Water-Supply and Irrigation Paper No. 140

Series O, Underground Waters, 43

DEPARTMENT OF THE INTERIOR

UNITED STATES GEOLOGICAL SURVEY

CHARLES D. WALCOTT, DIRECTOR

FIELD MEASUREMENTS

OF

THE RATE OF MOVEMENT OF UNDERGROUND WATERS

BY

CHARLES S. SLICHTER

WASHINGTON

GOVERNMENT PRINTING OFFICE

1905

CONTENTS.

ILLUSTRATIONS.

LETTER OF TRANSMITTAL.

Department of the Interior,
United States Geological Survey,
Hydrographic Branch,
Washington, D. C., August 10, 1904.

Sir: I transmit herewith, for publication, a manuscript entitled "Field Measurements of the Rate of Movement of Underground Waters," prepared by Prof. Charles S. Slichter, professor of mathematics, University of Wisconsin.

The paper presents an amplified exposition of the method of measuring the movement of underground waters which was devised by Professor Slichter in 1901 while working for the hydrographic branch of the United States Geological Survey and which has been already briefly described in Water-Supply Paper No. 67, 1902. Descriptions of the apparatus invented by him for the laboratory study of wells controlling horizontal and vertical movements of underground waters and the results of these studies are also presented. The laboratory studies are also supplemented by detailed accounts of several investigations made in the field.

This paper should be interesting and valuable to engineers and geologists, and the direct application of the results to the study of problems of vital interest to the users of artesian waters should be of great practical value to the general public. A very suggestive and interesting description of the California method of sinking "stovepipe" wells deserves the attention of drillers in unconsolidated deposits throughout our country, while the description of the carefully made tests on typical pumping plants in Texas and New Mexico should appeal to engineers and others who are interested in the problem of raising water for irrigation or other purposes.

Very respectfully,

F. H. Newell,
Chief Engineer.

Hon. Charles D. Walcott,
Director United States Geological Survey.

FIELD MEASUREMENTS OF THE RATE OF MOVEMENT OF UNDERGROUND WATERS.

By CHARLES S. SLICHTER.

INTRODUCTION.

The following paper describes the method and apparatus used in measuring the velocity of underground waters and gives the results of field work done with the apparatus in various parts of the United States, under authority of the hydrographic branch of the United States Geological Survey. The method used in making the measurements was devised by the writer after preliminary tests along the Arkansas River in western Kansas during the summer of 1901. This preliminary work indicated that it was practicable to measure the rate of flow of ground waters by the use of very simple apparatus. Several determinations of the rate of movement of the underflow of the Arkansas were made during that summer. These measurements, it is believed, constituted the first direct determinations of the rate of flow of ground water that had been made in this country. This preliminary work was done in the neighborhood of Dodge, Kans., and at one or two points near Garden, Kans. The photographs reproduced in Pl. I show the locations of the first successful stations, which were established near Garden, Kans. A brief description of the electrical method of measuring the velocities of underground waters resulting from this preliminary investigation was printed in the Engineering News of February 20, 1902, and in paper No. 67 of the Water-Supply and Irrigation series of the United States Geological Survey. Since then, as the result of work carried on in the field and in the laboratory, the apparatus has been gradually improved, and its present form is described in these pages.

The paper will also include some determinations of the manner and rate of flow of water into tubular wells, and descriptions of methods and simple apparatus designed to accurately estimate the capacity of such wells.

CHAPTER I.

THE CAPACITY OF A SAND TO TRANSMIT WATER.

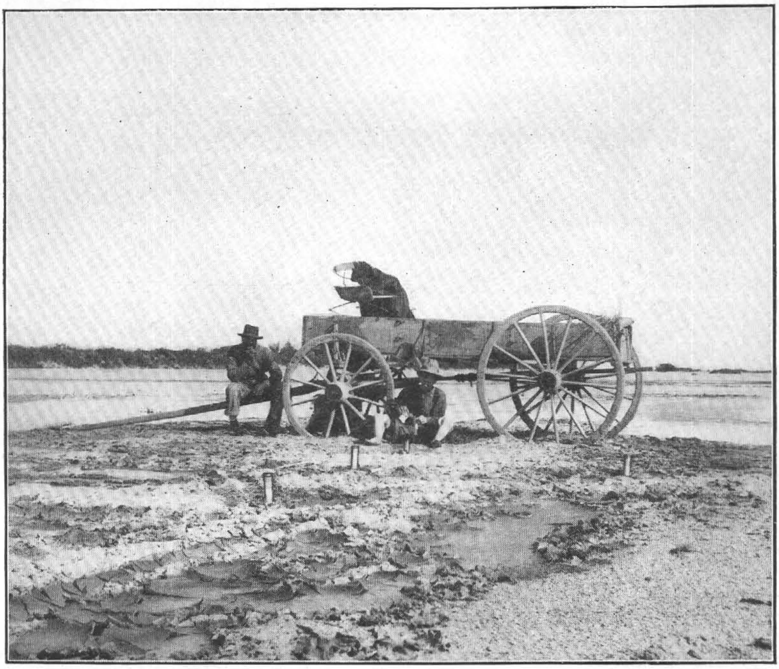
FACTORS INFLUENCING FLOW.

The general laws governing the flow of water through a mass of sand or gravel have been described by the writer in another paper,[a] and will not be repeated in this place. It is sufficient to state that experiments show that the flow of water in a given direction through a column of sand is proportional to the difference in pressure at the ends of the column, and inversely proportional to the length of the column, and is also dependent upon another factor, called the transmission constant of the sand.

TRANSMISSION CONSTANT.

The resistance offered by sand or gravel to the flow of water which is percolating through it is very great. The water is obliged to pass through very small pores, usually capillary in character; indeed, they are much smaller in cross section than the soil particles between which they pass. If the particles of sand or gravel which make up the water-bearing medium are well rounded in form the pores are somewhat triangular in cross section and the diameter of the individual pores is only one-fourth to one-seventh the diameter of the soil particles themselves. Thus if the individual grains of sand average 1 millimeter in diameter the pores through which the water must pass will average only one-fourth to one-seventh of a millimeter in diameter. If to a mass of nearly uniform sand particles larger particles be added the effect on the resistance to the flow of water will be one of two kinds, depending principally upon the ratio which the size of the particles added bears to the average size of grains in the original sand. If the particles added are only slightly larger than the original sand grains, the effect is to increase the capacity of the sand to transmit water, and the more particles of this kind that are added the greater will be the increase in the capacity of the sand to transmit water. If, however, large particles are added, the effect is the reverse. If particles seven to ten times the diameter of the original sand grains be added, each of the new particles tends to block the course of the

[a] The motions of underground waters: Water-Sup. and Irr. Paper No. 67, U. S. Geol. Survey, 1902.



A

B

LOCATION OF FIRST UNDERFLOW STATIONS, AUGUST, 1901, NEAR GARDEN, KANS.

A, Station 1, near Point of Rock; *B*, Station 2, south of island.

water. Thus, for example, a large bowlder placed in a mass of fine sand will tend to block the passage of the water. As more and more of the large particles are added to a mass of uniform sand, the rate of flow of water through it will be decreased until the amount of the large particles equals about 30 per cent of the total mass. From this time on the adding of the large particles will increase the capacity of the whole to transmit water until, if a very large quantity of the large particles be added, so that the original mass of fine particles becomes relatively negligible, the capacity to transmit will approach that of the mass of the large particles alone. These facts have an important bearing upon the capacity of gravels to furnish water to wells or to transmit water in the underflow of a river. The presence of large particles is not necessarily to be interpreted as indicating a high transmission capacity of the material, for this is indicated only when the large particles constitute a large fractional per cent of the total mass, as would be the case where the large particles equal 40 or 50 per cent of the whole.

The capacity of any sand or gravel to transmit water can be expressed by means of a single number which is called the transmission constant of the soil. This constant is defined to be the amount of water transmitted in unit time through a cylinder of the soil of unit length and unit cross section under unit difference in head at the ends. For example, if the foot and minute be the units of length and time, and if a column of sand 1 square foot in cross section and 1 foot in length will transmit 1 cubic foot of water a minute under a difference in head of 1 foot of water, the transmission constant is 1. The transmission constant of a soil varies very greatly with the size of the individual grains constituting the sand or gravel, and also depends in a marked degree upon the porosity or amount of open space in the soil. Table I, herewith, gives the transmission constants for a variety of sizes of soil grain and for a series of porosities varying from 30 to 40 per cent. This table is computed for a temperature of the water of 60° F. An auxiliary table, Table II, is one from which the transmission constants corresponding to other temperatures can readily be found.

Transmission constant k is the quantity of water, measured in cubic feet, that is transmitted in one minute through a cylinder of the soil 1 foot in length and 1 square foot in cross section, under difference in head at the ends of 1 foot of water.

The tabulated numbers express the transmission constant in cubic feet per minute.

TABLE I.—*Transmission constants from which the velocity of water in sands of various effective sizes of grain can be obtained.*

Table computed for temperature of 60° F.; results for other temperatures can be found by the use of Table II.]

Diameter of soil grain in mm.	Porosity.						Kind of soil.
	30 per cent.	32 per cent.	34 per cent.	36 per cent.	38 per cent.	40 per cent.	
0.01	0.000033	0.000040	0.000050	0.000060	0.000072	0.000085	Silt.
.02	.000131	.000162	.000198	.000239	.000286	.000339	
.03	.000296	.000364	.0004460	.000533	.000645	.000763	
.04	.000527	.000648	.0007940	.000958	.001145	.001355	
.05	.000822	.001012	.001240	.001495	.001790	.002120	Very fine sand.
.06	.001182	.001458	.001784	.002150	.002580	.003050	
.07	.001610	.001983	.002430	.002930	.003510	.004155	
.08	.002105	.002590	.003175	.003825	.004585	.005425	
.09	.002660	.003280	.004018	.004845	.005800	.006860	
.10	.003282	.004050	.004960	.005980	.007170	.008480	Fine sand.
.12	.004725	.005830	.007130	.008620	.01032	.01220	
.14	.006430	.007940	.009720	.01172	.01404	.01662	
.15	.007390	.009120	.01115	.01345	.01611	.01910	
.16	.008410	.01036	.01268	.01531	.01835	.02170	
.18	.01064	.01311	.01605	.01940	.02320	.02745	
.20	.01315	.01620	.01983	.02390	.02865	.03390	
.25	.02050	.02530	.03100	.03740	.04480	.05300	Medium sand.
.30	.02960	.03640	.04460	.05380	.06450	.07630	
.35	.04025	.04960	.06075	.07330	.08790	.01039	
.40	.05270	.06480	.07940	.09575	.1145	.1355	
.45	.06650	.08200	.1005	.1211	.1450	.1718	
50	.08220	.1012	.1240	.1495	.1780	.2120	Coarse sand.
.55	.09940	.1225	.1500	.1810	.2165	.2565	
.60	.1182	.1458	.1784	.2150	.2580	.3050	
.65	.1390	.1710	.2095	.2530	.3030	.3580	
.70	.1610	.1983	.2430	.2930	.3510	.4155	
.75	.1850	.2278	.2785	.3365	.4030	.4770	
.80	.2105	.2590	.3175	.3825	.4585	.5425	
.85	.2375	.2925	.3580	.4325	.5175	.6125	
.90	.2660	.3280	.4018	.4845	.5800	.6860	
.95	.2965	.3650	.4470	.5400	.6460	.7650	
1.00	.3282	.4050	.4960	.5980	.7170	.8480	Fine gravel.
2.00	1.315	1.620	1.983	2.390	2.865	3.390	
3.00	2.960	3.640	4.460	5.380	6.450	7.630	
4.00	5.270	6.480	7.940	9.575	11.45	13.55	
5.00	8.220	10.12	12.40	14.95	17.90	21.20	

TABLE II.—*Variation, with the temperature, of the flow of water of various temperatures through a sand, 60° F. being taken as the standard temperature.*

Temperature.	Relative flow.[a]	Temperature.	Relative flow.[a]
° F.	*Per cent.*	*° F.*	*Per cent.*
32	0.64	70	1.15
35	.67	75	1.23
40	.73	80	1.30
45	.80	85	1.39
50	.86	90	1.47
55	.93	95	1.55
60	1.00	100	1.64
65	1.08		

[a] "Relative flow" means flow at given temperature compared with flow at 60° F. It is expressed as a percentage.

It should be borne well in mind that the rate of transmission varies very greatly with the temperature of the water. For example, a change from 50° to 60° increases the capacity to transmit water under identical conditions by about 16 per cent, while a change from the freezing temperature to a temperature of 75° will nearly double the power of a soil to transmit water. This difference, of course, is not due to any change in the soil itself, but is due solely to the increased ease with which water flows at high temperatures compared to the ease with which it flows at low temperatures. The transmission constant of a sand can also be obtained by use of the diagram given in Pl. II. Graduated vertical lines will be found in this diagram corresponding to the diameter of the soil grains (d), the amount of water transmitted (q), the hydraulic gradient (s), and the porosity of the soil (m). The graduated line marked U is an auxiliary scale. The number d is expressed in millimeters, and q is expressed in cubic feet per minute. The hydraulic gradient s is expressed as a percentage. A slope of the ground water equal to 2 feet in 100 feet appears in the diagram as hydraulic gradient 0.02 and a slope of 528 feet per mile appears as 0.10. The porosity, m, also appears in the diagram as a percentage. The porosity or amount of voids in a sand will usually lie between 25 and 46 per cent of the total volume.

