowered if there had been no recharge—has been calculated from table 6 and is shown in table 13.

The effect of recharge upon the water level in the Tower well was computed by subtracting from the net change in adjusted water level (table 12) the lowering that would have been caused by discharge from the municipal-supply wells (table 13). The result, or the recharge component in the monthly changes of the water level in the Tower well, represents the rise in water level that is assumed to have been due to recharge. (See table 14.)

The monthly changes in storage in the artesian aquifer and the components that are assumed to produce those changes are depicted graphically in figure 25. The uppermost graph, which is the hydrograph for the Tower well adjusted for pressure effects (shown also in fig. 21), represents the effects of changes in storage in the artesian

TABLE 13.—*Discharge component, in feet, in the monthly changes of the adjusted water level in the Tower well*

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1933	1.9	1.8	1.9	1.9	2.0	2.2	2.5	2.6	2.4	2.0	1.9	1.9
1934	1.9	1.7	2.0	2.1	2.2	2.2	2.6	2.7	2.4	2.0	1.9	2.0
1935	2.0	1.8	1.9	1.9	1.9	2.0	2.2	2.5	2.4	2.2	2.0	2.1
1936	2.2	2.0	2.2	2.3	2.2	2.3	3.0	2.8	2.6	2.6	2.0	2.1
1937	2.2	2.1	2.2	2.1	2.5	2.2	2.8	3.1	2.9	2.7	1.9	1.7
1938	1.7	1.5	1.6	1.5	1.5	2.0	2.9	2.7	2.4	2.1	1.7	1.6
1939	1.7	1.5	1.6	1.4	2.0	2.2	3.1	3.0	2.2	1.7	1.9	1.8
1940	1.8	1.5	1.7	1.5	2.4	2.8	3.2	3.1	1.9	2.0	1.7	1.8
1941	1.8	1.5	1.4	1.2	2.0	2.2	2.2	2.4	2.4	1.8	1.5	1.6
1942	1.7	1.6	1.8	1.9	2.3	2.4	2.5	3.1	2.8	2.6	1.9	2.0
1943	2.0	1.8	1.9	2.3	2.8	2.3	2.8	3.3	3.1	2.6	2.0	2.0
1944	2.1	2.1	2.1	1.7	2.2	2.1	3.2	3.5	2.9	3.0	2.5	3.0
1945	3.0	2.3	2.3	1.9	2.3	2.0	2.9	3.1	3.0	2.9	2.7	2.8
1946	2.8	2.3	2.2	1.9	2.9	2.9	3.7	3.8	3.0	2.8	2.7	2.7
1947	2.8	2.4	2.6	2.4	2.8	2.6	3.5	3.3	3.0	2.8	2.6	2.8
1948	2.5	2.5	2.6	2.5	3.0	3.5	3.6	3.1	2.9	2.7	2.6	2.7
1949	2.9	2.6	2.7	2.7	2.8	3.1	3.5	3.5	3.5	2.8	2.8	2.8
1950	2.4	2.4	3.0	2.3	3.0	3.3	3.9	3.4	3.8	2.8	3.1	3.1
1951	2.9	2.4	2.8	3.1	3.2	3.7	3.7	3.3	3.2	3.1	2.9	2.9

TABLE 14.—*Recharge component, in feet, in the monthly changes of the adjusted water level in the Tower well*