The diagram is used as follows: Suppose that the amount of water transmitted by a sand per square foot of cross section is desired, if the effective size of soil grain is 0.55 millimeter, the hydraulic gradient 2 feet in 100 feet, and the porosity is 36 per cent. Apply a ruler or straight edge (the edge of a piece of letter paper will do) to the diagram, passing through the mark 0.55 on d and the mark 0.02 on s. The edge of the ruler will locate a point 0.47 on U, the exact location of which should be noted. Then move the ruler so that it will pass through this same point on *U* and through the mark 36 on *m*. The place where the ruler crosses the line *q* (0.0036), will give the discharge in cubic feet per minute. The diagram gives results based upon the assumed temperature of the water of 60° F.[a]

If any three of the four magnitudes *d*, *q*, *s*, *m* are known, the remaining one can be found in a manner similar to the above.

The removal of larger particles from a mixed sand may not only increase the transmission constant in the manner described above, but such removal may also increase the transmission capacity by permitting the remaining sand to pack in a more open manner, as would be shown by an increased porosity. Tables II and III give results which show that the removal of the larger grains from a sand does not necessarily decrease the transmission constant, but may even increase it. The results given in Table III were obtained by successively removing the larger particles from a mass of sand by means of standard sieves, and then determining the porosity, effective size,[b] and transmission constant for the finer material passing through the successive sieves. The gravel represented by Table III consisted of a mixture of all sizes of grains, from very fine grains to bowlders 2 feet in diameter. All pieces larger than 1 inch in diameter were discarded before the results shown in Table III were obtained. It is interesting to note that the 93.4 per cent of the total sand passing through sieve 2 (2 meshes to the inch) did not have as large an effective size as the 74.2 per cent which passed through sieve 20 (20 meshes to the inch).

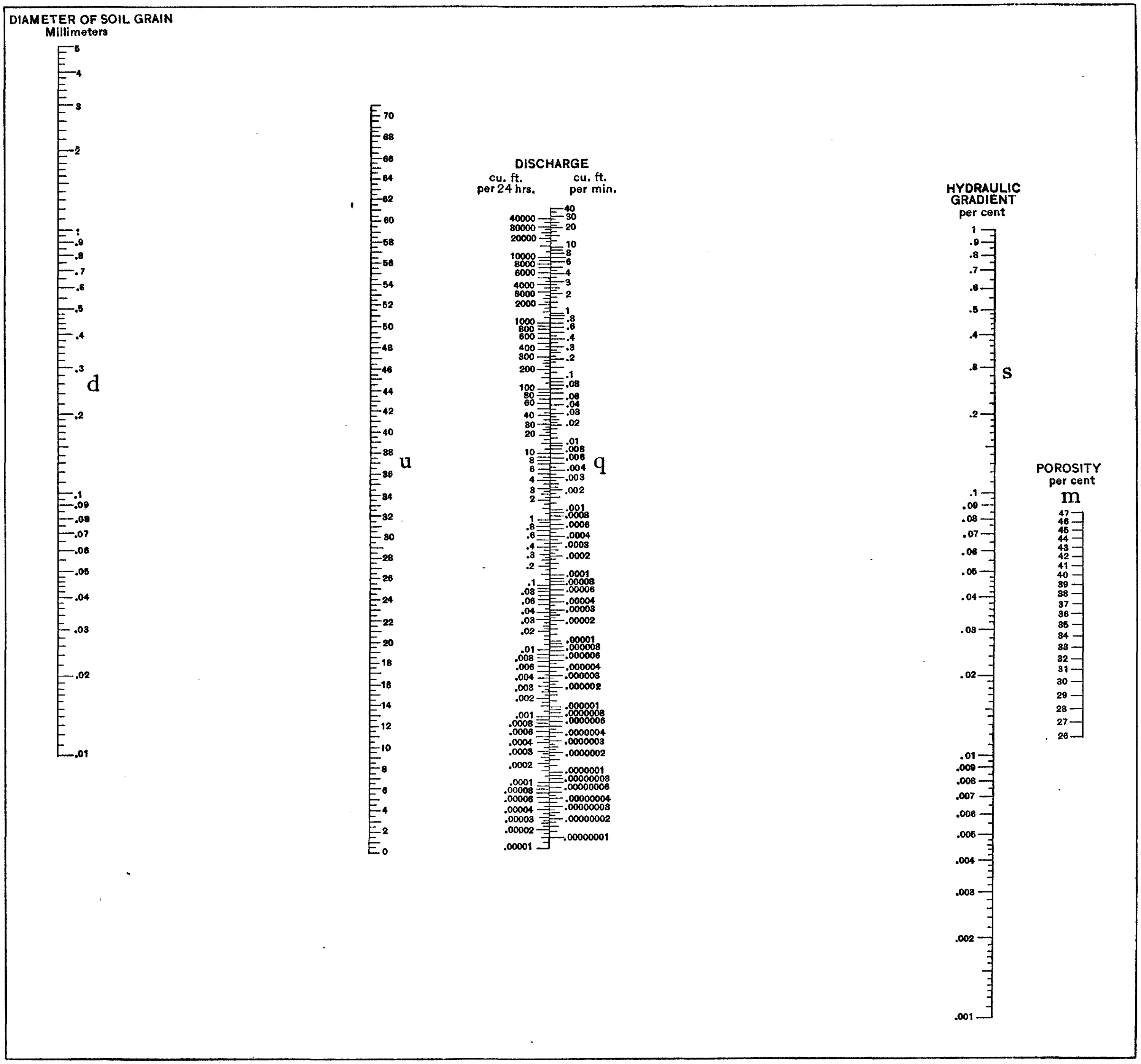
Table III is derived from a beach sand. The 54.3 per cent of this sand which passed through sieve 10 has a smaller transmission constant than the 36.8 per cent which passed through sieve 14.

The following table shows the effect of removing, by means of standard sieves, the coarser portions of a natural Arizona gravel. The data in columns 2, 3, 4, 5, and 6 apply to that portion of original sample that passed the sieve named in column 1.

---

[a] The diagram was computed and drawn for the writer by J. D. Suter, of the University of Wisconsin.

[b] The *effective size* of a sample of sand is such a number that if all grains were of that diameter the sand would have the same transmission capacity that it actually has. It is therefore, the true mean or average size of sand grain in that sample.



SCALE OR NOMOGRAPH FOR ESTIMATING GRAPHICALLY THE TRANSMISSION CONSTANT OF A SAND OR GRAVEL.

TABLE III.—*Effect of removing coarser portions of field gravel.*

1. No. of sieve.	2. Quantity of gravel passing.	3. Differences of numbers in column 2.	4. Porosity of portion passing.	5. Effective size.	6. Transmission constant at 80° F.
Meshes to inch.	*Per cent of total weight.*	*Per cent of total weight.*	*Per cent.*	*Mm.*	*Cubic feet per minute.*
2	93.4	6.6	38.1	0.325	0.102
8	No data.	....	40.0	.320	.120
10	83.7	9.7	38.6	.282	.080
12	82.6	1.1	40.3	.304	.108
14	80.3	2.3	39.5	.282	.086
16	78.0	2.3	39.7	.282	.088
18	76.4	1.6	39.6	.277	.085
20	74.2	2.2	40.6	.317	.119
30	55.9	8.3	41.0	.250	.076
40	32.2	23.7	40.6	.187	.042

The following table shows the effect of removing by means of standard sieves the coarser portions of a natural beach gravel. The data in columns 2, 3, 4, 5, and 6 apply to that portion of original sample that passed sieve named in column 1.

TABLE IV.—*Effect of removing coarser portions of a beach gravel.*

1. No. of sieve.	2. Quantity of gravel passing.	3. Differences of numbers in column 2.	4. Porosity of portion passing.	5. Effective size.	6. Transmission constant at 72° F.
Meshes to inch.	*Per cent of total weight.*	*Per cent of total weight.*	*Per cent.*	*Mm.*	*Cubic feet per minute.*
Total sample.	100.0	....	37.8	0.810	0.529
10.......	54.3	45.7	40.0	.634	.390
12.......	47.6	6.7	41.7	.640	.457
14.......	36.8	10.8	41.7	.603	.406
16.......	31.4	5.4	42.6	.539	.348
18.......	No data.	....	43.5	.520	.348
20.......	25.6	5.8	43.5	.494	.314

CHAPTER II.

UNDERFLOW METER USED IN MEASURING VELOCITY AND DIRECTION OF MOVEMENT OF UNDERGROUND WATERS.

TYPES OF APPARATUS.

The apparatus used is of two types: (1) Direct reading, or hand apparatus, requiring the personal presence of the operator every hour for reading of instruments, and (2) recording apparatus, which requires attention but once in a day. Both forms are described in this chapter. The arrangement of the test wells and manner of wiring the wells is essentially the same for both.

TEST WELLS.

The test wells suitable for use with the underflow meter in determining the velocity of ground waters may be common 1½-inch or 2-inch drive wells if the soil is easily penetrated and if the depths to be reached do not exceed 50 to 75 feet. For greater depths and harder soil wells of heavy construction should be used. The 1½-inch drive wells are much preferable to the 1¼-inch wells because of the fact that 1½-inch pipe is lap welded, while the 1¼-inch is butt welded, and less capable of standing severe pounding. The drive point used with the well may be 1½-inch standard brass jacket well points, 42 to 48 inches long, with No. 60 brass gauze strainer. The well points should be threaded with 1½ inches of standard thread, somewhat more than is usually found on the trade goods. The pipe should be full weight strictly wrought-iron standard pipe, cut in lengths of 6 or 7 feet, and threaded 1½ inches at each end. The couplings should be wrought-iron hydraulic recessed couplings, and the thread on the pipe should be cut in such a way that when properly screwed up the ends of the pipe will abut. The recessed couplings protect the pipe at its weakest point, while an ordinary coupling will leave exposed a thread or two of the pipe so that severe driving is liable to swell and ultimately rupture the pipe just above the coupling. Fig. 1 represents a hydraulic coupling, showing a properly made joint.

The driving head should be made of rolled steel shafting and should be about 4 inches long, carrying 1½-inches standard thread and an air hole to permit the free escape of air from the well while the driving is in progress. A driving ram for putting down the drive wells should be about 5½ feet long by 5½ inches in diameter, made of heavy oak or other tough wood, with iron bands shrunk on the ends, and bearing two handles of hard wood at each end in order to facilitate the handling of the ram by two men. It is convenient to have these handles placed one about 1 foot from one end, and the other about 2 feet from the other end. By reversing the ram the handles are brought in a more convenient position for driving as the well goes down.

Pl. III, *A* illustrates the method of putting down drive points. If the test wells are to be sunk to a depth exceeding that to which drive points can be readily driven, open-end 2-inch pipe should be used. These wells should be made with full weight strictly wrought-iron 2-inch pipe with long threads and recessed hydraulic couplings, as described above. The pipe can either be put down without a screen, in which case a 1¼-inch well point with turned coupling may be inserted through a drive shoe at the bottom of the casing after the pipe is

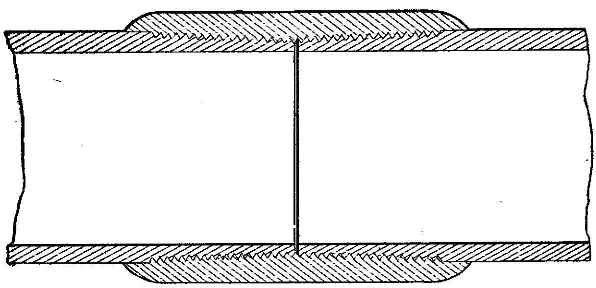


FIG. 1.—Pipe joint made with hydraulic coupling. This joint will stand hard driving.

driven into place, or an open-end brass jacket well point, 48 inches long, may be put down with the pipe. The pipe should be driven into place with a cast-iron ram varying in weight from 150 to 250 pounds, simultaneously hydraulicking a passage for pipe with water jet in three-fourths-inch wash pipe. There are many hand rigs on the market suitable for this work, or a rig can be readily constructed by any good mechanic. Such a rig is shown in Pl. VI, *A*. A suitable pump for the hydraulic jet is a double-acting horizontal force pump with a 4- by 4½-inch cylinder. If the material in which the well is to be drilled is not too hard nor too full of bowlders, the writer recommends that an open-end well point be put down with the casing. This is apt to cause some difficulty in the proper working of the hydraulic jet, by the escape of water through the screen of the well point. This difficulty can be obviated and a more powerful wash secured by admitting a considerable quantity of air along with the water at the suction end of the force pump. The exact amount of air to be admitted can be readily determined with a little experience. The effect of the air entering the well under high pressure is to form a powerful air lift which will throw the water and gravel out of the top of the well casing with great force. It has been the writer's experience that the best hydraulic samples are obtained with the combination hydraulic pneumatic jet. If the hydraulic jet alone is used the coarser particles have a tendency to remain at the bottom of the well.

After a test is completed the well casing can readily be pulled by a No. 2 cast-iron pipe puller and two 5-ton railroad jacks. Sets of dies for the pipe puller to fit both 1½- and 2-inch pipe can be obtained at small cost. Pl. III, *B*, shows the operation of the pipe puller and railroad jacks.

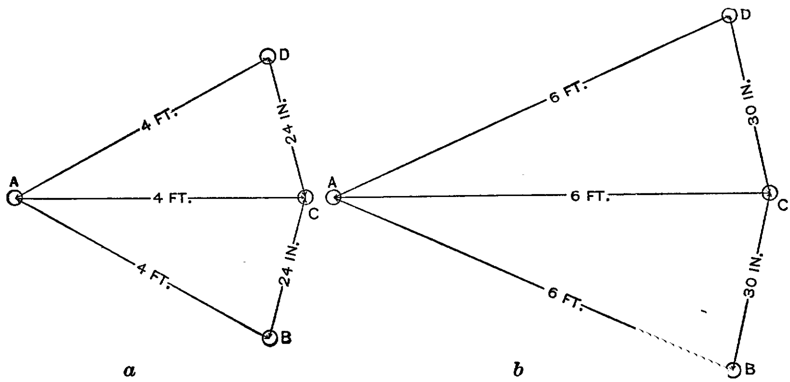
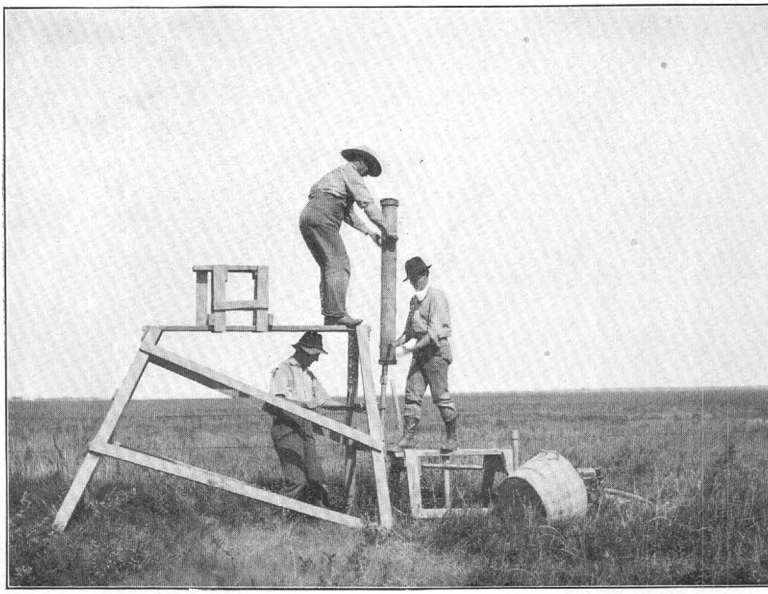
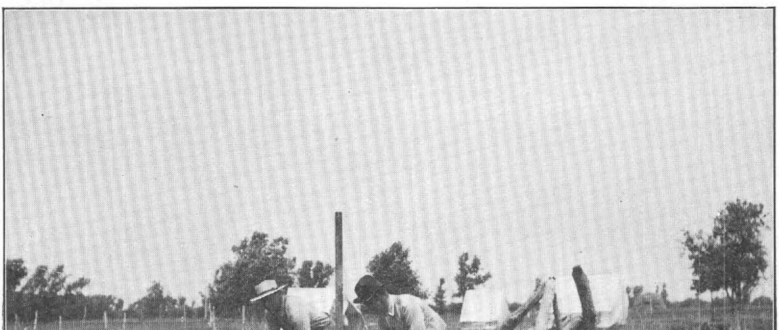


FIG. 2.—Plan of arrangement of test wells used in determining the velocity and direction of motion of ground water; A, B, C, D are the test wells. The direction A–C is the direction of probable motion of the ground water. The dimensions given in plan *a* are suitable for depths up to about 25 or 30 feet, those in plan *b* for depths up to about 75 feet. For greater depths the distances A–B, A–C, A–D should be increased to 9 or 10 feet, and the distances B–C and C–D to 4 feet. The well A is the "salt well" or well into which the electrolyte is placed.

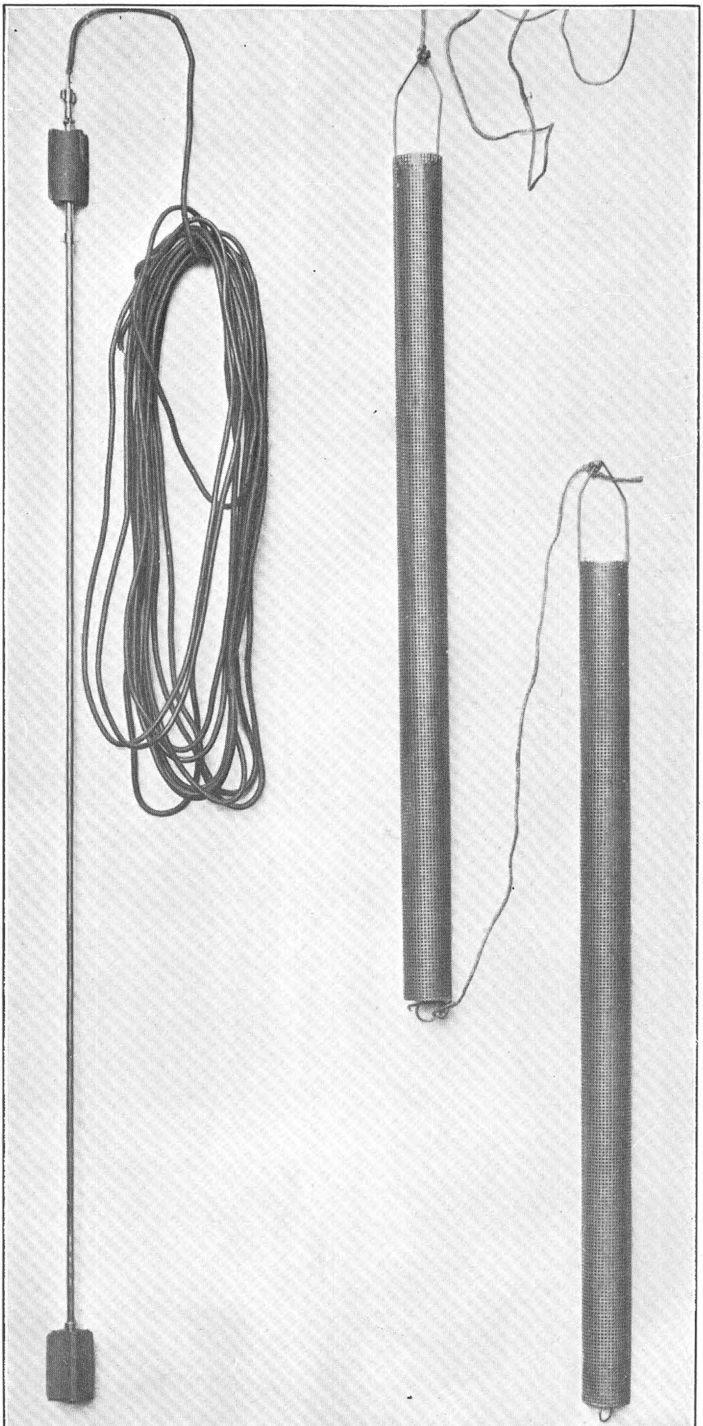
The test wells are driven in groups, as shown in fig. 2, each group of wells constituting a single station for the measurement of the direction and rate of flow of the ground water. In case the wells are not driven deeper than 25 feet, the "upstream" or "salt well" A is located, and three other wells, B, C, and D, are driven at a distance of 4 feet from A, the distance between B and C and C and D being about 2 feet. The well C is located so that the line from A to C will coincide with the probable direction of the expected ground-water movement. This direction should coincide, of course, with the local slope of the water plane, and if this is not accurately known, it should be determined by means of leveling with a level. For deeper work the wells should be located farther apart, as shown in the right portion of fig. 2. For depths exceeding 75 feet, a radius of 8 or 9 feet and chords of 4 feet should be used, the general requirement being that the wells should be as close together as possible, so as to cut down to



A. RAM USED FOR DRIVING SMALL WELLS BY HAND.



B. PULLING WELL CASING WITH RAILROAD JACK AND NO. 2 PIPE PULLER.



ELECTRODE AND PERFORATED BRASS BUCKETS USED IN CHARGING WELLS.

a minimum the time required for a single measurement, but not so close that important errors are liable to be introduced by the inability to drive the wells perfectly straight and plumb. On this account the deeper the wells the farther apart they should be placed. The angles B A C and C A D should not exceed 30°.

DIRECT-READING INSTRUMENTS.

Electrical connection is made with the casing of each test well by means of a drilled coupling carrying a binding post. Each of the downstream wells (B, C, D) contains within the well point or screen section an electrode consisting of a nickeled brass rod three-eighths inch in diameter by 4 feet long, insulated from the casing by wooden spools. The end of rod receives a No. 14 rubber-covered wire, to which good contact is made by a chuck clutch. An electrode is shown in Pl. IV. This electrode communicates with the surface by means of a rubber-covered copper wire. Pl. IV also shows two buckets of perforated brass used in charging wells with granulated sal ammoniac; each is 1¾ by 30 inches.

Fig. 3 illustrates the arrangement of electric circuits between the upstream well and one of the downstream wells. Each of the downstream wells is connected to the upstream well in the manner shown in this figure.

A view of the direct-reading underflow meter is shown in Pl. V, *A*. Six standard dry cells are contained in the bottom of the box, their poles being connected to the six switches shown at the rear of the case. By means of these switches any number of the six cells may be thrown into the circuit in series. One side of the circuit terminates in eight press keys, shown at the left end of the box. The other side of the circuit passes through an ammeter, shown in the center of the box, to two three-way switches at right end of the box. Four of the binding posts at the left end of the box are connected, respectively, to the casing of well A, and to the three electrodes of wells B, C, and D, in the order named. The binding posts at the right end of the box are connected to the casings of wells B, C, and D. There are enough binding posts to connect two different groups of wells to the same instrument. When the three-way switch occupies the position shown in the photograph, pressing the first key at left end of the box will cause the ammeter to show the amount of current passing between casing of well A and casing of well B. When the next key is pressed the ammeter will indicate the current between the casing of well B and the electrode contained within it. In one instance the current is conducted between the two well casings by means of the ground water in the soil; in the second case the electric circuit is completed by means of the water within well B. By putting the three-way switch in second position and pressing the first and third keys in turn, similar readings can be had for current between casings A and C and between casing C and its internal electrode. Similarly with switch in third position, readings are taken by pressing first and fourth keys. The results may be entered in a notebook, as shown in Table V.

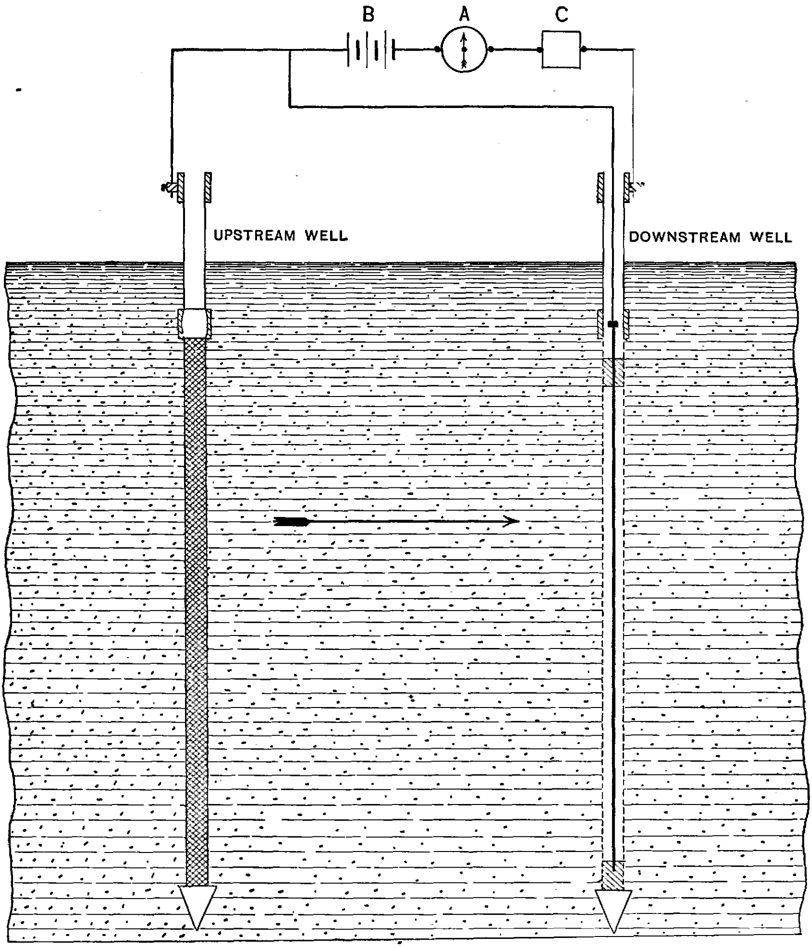
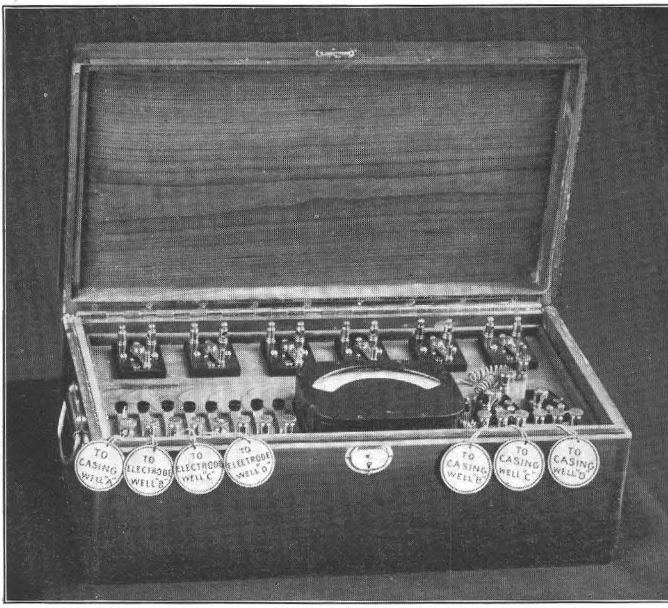