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
1933	+0.5	+0.6	+2.9	+5.6	+2.5	+2.6	+1.6	+1.7	+1.4	+2.6	+1.9	+1.5	25.4
1934	+.8	+1.4	+3.7	+3.8	+1.5	+1.0	+.6	+.2	.0	+2.8	+4.5	+2.1	22.4
1935	+1.6	+4.1	+3.5	+2.7	+2.2	+1.9	+1.3	+1.1	+1.9	+2.8	+1.3	+.9	25.3
1936	+1.1	+2.3	+6.9	+3.8	+2.4	+2.1	+2.3	+2.4	+3.8	+3.2	+1.4	+.7	32.4
1937	+.6	+1.8	+4.5	+3.1	+1.6	+2.2	+2.6	+2.7	+2.3	+3.6	+3.4	+1.8	30.2
1938	+.4	+1.1	+2.9	+1.4	+1.7	+1.9	+2.4	+2.2	+2.4	+3.1	+.8	+2.3	22.6
1939	+2.0	+.2	+2.0	+1.5	+2.7	+2.0	+2.0	+2.3	+2.3	+3.1	+1.3	+.6	22.0
1940	+1.2	+1.2	+3.5	+2.0	+2.6	+2.2	+1.9	+3.0	+1.2	+5.0	+3.0	+.3	27.1
1941	+.4	+2.1	+4.5	−1.0	+3.3	+2.2	+1.4	+1.0	+.2	+3.2	+2.3	+2.3	21.5
1942	+2.8	+3.1	+3.1	−.6	+2.2	+2.7	+1.4	+1.8	+1.4	+2.5	+2.9	+2.9	26.2
1943	+3.1	+3.1	+1.4	+2.1	+2.3	+2.3	+2.6	+2.6	+2.6	+4.2	+.1	+1.9	28.3
1944	+1.1	+1.1	+3.7	+2.0	+4.1	+2.2	+2.0	+1.9	+3.2	+4.9	+3.8	+.1	30.1
1945	+2.6	+4.0	+3.0	+1.7	+2.9	+2.1	+2.2	+3.1	+2.8	+6.0	+2.5	+3.6	36.5
1946	+3.2	+1.7	+1.2	+.1	+3.9	+2.1	+2.8	+3.2	+3.5	+5.0	+2.3	+4.2	33.2
1947	+2.0	+1.9	+1.9	+1.6	+3.1	+3.0	+2.5	+3.0	+3.2	+4.1	+3.4	+2.0	31.7
1948	+3.1	+2.8	+2.9	+.1	+4.1	+3.4	+2.7	+2.4	+3.7	+2.6	+1.4	+2.4	31.6
1949	+4.4	+3.4	+4.5	−.4	+4.1	+3.5	+2.0	+3.0	+3.8	+4.6	+2.9	+2.9	38.7
1950	+3.6	+2.6	+4.2	− 3	+2.3	+3.3	+3.6	+2.6	+4.2	+2.6	+3.4	+4.3	36.4
1951	+2.7	+3.5	+4.2	+1.3	+2.4	+3.6	+3.1	+3.8	+3.5	+3.0	+2.7	+3.8	37.6