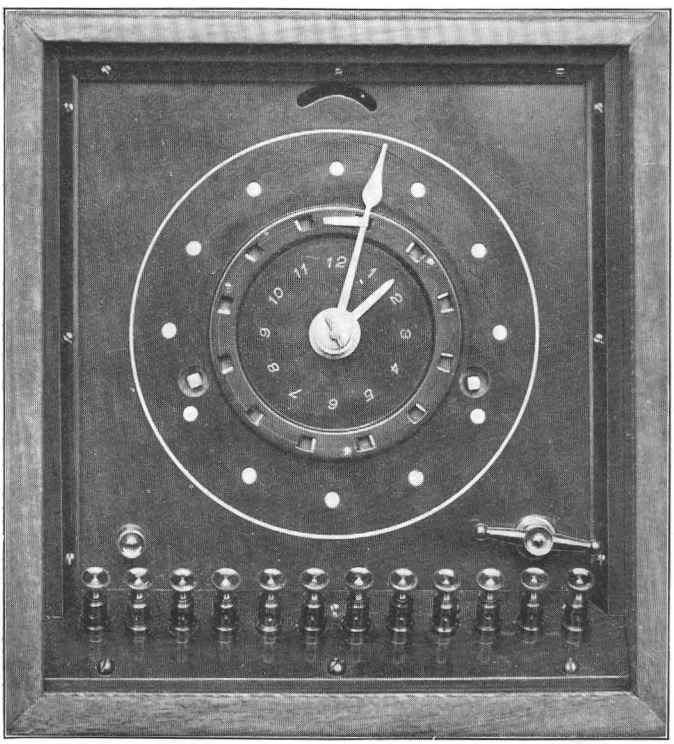
FIG. 3.—Diagram illustrating electrical method of determining the velocity of flow of ground water. The ground water is supposed to be moving in the direction of the arrow. The upstream well is charged with an electrolyte. The gradual motion of the ground water toward the lower well and its final arrival at that well are registered by the ammeter A B is the battery and C a commutator clock which is used when A is a recording ammeter.

The principles involved in the working of the apparatus are very simple. The upstream well A is charged with a strong electrolyte, such as sal ammoniac, which passes down stream with the moving ground water, rendering the ground water a good electrolytic conductor of electricity. If the ground water moves in the direction of one of the lower wells, B, C, D, etc., the electric current between



A UNDERFLOW METER, SHOWING CONNECTIONS WHEN USED AS DIRECT-READING APPARATUS.

When used with recording ammeter, only two connections are made, one to each side of battery circuit; but the ammeter is left in circuit with the recording instrument to indicate whether the latter is working properly.



B. COMMUTATOR CLOCK, FOR USE WITH RECORDING AMMETER.

The clock makes electrical contact at any five-minute interval.

A and B, A and C, or A and D will gradually rise, mounting rapidly when the electrolyte begins to touch one of the lower wells. When the electrolyte finally reaches and enters inside of one of the wells B, C, D, it forms a short circuit between the casing of the well and the internal electrode, causing an abrupt rise in the electric current. The result can be easily understood by consulting Table V and fig. 4, in which the current is depicted graphically.

TABLE V.—*Field record of electric current during underflow measurements at station 5, Rio Hondo and San Gabriel River, California, August 5 and 6, 1902.*

[Readings in ampères and decimals of an ampère.]

Time.	Well B.		Well C.		Well D.		Remarks.[a]	
	Casing.	Electrode.	Casing.	Electrode.	Casing.	Electrode.		
8 a. m	0.140	0.360	0.142	0.332	0.150	0.390		
8.15 a. m	Salt.		Salt.		Salt.		1 NaCl	2 NH_4Cl
8.30 a. m	.160		.163		.170			1 NH_4Cl
9 a. m	.168		.170		.180		1 NaCl	
10 a. m	.180	.360	.182	.330	.192	.390		1 NH_4Cl
11.40 a. m	.192	.345	.195	.325	.202	.380		
1 p. m	.202	.340	.202	.320	.210	.370		1 NH_4Cl
2 p. m	.205	.345	.204	.340	.210	.370		
3 p. m	.208	.342	.205	.320	.210	.360	1 NaCl	
4 p. m	.210	.350	.205	.320	.210	.370		
5 p. m	.218	.330	.210	.310	.212	.360		1 NH_4Cl
6 p. m	.225	.330	.210	.310	.218	.360		
7 p. m	.230	.330	.218	.310	.220	.360		
8 p. m	.240	.330	.222	.310	.223	.350	1 NaCl	
9 p. m	.250	.330	.222	.320	.225	.352		
10.30 p. m	.275	.340	.225	.315	.225	.360		
12 p. m	.350	.600	.230	.310	.230	.340		1 NH_4Cl
1 a. m [b]	.420	.850	.240	.310	.230	.340		
2.30 a. m	.510	1.550	.240	.310	.230	.340		
4.15 a. m	.560	2.000	.240	.310	.230	.340		
5.30 a. m	.550	2.200	.230	.310	.230	.330		
7.45 a. m	.520	2.250	.230	.310	.225	.330		
8.15 a. m		2.250						
9 a. m		2.200						

[a] The electrolyte was lowered into well A by means of a perforated brass bucket, 1¾ by 30 inches in size. The formula "2 NH_4Cl" means that two of these buckets, full of ammonium chloride, were introduced into well A at the time indicated. Each of these buckets held 2 pounds of the salt.
[b] August 6.

The time that elapses from the charging of the well A to the arrival of the electrolyte at the lower well gives the time necessary for the ground water to cover the distance between these two wells. Hence, if the distance between the wells be divided by this lapse of time, the result will be the velocity of the ground water. The electrolyte does not appear at one of the downstream wells with very great abruptness; its appearance there is somewhat gradual, as shown in the curves in

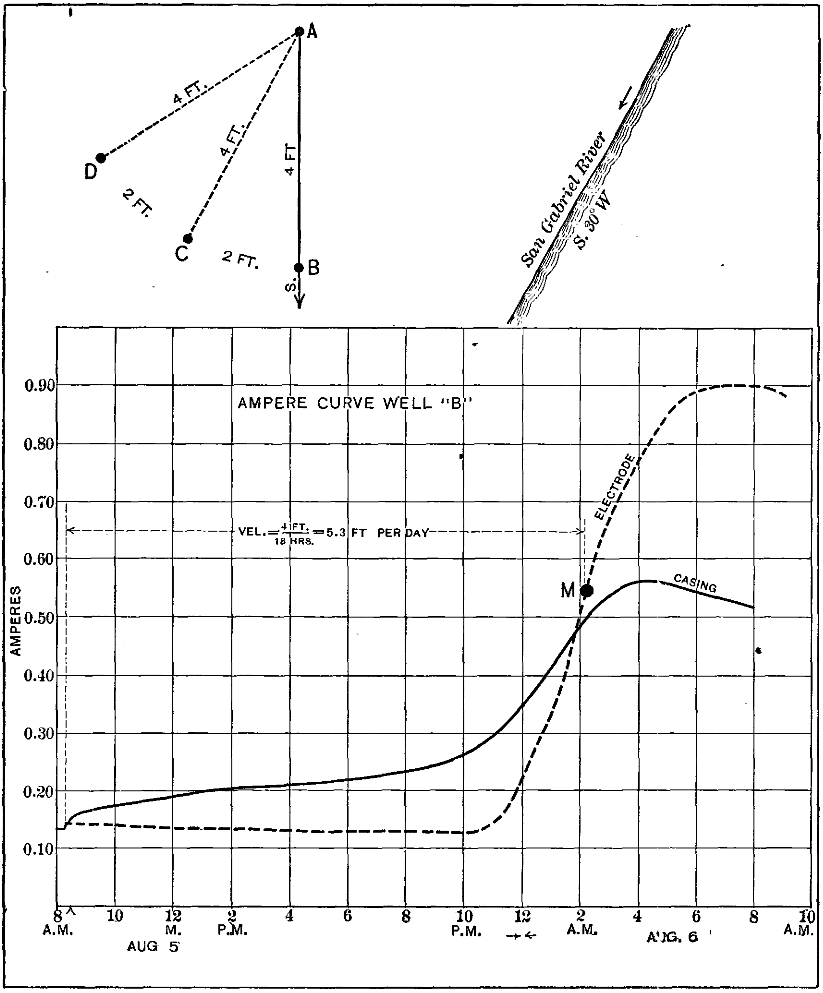


FIG. 4.—Diagram showing ampère curves at station 5 in the narrows of the San Gabriel River, California. The heavy curve represents the strength of electric current between the casing of well A and casing of well B. The dotted curve represents the strength of current between the electrode in well B and the casing of well B. These curves illustrate results obtained with the direct-reading form of apparatus.

figs. 4 and 5. The time required for the electrolyte to reach its maximum strength in one of the downstream wells (and hence, for the current to reach its maximum value) may vary from a few minutes in a case of high ground-water velocity to several hours in a case of low velocity. The writer formerly supposed that the gradual appearance of the electrolyte at the downstream well was largely due to the diffusion of the dissolved salt, but it is now evident that diffusion plays but a small part in the result. The principal cause of the phenomena is now known to be due to the fact that the central thread of water in each capillary pore of the soil moves faster than the water at the walls of the capillary pore, just as the water near the central line of a river channel usually flows faster than the water near the banks. For this reason, if the water of a river suddenly be made muddy at a certain upstream point the muddy character of the water at a downstream point will appear somewhat gradually, being first brought down by the rapidly moving water in the center of the channel, and later by the more slowly moving water near the banks. The effect of the analogous gradual rise in the electrolyte in the downstream well requires us to select the "point of inflection" of the curve of electric current as the proper point to determine the true time at which the arrival of the electrolyte should be counted. This point is designated by the letter M in figs. 4 and 5.

Owing to the repeated branching and subdivision of the capillary pores around the grains of the sand or gravel, the stream of electrolyte issuing from the well will gradually broaden as it passes downstream. The actual width of this charged water varies somewhat with the velocity of the ground water, but in no case is the rate of the divergence very great. The manner in which the electrolyte spreads has been carefully investigated and will be described in a later page.

It is possible to dispense with the circuit between the casing of well A and the casing of each of the other wells, as the short circuit between the well and electrode forms the best possible indication of the arrival of the electrolyte at the downstream well. For cases in which the velocity of ground water is high, the circuit to well A is practically of no value; but for slow motions this circuit shows a rising current before the arrival of the electrolyte at the lower well, often giving indications of much value to the observer.

The method can be used successfully even though nothing but common pipe be used for the wells. In this case, however, the absence of screen or perforations in the wells renders the internal electrodes useless, and one must depend upon the circuit from well casing of the upstream well to well casing of downstream well.

The results shown in fig. 5 present such a case. In this case the wells were not provided with well points, but merely possessed a 4-foot length of pipe, provided with four or five holes on opposite sides of the pipe containing small ½-inch washer screens. These few openings are not sufficient to permit the electrolyte to enter the well freely, so that readings between casings were relied upon for results. As a matter of fact, enough of the electrolyte did get into the well to give small increased readings, but in order to obtain the electrode readings shown in the diagram water was removed from the downstream wells by a small bucket holding about 6 ounces, so as to force a quantity of the water surrounding the well into the perforated sections. In cases where good well points are used the ground water charged with the electrolyte finds its way gradually and naturally into the well. The well point should be clear enough to allow as free passage into the well as through the soil itself. This is easily accomplished by pumping water from each test well with a common pitcher pump for a few minutes or until the water is fairly clear.

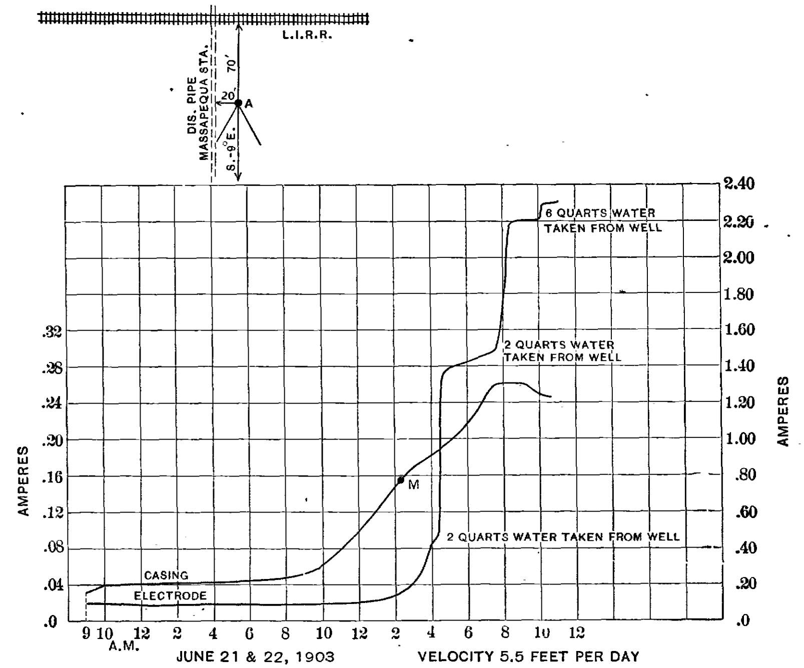


FIG. 5.—Ampere curves at station 1, Long Island, N. Y., showing possibility of use of direct-reading apparatus when well points are not used. The casing in this instance consisted of common black 2-inch pipe, with a few small holes in bottom section. The "casing" curve must be relied upon for determining velocity. The "electrode" curve was obtained by drawing water from well C, as shown on diagram, the charged water being drawn into the well through the small holes and the open end of well.

Granulated sal ammoniac is used to dose well A. A single charge may vary from 4 to 10 pounds. If common pipe without points or screen is used for the wells, so that internal electrodes must be dispensed with, doses of about 2 pounds each should be repeated about every hour. The dry salt should not be poured directly into the well, but should be lowered in perforated buckets, a photograph of one being shown in Pl. IV. These buckets are $1\frac{3}{4}$ by 30 inches and hold about 2 pounds of the salt. Two of these buckets may be tied one above the other for the initial charge, and followed by two more in ten or twenty minutes.

If the wells are not too deep, the sal ammoniac may be introduced into the well in the form of a solution. A common bucket full of saturated solution is sufficient. There is an uncertainty in introducing the sal ammoniac in solution in deep wells, as the time required for the solution to sink to the bottom of the well may be considerable.

The direct-reading ammeter used in the work has two scales, one reading from 0 to 1.5 amperes and the other from 0 to 5 amperes. With a given number of cells, the amount of current between the upstream and a downstream well will depend, of course, upon several factors, such as the depth and distance apart of the wells, but more especially upon the amount of dissolved mineral matter in the ground water. The initial strength of the current can be readily adjusted, however, after the wells have been connected with the instruments, by turning on or off some of the battery cells by means of the switches at the rear of the box. It is a good plan to use enough cells to give an initial current between one-tenth and two-tenths of an ampere.

RECORDING INSTRUMENTS.

In the second form of underflow meter a self-recording instrument is used in place of the direct-reading ammeter, thus doing away with the tedious work of taking the frequent observations day and night, which are required when direct-reading instruments are used. The arrangement of the apparatus is not materially different from that described above. In the place of the direct-reading ammeter a special recording ammeter is used, of range 0 to 2 amperes. It has been found practicable, although it is a matter of some difficulty, to construct an instrument of this low range that is sufficiently portable for field use and not too delicate for the purpose for which it is intended. The ammeter has a resistance of about 1.6 ohms and is provided with oil dash pot to dampen swing of arm carrying the recording pen. The instruments were manufactured by the Bristol Company. They have gone through hard usage in the field without serious breakage or mishap. The portability of the instruments will be materially increased by changes in design which are now being made.

The method of wiring the wells when the recording instruments are used is slightly changed. In this case one side of the battery circuit is connected to casing of well A and to all of the electrodes of wells B, C, and D. The other side of the battery is run through the recording ammeter to a commutator clock, which once every hour makes a contact and completes the circuit, one after the other, to a series of binding posts. One of these binding posts is connected to the casing of well B, one to the casing of well C, and one to the casing of well D. The period of contact is ten seconds, which gives an abundance of time for the pen to reach its proper position and to properly ink its record.

Pl. V, *B* shows a commutator clock made for this purpose by the instrument maker of the College of Engineering, University of Wisconsin. The clock movement is a standard movement of fair grade, costing less than $5. It can readily be taken from the case for cleaning or oiling and quickly replaced. A good movement with powerful springs is best for this purpose.

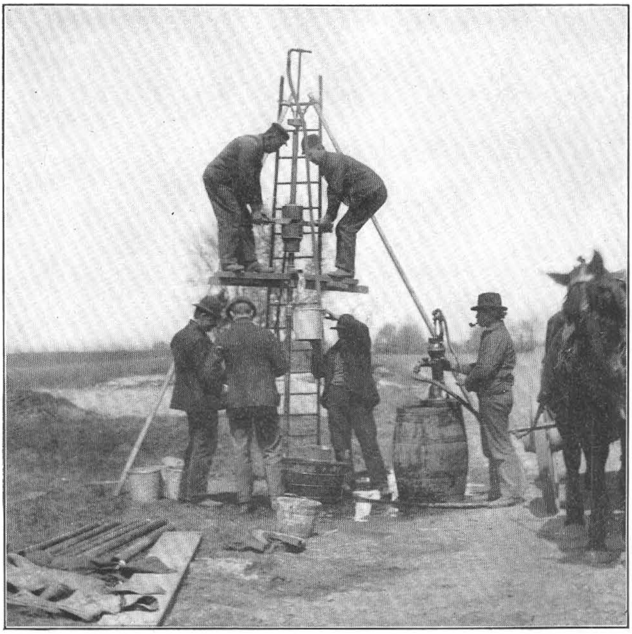
It will be seen from the method of wiring the wells that the record will show the sum of the current between well A and well B added to the current between the casing of well B and its electrode. The removal of the connection to well A would permit the record to show the current between the casing of a downstream well and its electrode, but the connection to the upstream well involves no additional trouble and occasionally its indications are of much service, especially if the velocities are low.

One of the instruments above mentioned can be placed in a common box, 16 by 22 by 36 inches, covered with tar paper and locked up. Pl. VI, *B*, is a view of the instruments thus arranged. The shelf contains the recording ammeter (shown at left of cut) and the commutator clock (shown at right of cut).

The contacts on the commutator clock are arranged about five minutes apart, so that the record made for the wells will appear on the chart as a group of lines, one for each downstream well, of length corresponding to the strength of the current. The increasing current corresponding to one of the wells will finally be indicated by the lengthening of the record lines for that well. This can be seen by consulting the records shown in Pl. VII. The record charts are printed in light-green ink and red ink is used in the recording pen, so that record lines can be distinguished when superimposed upon the lines of the chart. A special chart has been designed for this work and is furnished by the Bristol Company as chart 458.

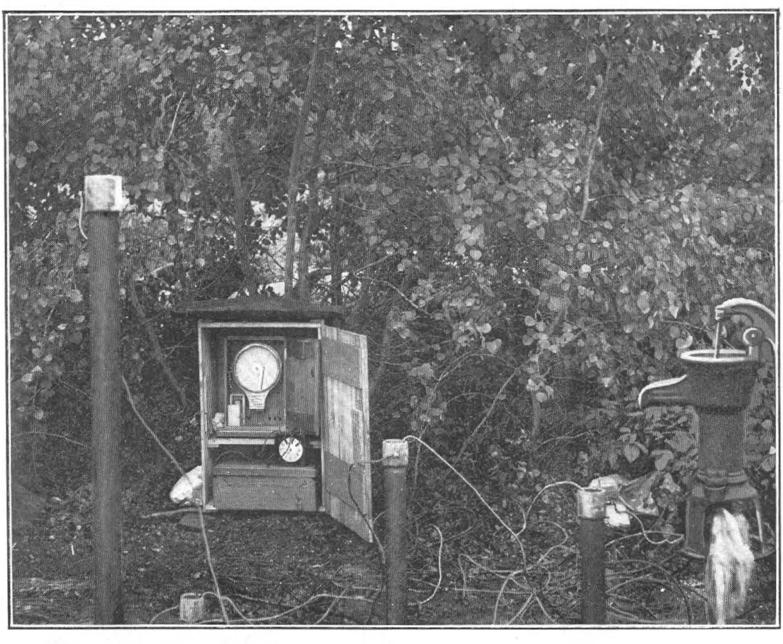
Pl. VII shows two charts made by recording ammeter. In the upper the electrical current for wells B, C, and D, at station 14, Long Island, is recorded, in the order named, at 2.10, 2.15, and 2.20 p. m., and hourly thereafter, the current remaining nearly constant at .22 to .24 ampère until 10.15 p. m., when the current for well C rises as indicated in the chart. In the lower chart the electrical current for wells B, C, and D is recorded, in the order named, at 6.30, 6.35, and 6.40 p. m., and hourly thereafter. The current for wells B and D remains constant at .25 ampere, but the current for well C rises as shown.

The recording instruments in use have given perfect satisfaction and the method is a great improvement in accuracy and convenience over the direct-reading method. The highest as well as the lowest ground-water velocities yet found have been successfully measured

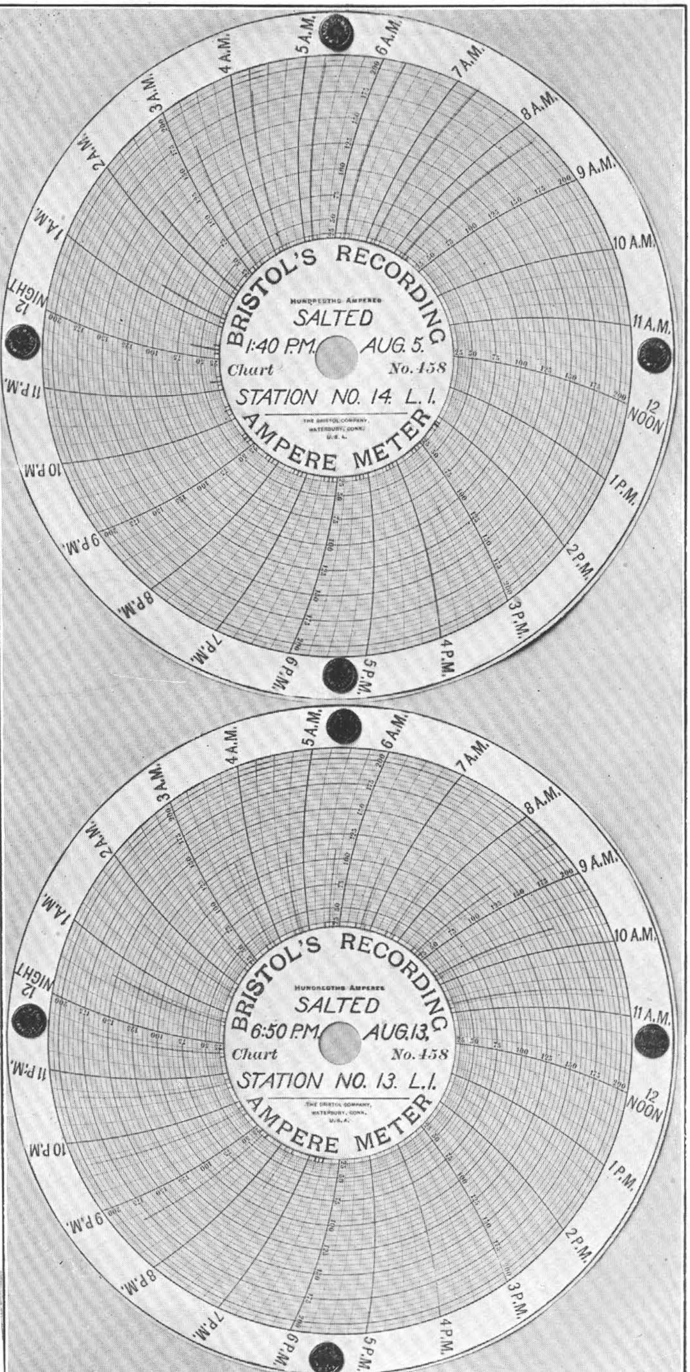


A. SIMPLE FORM OF SMALL WELL-JETTING RIG.

The men driving with 150-pound weight stand on platform attached to drivepipe.



B. RECORDING AMMETER, COMMUTATOR CLOCK, AND BATTERY BOX IN USE IN THE FIELD, ARRANGED IN A ROUGH BOX, 16 BY 22 BY 36 INCHES IN SIZE.