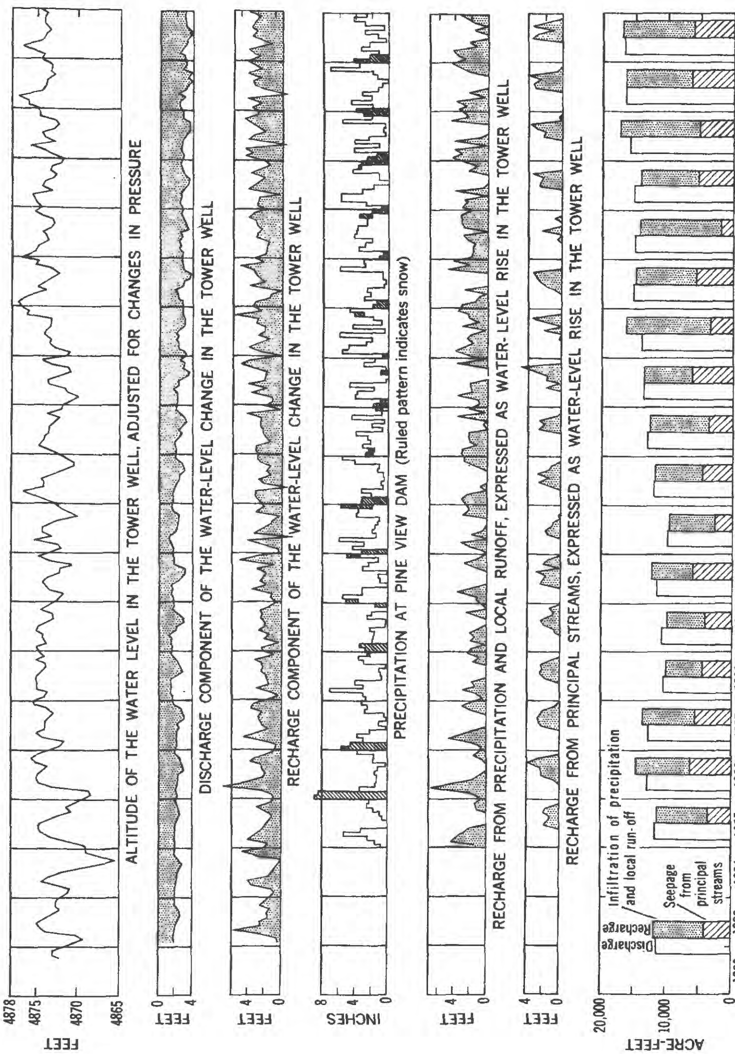

FIGURE 25.—Hydrologic analysis of changes in storage in the artesian aquifer in Ogden Valley.

aquifer. The second graph shows the downward component produced by discharge from the municipal-supply wells, and the third shows the upward component due to recharge. With few exceptions, the second and third graphs are compensatory.

RECHARGE TO THE ARTESIAN AQUIFER

The artesian aquifer may be recharged either by direct infiltration of precipitation and local runoff or by seepage from the principal streams that cross the valley floor. Seepage from the principal streams occurs chiefly during the period April through July. Recharge from local runoff is most likely to occur in February or March when the snow melts from the foothills. Although infiltration from precipitation may occur in any month of abundant precipitation, it is least likely in July, August, and September, because of the customary depletion of soil moisture by evapotranspiration, and in January, because of frozen ground. Recharge from the various sources can be differentiated to some extent on the basis of time of occurrence. For example, any large amount of recharge during October or November ordinarily can be ascribed to precipitation because at that time the perennial streams are at low stage and the ephemeral streams generally are dry.

In the fourth graph in figure 25, the monthly precipitation at Pine View Dam is differentiated as to whether it fell as rain or snow. Comparison of this graph with the graph just above it indicates that significant recharge occurred in several months when rainfall exceeded 4 inches. It was especially great in November 1934, October 1943 August 1945, October 1946, and October 1949. Significant recharge also resulted from the melting of abundant snow in 1936 and 1937.

Autumn periods of 1 to 3 months during which significant precipitation occurred are listed in table 15, and for each is given the total precipitation as given in table 1 and the total recharge components as given in table 14. A plot of the recharge components against the precipitation for each period (fig. 26) indicates that, after the soil-moisture deficiency has been satisfied, each inch of precipitation raises the water level in the Tower well about 1.2 feet. Probably, in the fall, the first 1.5 inches of precipitation is needed to satisfy the soil-moisture deficiency, but lesser amounts generally are needed at other times.

The potential recharge from precipitation and local runoff, expressed in feet of water-level rise in the Tower well, was computed for each month in the period 1935–51. The computed values are given in table 16. For each of the periods December through April, the total potential recharge from precipitation and local runoff exceeded the total recharge components of the water-level changes in the corresponding periods (table 14). As the same relationship did not characterize all the individual months in those periods, it is assumed that recharge occasionally was delayed because the soil was frozen or the