CHARTS MADE BY RECORDING AMMETER.

by the recording instruments. By using one or two additional dry cells the instrument may be made quite as sensitive as the direct-reading type. In using the recording instruments but a single dose of salt need be placed in the upstream well. If the wells are deep, it is important to use enough salt solution to make sure that the salt reaches as deep as the screen of the well point immediately after the solution is poured into the well. A gallon of solution will fill about 6 feet of full-weight wrought-iron pipe, so that 10 gallons of solution should be used if well is 60 feet deep. If the proper amount of solution be not used, it will take an appreciable time for the solution to reach the bottom of the well by convection currents, and the results

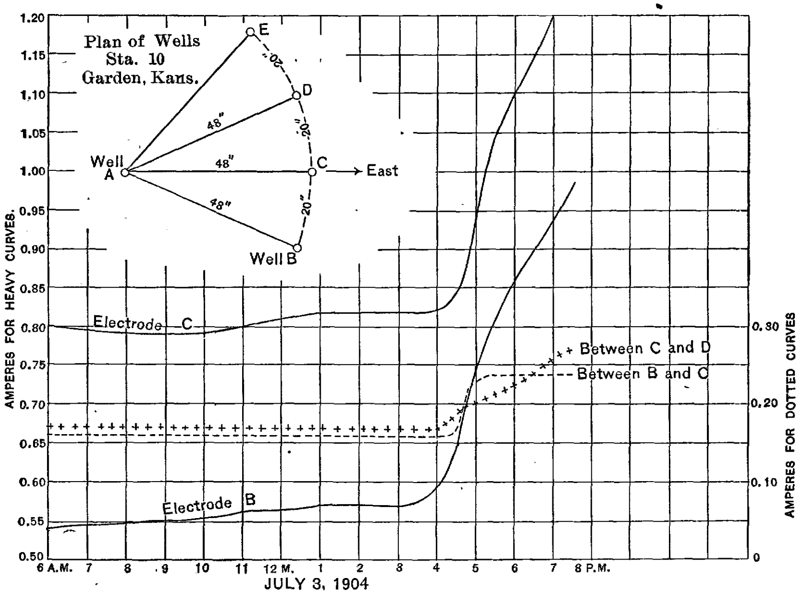


FIG. 6.—Ampere curves at station 10, Garden, Kans. The heavy curves represent the electric current between the casings of wells B and C and the electrodes inside of them. The dotted curves represent the electric current between wells B and C and between C and D. The electric current for the electrode of well B rose earlier than for well C, and the electric current between wells B and C rose earlier and more abruptly than for wells C and D, indicating that the principal stream of electrolyte passed between wells B and C and nearer to well B than to well C.

will be vitiated to that extent. As before stated, it is preferable to introduce into the well granulated sal ammoniac contained in a suitable bucket in case the depth of the well renders the use of a solution uncertain.

In order to properly interpret results obtained in the field with the apparatus, it becomes necessary to investigate the behavior of the dissolved electrolyte as it moves onward with the ground water after leaving the salted well. This matter could be investigated only in the laboratory, and it was sought to reproduce as nearly as possible the conditions found in the field.

Before salting the upstream well of any set of test wells the electric circuit should be closed between each adjacent pair of downstream wells, and the current should be measured with the direct-reading ammeter and recorded in the notebook. An occasional reading of these same circuits will prevent the electrolyte from passing between two of the downstream wells without the knowledge of the observer. This is clearly shown by the results obtained with the set of wells represented in fig. 6. At the location of this station the direction of the flow was at first not correctly estimated on account of its nearness to a river whose height was fluctuating. For that reason the downstream wells were redriven at distances of but 20 inches from one another. The diagram gives the ampère curves for wells B and C, both of which were reached by the electrolyte, and also the curves of current between wells B and C and wells C and D. The actual direction of flow can be seen from these curves to lie between B and C, and probably nearer B than C, since the curve for B rises somewhat earlier and the percentage increase in current is greater. The same fact is shown by the curves representing the current between B and C and between C and D. The main stream of electrolyte must have passed between B and C, as is shown by the more abrupt and earlier use in the current between B and C as compared to that between C and D.

CHAPTER III.

LABORATORY EXPERIMENTS ON THE FLOW OF WATER THROUGH SANDS AND GRAVELS.

OBJECTS OF THE EXPERIMENTS.

During the winters of 1902–3 and 1903–4 experiments were carried on in the laboratory upon the flow of water through sands and gravels contained in tanks. The objects of these experiments were: (1) To verify the law of flow of water through sands and gravels under gradients similar to those found in the field; (2) to ascertain the law of distribution in a horizontal plane of the electrolyte used in the electrical method of determining the rate of flow of underground water; (3) to determine the influence of varying velocities upon this distribution; (4) to determine, if possible, by means of apparatus approximating actual field conditions, the relation between the distribution of the electrolyte and the current curve obtained by the electrical method of measuring ground-water velocities, thereby checking the accuracy of the method and furnishing data indicating more definitely the point on the current curve which should be selected in order to find the velocity of flow.

For the laboratory work of 1902–3 the writer had the assistance of Mr. Henry C. Wolff, and the work of 1903–4 was done by Mr. Ray Owen and H. L. McDonald.

EXPERIMENTS IN THE HORIZONTAL TANK.

The apparatus used in the first experiments consisted of a horizontal wooden tank of inside dimensions 4 feet 6 inches long, 4 feet wide, and 8 inches deep. A chamber of perforated sheet brass 3 inches wide was inserted in each end of the tank, so that the dimensions of the compartment left for the gravel was 4 by 4 feet in horizontal extent. The area 4 by 4 feet was divided into squares 6 inches on a side, at the corner of each of which a small well of slotted sheet brass, one-half inch in diameter, was fixed in position. A larger well, 2 inches in diameter, of the same material was placed in position as shown in the plan, fig. 7. For the first experiments the tank was filled with about 7 inches of gravel, which we have designated as Picnic Point gravel. The effective size of this gravel, as determined by King's aspirators, was 0.93 mm. Mechanical analysis of the Picnic Point gravels will be found in Table VI.

TABLE VI.—*Mechanical analysis by standard sieves of several gravels referred to in the text.*

No. of screen-meshes to inch.	Size of separation of screen in millimeters.	Per cent of total weight of sand passing sieve.		
		Picnic Point gravel.	Madison glacial gravel.	Victorville gravel.
100	0.18	00.6	00.8	00.1
80	.23	1.0	1.4	0.2
60	.32	1.6	6.3	1.3
40	.46	4.2	38.6	4.7
30	.70	14.3	83.9	13.1
20	.93	25.6	98.1	27.8
16	1.30	31.4	99.6	37.2
14	1.40	36.8	100	46.3
12	1.70	47.6	100	63.9
10	2.04	54.3	100	71.0
8	2.48	67.5	100	82.7
Held by 8	....	32.5	....	17.3

TABLE VII.—*Effect of formalin in preventing clogging of sand filter.*

1 Duration of experiment.	2 Average head.	3 Average flow of water per one-fourth hour.	4 Flow per unit head.	5 Temperature.	6 Mean hydraulic gradient per mile.	7 Velocity of water per diem.
First experiment, Dec. 8:	*Inches.*	*Pounds.*		°*C.*	*Feet.*	*Feet.*
First 10/4 hours	0.230	6.57	28.56	14.4	25.3	15.4
Second 11/4 hours	.227	6.48	28.54	....	....	....
Second experiment, Dec. 9:						
First 11/4 hours	.188	6.13	30.96	14.0	20.5	14.2
Second 11/4 hours	.185	6.01	30.90	....	....	....
Third experiment, Dec. 11:						
First 5/4 hours	.170	5.75	29.22	14.0	18.9	13.7
Second 5/4 hours	.174	5.89	29.24	....	....	....

NOTE.—This table shows the influence of a small amount of formalin in preventing the clogging of a sand filter when water is run through it continuously. Compare the flow per unit head during first portion of each experiment with the flow during the second period, as given in column 4. The experimental error is greater than the small differences in these numbers. The low gradients and the low velocities used can be seen in columns 6 and 7.

The tank of gravel was securely mounted in a horizontal position and gages of glass tubing communicating with the chambers at the ends of the tank were adjusted to show the level of water at each end of the tank. By means of these gages it was easily possible to measure the height of the water in the end compartments within one two-hundredths of an inch. Water was permitted to flow into one of the end compartments from galvanized tubs placed on a platform scale. From the tubs the water passed through 3 or 4 feet of rubber tubing

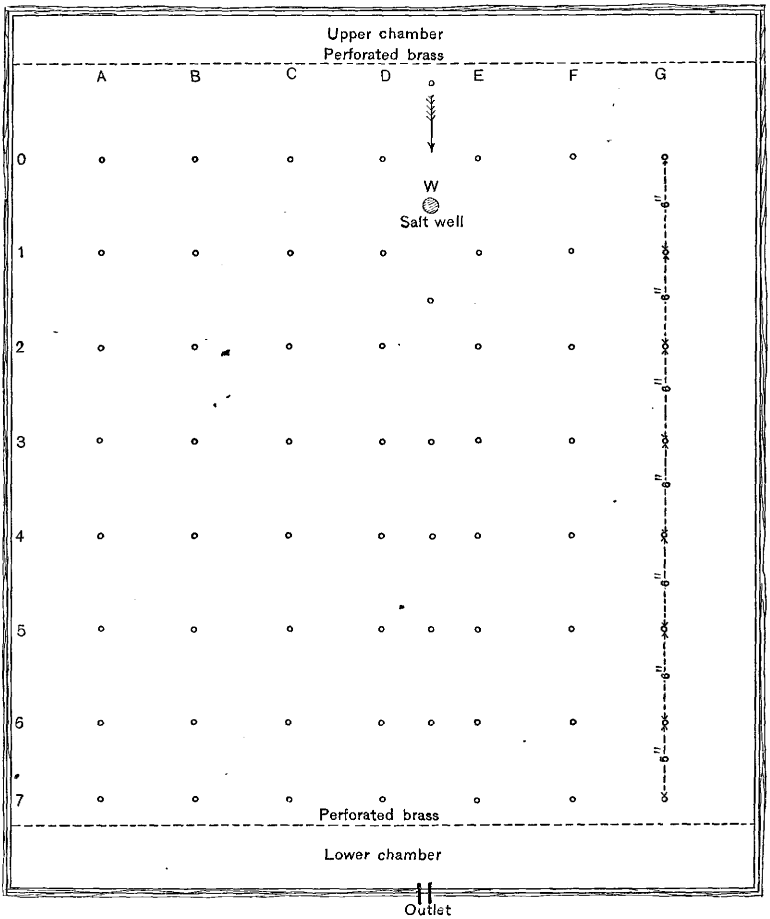


FIG. 7.—Plan of the horizontal tank used in the determination of the spread of an electrolyte when flowing with the water through a sand or gravel. The tank was 4 feet 6 inches long, 4 feet wide, and 8 inches deep. Two perforated brass screens 3 inches from each end left a compartment for gravel 4 by 4 feet in area. A 2-inch well of perforated brass was set at the point marked W, in which the electrolyte was placed. The small circles represent the location of the test wells, from which samples of water could be taken as desired.

to a conically ground needle valve operated by a float placed in the upper compartment or chamber of the tank. It was found possible so to adjust this valve that the level of the water in the upper compartment was maintained constant during an experiment extending over several hours. The water was permitted to escape from the lower compartment in the tank by means of a ½-inch pipe, the height of the overflow being adjustable.

TABLE VIII.—*Data obtained during experiments on flow of water in horizontal tank.*

No.	Date of experiment, 1902-3.	Hydraulic gradient.	Average depth of water.	Velocity of ground water.	Velocity per unit head.	Temperature of water.	Salt used in experiment.
		Ft. per mile.	*Inches.*	*Ft. in 24 hrs.*	*Ft. in 24 hrs.*	°C.	
1....	Dec. 8	25.30	5.84	15.4	0.61	14.4	None used.
2....	Dec. 9	20.50	5.83	14.2	.69	14.0	Do.
3....	Dec. 11	18.90	5.82	13.7	.63	14.0	Do.
4....	Dec. 20	18.70	5.88	13.2	.70	20.5	Dry NH_4Cl.
5....	Jan. 3	17.60	5.12	12.9	.73	20.0	Do.
6....	Jan. 7	21.45	5.10	12.1	.56	18.8	Dry NaCl.
7....	Jan. 14	22.00	5.12	13.8	.63	17.8	Con. NH_4OH.
8....	Jan. 17	18.54	5.09	9.3	.50	18.8	Do.
9....	Jan. 30	18.92	5.18	11.6	.61	17.8	Dry $\frac{9}{10}$ H_4Cl. $\frac{1}{10}$ NaOH.
10....	Feb. 9	19.03	5.17	11.25	.59	20.0	Dry $\frac{8}{10}$ NH_4Cl. $\frac{2}{10}$ NaOH.
11....	Feb. 18	21.45	5.15	11.68	.54	18.8	Sol. NH_4Cl.
12....	Feb. 23	42.35	5.28	21.70	.51	19.1	Do.
13....	Mar. 3	64.90	5.21	36.00	.55	20.1	Do.
14....	Mar. 9	64.24	5.21	35.5	.55	20.3	Sol. $\frac{9}{10}$ NH_4Cl. $\frac{1}{10}$ NaOH.
15....	Mar. 16	66.55	5.25	36.4	.55	21.7	Dry $\frac{9}{10}$ NH_4Cl. $\frac{1}{10}$ NaOH.
16....	May 4	103.2	6.68	11.47	.11	22.0	NH_4Cl.
17....	May 14	105.6	6.70	11.60	.11	18.2	$\frac{9}{10}$ NH_4Cl. $\frac{1}{10}$ NaOH.
18....	May 23	107.8	6.69	11.90	.11	....	NaOH.

NOTE.—In experiments 1–15 "Picnic Point gravel" was used, and in experiments 16, 17, 18 Madison glacial sand was used.