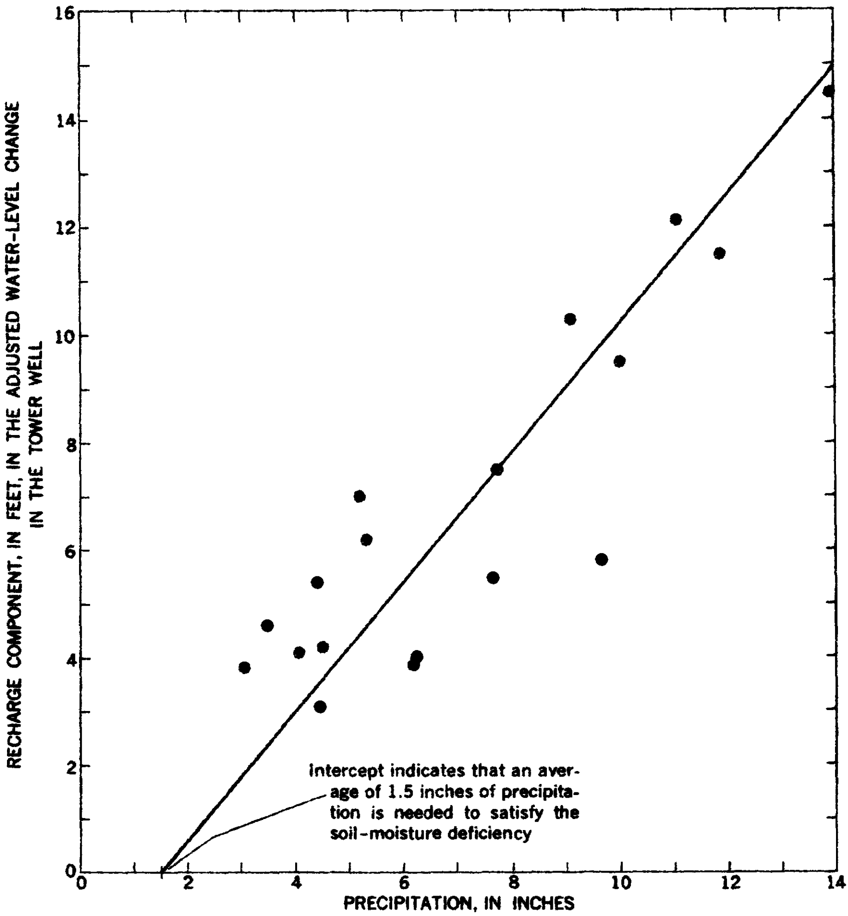

FIGURE 26.—Relation of computed recharge components to precipitation during selected autumn periods. Slope of line indicates that 1 inch of precipitation causes the water level in the Tower well to rise 1.2 feet, provided there is no deficiency in soil moisture.

TABLE 15.—*Precipitation at Pine View Dam and recharge component in the adjusted water-level changes in the Tower well during selected autumn periods*

Period	Precipitation (inches)	Recharge component (feet)	Period	Precipitation (inches)	Recharge component (feet)
October-November 1935	4.08	4.1	November 1944	3.06	3.8
October-November 1936	3.52	4.6	August 1945	4.45	3.1
October-November 1937	5.20	7.0	October-December 1945	11.07	12.1
October-November 1938	6.22	3.9	October-December 1946	11.88	11.5
September-October 1939	4.40	5.4	August-October 1947	9.11	10.3
September-October 1940	5.37	6.2	October-November 1948	6.25	4.0
October-November 1941	7.69	5.5	October-November 1949	7.78	7.5
November-December 1942	9.67	5.8	September-December 1950	13.92	14.5
October 1943	4.52	4.2	October-December 1951	10.00	9.5

precipitation was stored temporarily in the form of snow and ice. In May and November the potential recharge from precipitation and local runoff generally exceeded the recharge components, but in most months of the growing season the recharge component was greater. Obviously, then, recharge from precipitation and local runoff does not account for all the recharge that occurs in the course of a year. The values in tables 17 and 18 are the result of an attempt to differentiate, for each monthly recharge component in table 14, the part attributable to recharge from precipitation and local runoff and the part attributable to seepage from the principal streams that cross the valley floor. The values in these two tables are based on the following assumptions: (a) Recharge throughout the period December through April is due wholly to infiltration of precipitation and local runoff; (b) recharge in other months is due to infiltration from precipitation and local runoff only to the extent that the potential recharge, as given in table 16, is more than zero and not greater than the corresponding recharge component; (c) recharge not due to infiltration of precipitation and local runoff is attributable to seepage from the principal streams that cross the valley floor. The recharge increments due to infiltration of precipitation and local runoff and those due to seepage from the principal streams are shown graphically in figure 25.