The water used in the experiment was obtained from Lake Mendota, Madison, Wis., and before use was freed from suspended material by passing through a filter of charcoal and sand. Before passing through the gravel in the tank, one part in 500 of 40 per cent solution of formalin was added to the water so as to inhibit the growth of organisms. Previous experimenters on the flow of water through sands and gravels experienced much difficulty on account of the progressive reduction in flow of water through the sand when an experiment extended over a considerable length of time. No means had been found for avoiding this difficulty; even the use of distilled water was not entirely effective. It was difficult to explain this phenomenon except on the basis of the growth of organisms in the pores of the

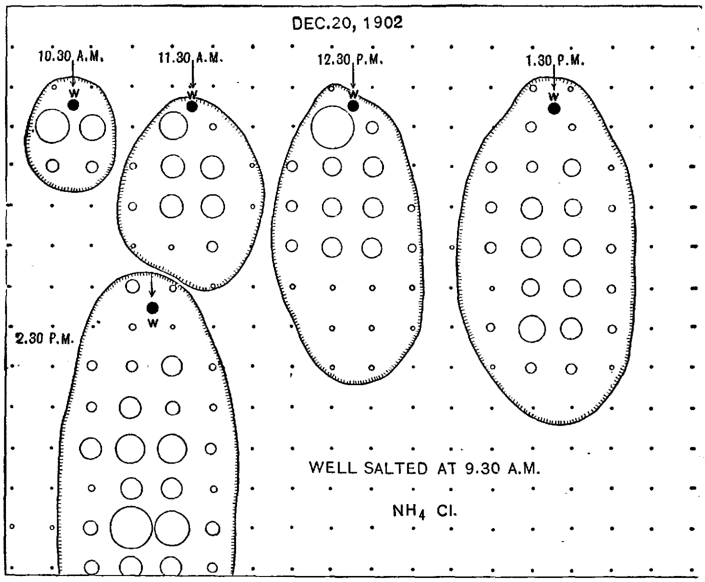


FIG. 8.—Diagram showing the manner in which the electrolyte spread in passing downstream with the ground water, in experiment 4, in the horizontal tank. The dot at W shows the location of the salted well, and samples were taken from the sand from the small test wells represented by dots in the diagram. The areas of the circles are proportional to the strength of the electrolyte found at their centers. The area covered by the charged water at the time specified is shown by a roughly sketched outline. The velocity of the ground water in the direction of the arrows was 13.2 feet for twenty-four hours. Electrolyte used was sal ammoniac.

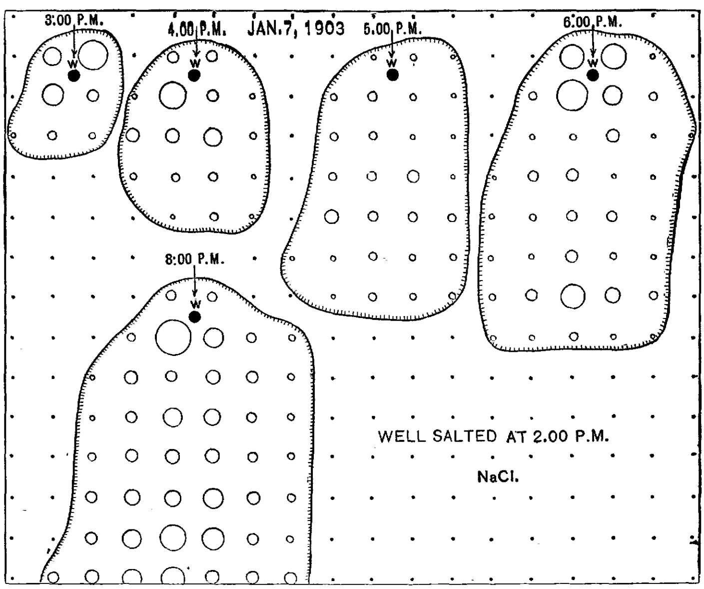


FIG. 9.—Diagram showing the results of experiment 6. Representation of wells and other features as in fig. 8. The velocity of the ground water was 12.1 feet for twenty-four hours. The electrolyte used was common salt.

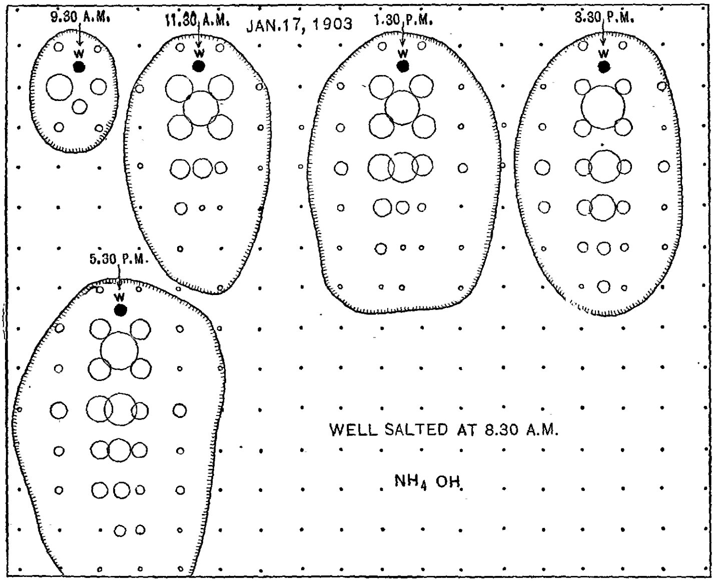


FIG. 10.—Diagram showing the results of experiment 8. Representation of wells and other features as in fig. 8. The velocity of the ground water was 9.3 feet for twenty-four hours. The electrolyte used was concentrated ammonia water.

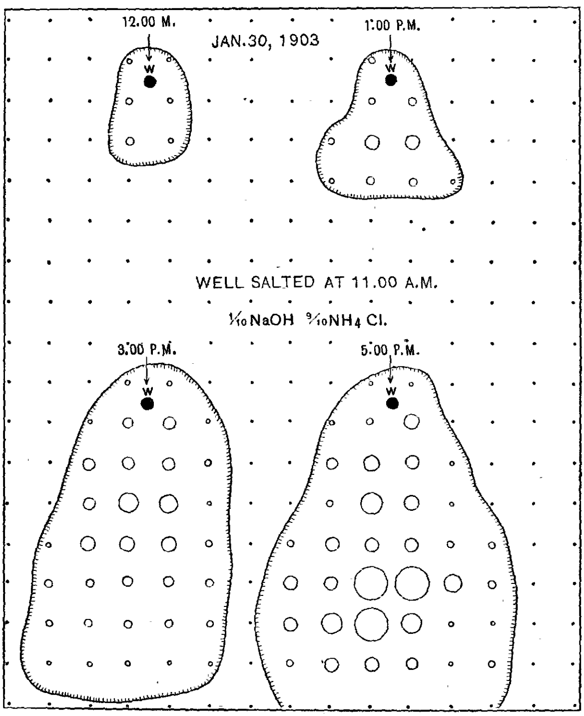


FIG. 11.—Diagram showing the results of experiment 9. Representation of wells and other features as in fig. 8. The velocity of the ground water was 11.6 feet for twenty-four hours. The electrolyte used was one-tenth caustic soda and nine-tenths sal ammoniac.

sand used in the experiments. For this reason the formalin was added to the water in the hope that if this were the correct explanation the difficulty would vanish. Several experiments were made for the especial purpose of determining the effect of the formalin in inhibiting the organic growth in the filter. Table VII gives the result of three such experiments. The duration of each experiment was divided into two nearly equal periods, and the average head of water as shown by the gages and the average flow of water, as determined by weighing both the water admitted to the tank and the water leaving it at the

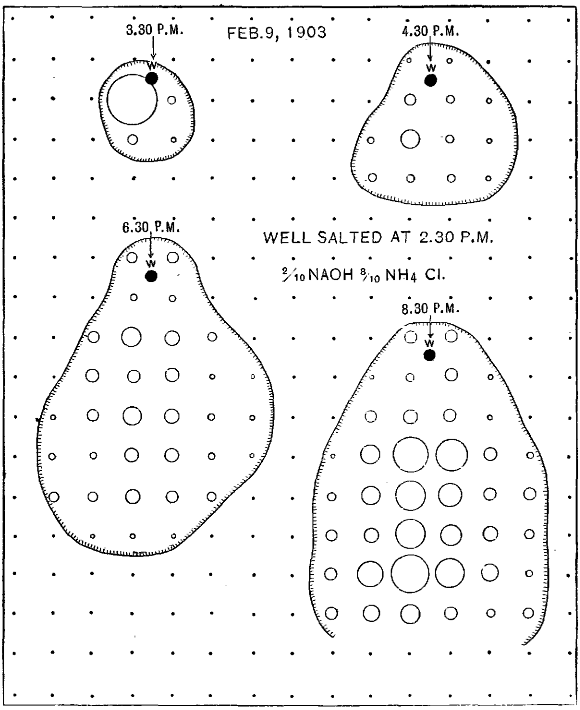


FIG. 12.—Diagram showing the results of experiment 10. Representation of wells and other features as in fig. 8. The velocity of the ground water was 11¼ feet for twenty-four hours. The electrolyte was two-tenths caustic soda and eight-tenths sal ammoniac.

lower end, were determined for each of the two periods into which each experiment was divided. It will be seen by consulting column 4 of the table that the flow of water per unit head during the first portion of each experiment was essentially identical per unit head to the second portion of each experiment. The slight differences in the numbers is much smaller than the unavoidable experimental error. It was concluded, therefore, that the progressive clogging of a sand filter is due to the growth of organisms, and that the formalin added constituted an effective remedy.

Altogether 18 experiments were carried out in this tank. In the first 15 tests Picnic Point gravel was used in the tank; during the last 3 fine glacial sand replaced the Picnic Point gravel. The glacial sand had effective size of grain, as determined by King's aspirator, of 0.40 mm. A mechanical analysis of the sand is given in Table VI,

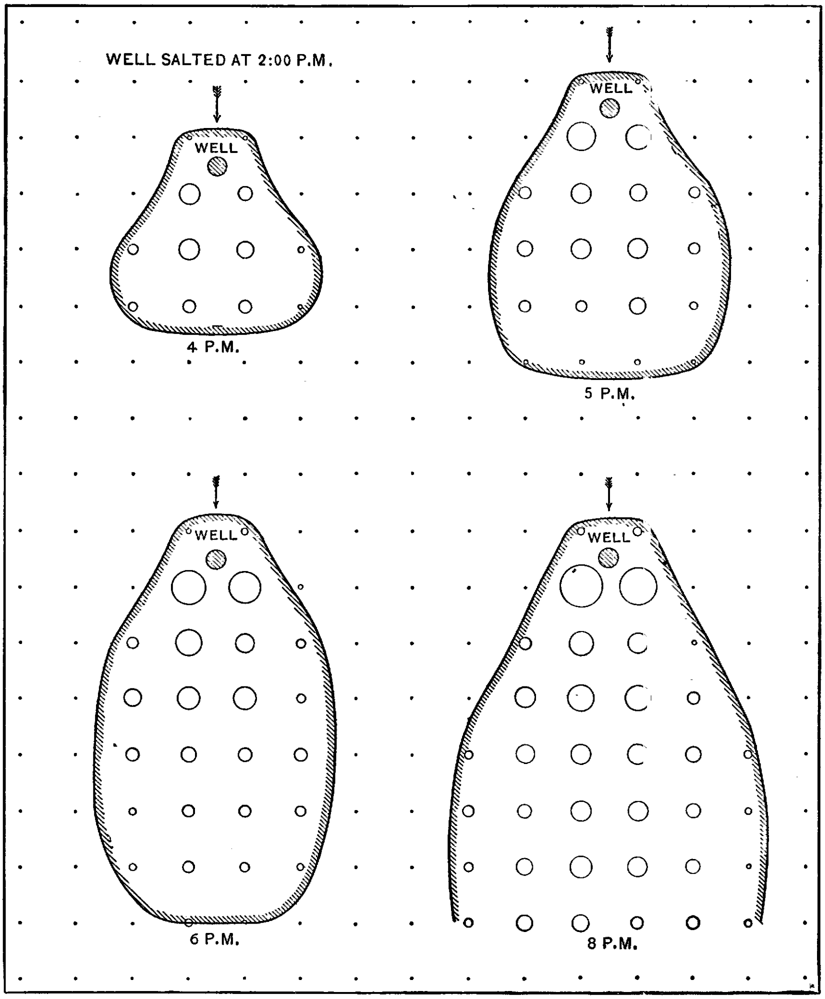


FIG. 13.—Diagram showing the results of experiment 11. Representation of wells and other features as in fig. 8. The velocity of the ground water was 11.7 feet for twenty-four hours. The electrolyte was sal ammoniac in concentrated solution.

(p. 30), and a summary of the data obtained during the experiments is placed in Table VIII.