TABLE 16.—*Maximum possible water-level rise, in feet, in the Tower well attributable to recharge from precipitation and local runoff*

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1935	0.9	1.8	2.9	6.4	3.8	0.0	0.0	0.0	0.0	1.2	2.9	2.7
1936	10.5	10.0	4.1	1.7	1.7	.0	.1	.0	.0	.4	2.0	4.4
1937	6.7	5.4	3.5	4.4	2.6	.0	.0	.0	.0	1.5	2.9	3.7
1938	3.2	3.6	8.2	3.5	4.8	.0	.0	.0	.0	1.7	4.0	3.0
1939	3.2	4.2	2.3	2.2	2.0	1.0	.0	.0	1.1	2.4	.0	1.9
1940	6.0	6.6	3.7	3.8	.1	.0	.0	.0	1.8	2.8	1.4	5.9
1941	3 9	5.2	3.5	7.1	1.8	.4	.2	.0	.0	2.9	4.5	7.0
1942	4.0	3.8	2.5	3.9	.8	.0	.0	.0	.0	1.3	4.9	6.7
1943	3.4	2.9	3.7	2.6	3.0	2.9	.0	.6	.0	3.6	1.0	1.9
1944	2.3	1.1	4.9	4.7	2.2	3.9	.0	.0	.0	.0	3.7	2.1
1945	.9	6.9	5.9	3.4	2.6	5.4	.0	3.5	1.1	2.4	5.1	5.8
1946	2.4	1.7	3.6	2.7	3.0	.0	.0	.0	.0	5.3	3.5	3.6
1947	1.5	.9	4.5	3.6	2.5	3.3	.0	2.8	3.2	3.2	4.4	2.5
1948	1.0	3.4	5.9	5.9	4.0	.6	.0	.0	.0	2.3	3.4	3.9
1949	3.2	1.8	5.1	1.3	5.0	1.1	.0	.0	.0	5.0	2.5	3.8
1950	4.9	2.3	5.4	2.5	3.9	.0	.0	.0	.0	2.1	8.6	4.2
1951	5.2	2.9	1.4	4.2	2.9	.0	.0	1.7	.0	1.7	5.2	3.3

On an annual basis, the amount of recharge attributable to infiltration of precipitation and local runoff correlates fairly closely with the precipitation. Thus, in 1945, the year of greatest precipitation during the period of record, the recharge was the greatest. Exceptions to this general relationship probably can be accounted for by vagaries of the weather and varying capacity of the soil to absorb moisture. The values in table 19, which are the differences between the corresponding values in tables 16 and 17, show that in some months a large part of

TABLE 17.—*Portion of the monthly recharge component, in feet, attributed to infiltration of precipitation and local runoff*

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1935	1.6	4.1	3.5	2.7	2.2	0.0	0.0	0.0	0.0	1.2	1.3	0.9	17.5
1936	1.1	2.3	6.9	3.8	1.7	.0	.1	.0	.0	.4	1.4	.7	18.4
1937	.6	1.8	4.5	3.1	1.6	.0	.0	.0	.0	1.5	2.9	1.8	17.8
1938	.4	1.1	2.9	1.4	1.7	.0	.0	.0	.0	1.7	.8	2.3	12.3
1939	2.0	.2	2.0	1.5	2.0	1.0	.0	.0	1.1	2.4	.0	.6	12.8
1940	1.2	1.2	3.5	2.0	.1	.0	.0	.0	1.2	2.8	1.4	.3	13.7
1941	.4	2.1	3.1	------	1.8	.4	.2	.0	.0	2.9	2.3	2.3	15.5
1942	2.8	3.1	2.5	------	.8	.0	.0	.0	.0	1.3	2.9	2 9	16.3
1943	3.1	3.1	1.4	2.1	2.3	2.3	.0	.6	.0	3.6	.1	1.9	20.5
1944	1.1	1.1	3.7	2.0	2.2	2.2	.0	.0	.0	.0	3.8	.1	16.2
1945	2.6	4.0	3.0	1.7	2.6	2.1	.0	3.1	1.1	2.4	2.5	3.6	28.7
1946	3.2	1.7	1.2	.1	3.0	.0	.0	.0	.0	5.0	2.3	4 2	20.7
1947	2.0	1.9	1.9	1.6	2.5	3.0	.0	2.8	3.2	3.2	3.4	2.0	27.5
1948	3.1	2.8	2.9	.1	4.0	.6	.0	.0	.0	2.3	1.4	2.4	19.6
1949	4.4	3.4	4.1	------	4.1	1.1	.0	.0	.0	4.6	2.5	2.9	27.1
1950	3.6	2.6	3.9	------	2.3	.0	.0	.0	.0	2.1	3.4	4.3	22.2
1951	2.7	3.5	4.2	1.3	2.4	.0	.0	1.7	.0	1.7	2.7	3.8	24.0

TABLE 18.—*Portion of the monthly recharge component, in feet, attributed to seepage from streams*

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1935	0.0	0.0	0.0	0.0	0.0	1.9	1.3	1.1	1.9	1.6	0.0	0.0	7.8
1936	.0	.0	.0	.0	.7	2.1	2.2	2.4	3.8	2.8	.0	.0	14.0
1937	.0	.0	.0	.0	.0	2.2	2.6	2.7	2.3	2.1	.5	.0	12.4
1938	.0	.0	.0	.0	.0	1.9	2.4	2.2	2.4	1.4	.0	.0	10.3
1939	.0	.0	.0	.0	.7	1.0	2.0	2.3	1.2	.7	1.3	.0	9.2
1940	.0	.0	.0	.0	2.5	2.2	1.9	3.0	.0	2.2	1.6	.0	13.4
1941	.0	.0	.0	.0	1.5	1.8	1.2	1.0	.2	.3	.0	.0	6.0
1942	.0	.0	.0	.0	1.4	2.7	1.4	1.8	1.4	1.2	.0	.0	9.9
1943	.0	.0	.0	.0	.0	.0	2.6	2.0	2.6	.6	.0	.0	7.8
1944	.0	.0	.0	.0	1.9	.0	2.0	1.9	3.2	4.9	.0	.0	13.9
1945	.0	.0	.0	.0	.3	.0	2.2	.0	1.7	3.6	.0	.0	7.8
1946	.0	.0	.0	.0	.9	2.1	2.8	3.2	3.5	.0	.0	.0	12.5
1947	.0	.0	.0	.0	.6	.0	2.5	.2	.0	.9	.0	.0	4.2
1948	.0	.0	.0	.0	.1	2.8	2.7	2.4	3.7	.3	.0	.0	12.0
1949	.0	.0	.0	.0	.0	2.4	2.0	3.0	3.8	.0	.4	.0	11.6
1950	.0	.0	.0	.0	.0	3.3	3.6	2.6	4.2	.5	.0	.0	14.2
1951	.0	.0	.0	.0	.0	3.6	3.1	2.1	3.5	1.3	.0	.0	13.6

the potential recharge from precipitation and local runoff fails to become actual recharge. An even greater part of the potential recharge from seepage fails to become actual recharge because, in the early part of the annual period of high runoff from snowmelt in the mountains, the aquifer ordinarily is filled to capacity and so can store no more. Not until recharge from precipitation fails to replenish the aquifer at a rate equal to discharge from the aquifer does seepage from the principal streams become an important source of recharge. Annually, however, the amount of recharge from seepage (table 18) correlates fairly closely with the discharge of the South Fork of the Ogden River (table 2).

WATER BUDGET FOR OGDEN VALLEY

The water budget for the artesian aquifer in Ogden Valley (table 20 and bottom-graph in figure 25) is based on the foregoing analysis of the available hydrologic data for the period 1935–51. In making the

TABLE 19.—*Rejected recharge, in feet, from precipitation and local runoff, expressed as water-level change in the Tower well*

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
1935	−0.7	−2.3	−0.6	3.7	1.6	0.0	0.0	0.0	0.0	0.0	1.6	1.8	5.1
1936	9.4	7.7	−2.8	−2.1	.0	.0	.0	.0	.0	.0	.6	3.7	16.5
1937	6.1	3.6	−1.0	1.3	1.0	.0	.0	.0	.0	.0	.0	1.9	12.9
1938	2.8	2.5	5.3	2.1	3.1	.0	.0	.0	.0	.0	3.2	.7	19.7
1939	1.2	4.0	.3	.7	.0	.0	.0	.0	.0	.0	.0	1.3	7.5
1940	4.8	5.4	.2	1.8	.0	.0	.0	.0	.6	.0	.0	5.6	18.4
1941	3.5	3.1	.4	7.1	.0	.0	.0	.0	.0	.0	2.2	4.7	21.0
1942	1.2	.7	.0	3.9	.0	.0	.0	.0	.0	.0	2.0	3.8	11.6
1943	.3	−.2	2.3	.5	.7	.6	.0	.0	.0	.0	.9	.0	5.1
1944	1.2	.0	1.2	2.7	.0	1.7	.	.0	.0	.0	−.1	2.0	8.7
1945	−1.7	2.9	2.9	1.7	.0	3.3	.0	.4	.0	.0	2.6	2.2	14.3
1946	−.8	.0	2.4	2.6	.0	.0	.0	.0	.0	.3	1.2	−.6	5.1
1947	−.5	−1.0	2.6	2.0	.0	.3	.0	.0	.0	.0	1.0	.5	4.9
1948	−2.1	.6	3.0	5.8	.0	.0	.0	.0	.0	.0	2.0	1.5	10.8
1949	−1.2	−1.6	1.0	1.3	.9	.0	.0	.0	.0	.4	.0	.9	1.7
1950	1.3	−.3	1.5	2.5	1.6	.0	.0	.0	.0	.0	5.2	−.1	11.7
1951	2.5	−.6	−2.8	2.9	.5	.0	.0	.0	.0	.0	2.5	−.5	4.5

analysis, it was assumed that the withdrawals from the Ogden municipal-supply wells constituted the entire discharge from the artesian aquifer, that the artesian aquifer operates as a single storage unit, and that the data used were reasonably representative of the valley as a whole.

According to the budget, the annual discharge from the artesian aquifer averaged 13,350 acre-feet and was slightly more than balanced by an average 8,760 acre-feet of recharge from precipitation and local runoff and 4,780 acre-feet of recharge from the principal streams. Also, the amount of water stored in the aquifer at the end of the 17-year period was 3,100 acre-feet greater than at the beginning of the period.

TABLE 20.—*Water budget for the artesian aquifer in Ogden Valley, 1935–51*
[Data are given in acre-feet]

Year	Discharge	Recharge			Net changes in storage	
		Infiltration of precipitation and local runoff	Seepage from principal streams	Total	Annual	Cumulative
1935	11,700	7,900	3,500	11,400	−300	−300
1936	12,800	8,300	6,300	14,600	+1,800	+1,500
1937	12,700	8,000	5,600	13,600	+900	+2,400
1938	10,400	5,500	4,600	10,100	−300	+2,100
1939	10,800	5,800	4,100	9,900	−900	+1,200
1940	11,500	6,200	6,000	12,200	+700	+1,900
1941	9,900	7,000	2,700	9,700	−200	+1,700
1942	11,900	7,300	4,500	11,800	−100	+1,600
1943	13,000	9,200	3,500	12,700	−300	+1,300
1944	13,700	7,300	6,300	13,600	−100	+1,200
1945	14,000	12,900	3,500	16,400	+2,400	+3,600
1946	15,200	9,300	5,600	14,900	−300	+3,300
1947	15,100	12,400	1,900	14,300	−800	+2,500
1948	15,300	8,800	5,400	14,200	−1,100	+1,400
1949	15,800	12,200	5,200	17,400	+1,600	+3,000
1950	16,500	10,000	6,400	16,400	−100	+2,900
1951	16,700	10,800	6,100	16,900	+200	+3,100

The analysis does not support the conclusion of earlier investigators that the artesian aquifer in Ogden Valley is recharged principally by seepage from streams. Instead, it indicates that recharge by seepage from streams constitutes about 35 percent of the total and that infiltration of precipitation and local runoff constitutes the remainder. It follows, therefore, that only about a third of the total withdrawals from the Ogden municipal-supply wells should be regarded as a direct depletion of the flow of the Ogden River.

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