No difficulty was experienced in maintaining very low gradients to the water plane in the tank, a slope of water of 18 feet to the mile being easily brought about by proper adjustment in the apparatus. In this way actual field conditions of the flow of water were very closely approximated, and velocities less than 10 feet a day could be maintained by the use of the low gradients. The large well marked W was designed to receive various electrolytes while the water was moving through the gravel under the selected uniform head. The small one-half inch wells placed at the corners of the 6 inch squares were designed to serve as test wells from which samples of the water could be taken at stated intervals, and the exact area spread over by the electrolyte could be ascertained by chemical analyses. A series of pipettes were coupled together in such a way as to permit the taking of a sample from each row of test wells at the same time. By the use

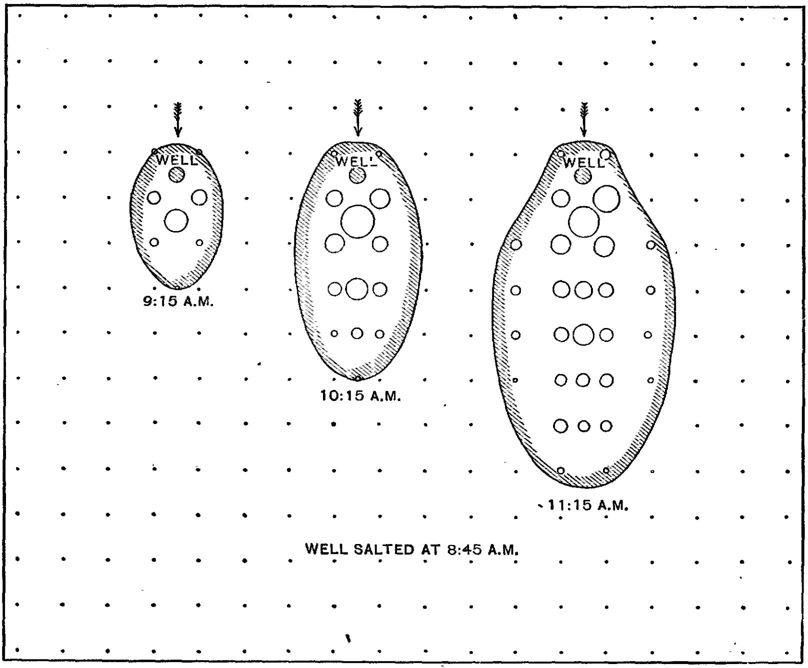


FIG. 14.—Diagram showing the results of experiment 12. Representation of wells and other features as in fig. 8. The velocity of the ground water was 21.7 feet for twenty-four hours. The electrolyte was sal ammoniac in concentrated solution.

of this device a complete set of samples could be taken from all the test wells in the tank in a very few minutes.

The results of the experiments are best shown by the series of diagrams figs. 8 to 20, in which the strength of the electrolyte found at each test well is shown by a circle of appropriate size.

Among the various electrolytes tested were ammonium chloride (sal ammoniac), sodium chloride (common salt), concentrated ammonia water, and mixtures of ammonium chloride and caustic soda, or lye. One of the most remarkable conclusions from the experiments was that diffusion plays but a very small part in the spread of the electrolyte through the ground water. In none of the experiments was it found

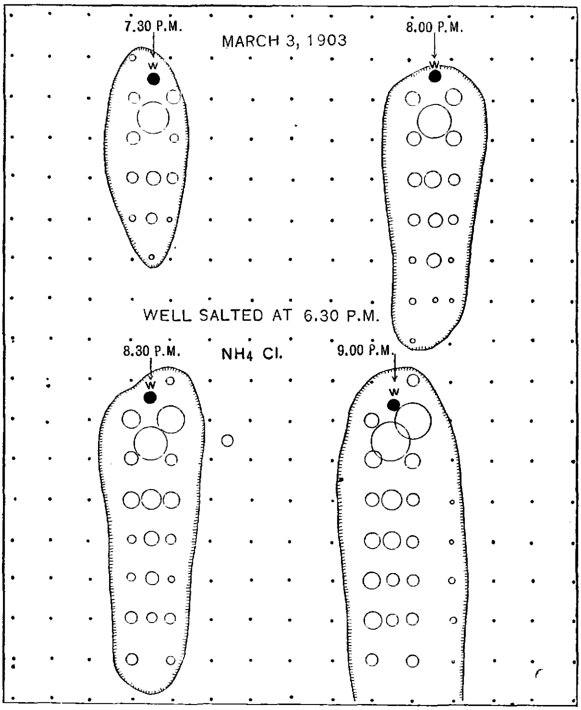


FIG. 15.—Diagram showing the results of experiment 13. Representation of wells and other features as in fig. 8. The velocity of the ground water was 36 feet for twenty-four hours: The electrolyte was sal ammoniac in concentrated solution. Note the narrow stream of electrolyte due to the high velocity.

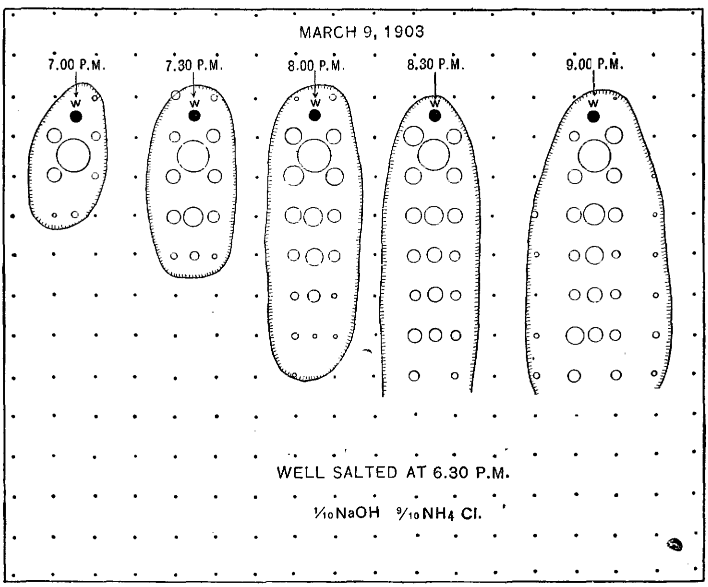


FIG. 16.—Diagram showing the results of experiment 14. Representation of wells and other features as in fig. 8. The velocity of the ground water was 35½ feet for twenty-four hours. The electrolyte was one-tenth caustic soda and nine-tenths sal ammoniac in solution.

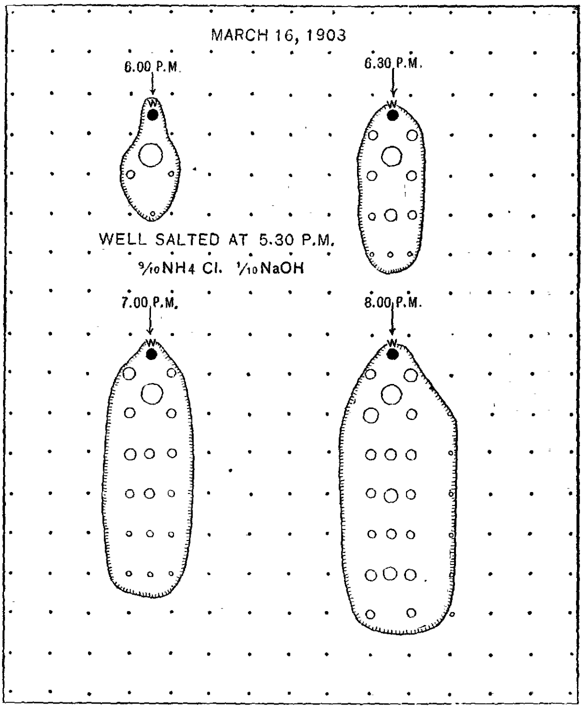


FIG. 17.—Diagram showing the results of experiment 15. Representation of wells and other features as in fig. 8. The velocity of the ground water was 36.4 feet for twenty-four hours. The electrolyte was one-tenth caustic soda and nine-tenths sal ammoniac in dry crystals.

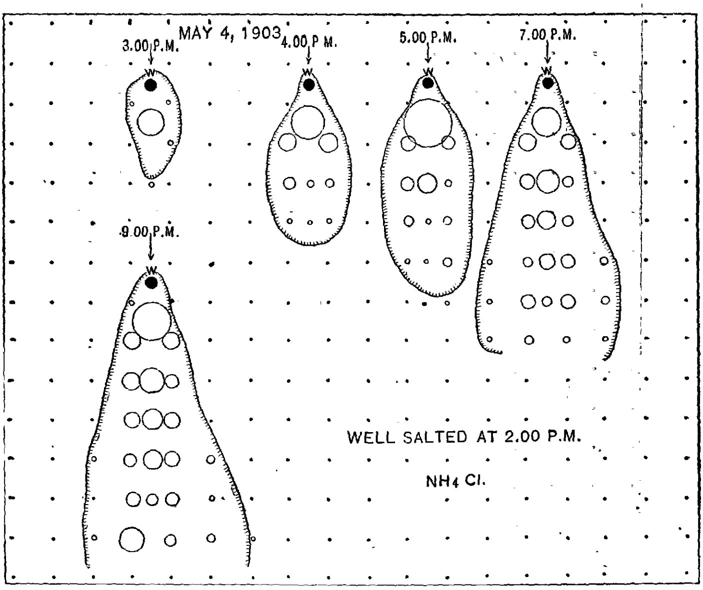


FIG. 18.—Diagram showing the results of experiment 16. Representation of wells and other features as in fig. 8. The velocity of the ground water was 11.5 feet for twenty-four hours. The electrolyte was sal ammoniac.

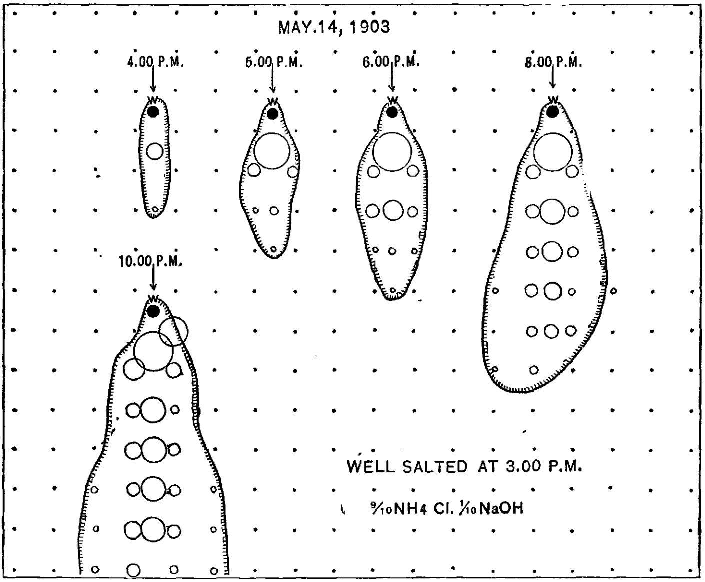


FIG. 19.—Diagram showing the results of experiment 17. Representation of wells and other features as in fig. 8. The velocity of the ground water was 11.6 feet for twenty-four hours. The electrolyte was one-tenth caustic soda and nine-tenths sal ammoniac.

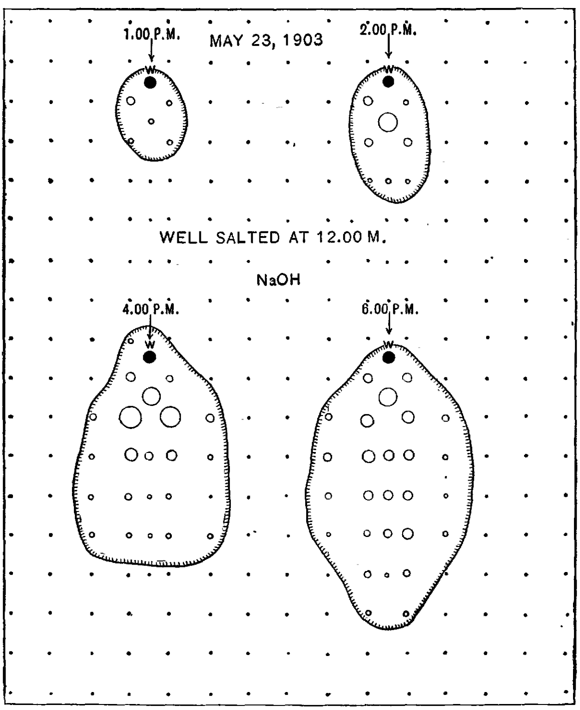


FIG. 20.—Diagram showing the results of experiment 18. Representation of wells and other features as in fig. 8. The velocity of the ground water was 11.9 feet for twenty-four hours. The electrolyte was caustic soda.

that the electrolyte extended more than about 3 inches upstream from the large well W. This fact can be seen by consulting the series of diagrams illustrating the distribution of electrolyte. In general, it can be seen that the electrolyte moves downstream in a pear-shaped mass, the width of the stream varying somewhat with the nature of the electrolyte used. The high velocities always gave a stream of electrolyte which was quite narrow and the low velocities gave broader streams. The solution of concentrated ammonia water gave the broadest stream. This was probably due not so much to the diffusion of the ammonia gas in the water as to the low coefficient of viscosity of the ammonia water. Experiments in the field had indicated that the mixture of sal ammoniac and caustic soda would spread in a broader stream than sal ammoniac alone. By comparing the results of experiments 14 and 15 with that of experiment 13, it will be seen that this assumption could not be verified to any considerable extent. In a similar way, experiments 9 and 10 may be compared with experiment 8, and experiments 17 and 18 may be compared with experiment 16.

It seems to be conclusively shown by these experiments, as has been already stated (pp. 22–23), that the diffusion of the dissolved salt plays a very small part in the way in which the electrolyte is distributed in the moving current of ground water, but, as already stated, that the central thread of water in each capillary pore of the soil moves faster than the water in contact with the walls of the capillary pore. Likewise the spread of the electrolyte, as shown by these experiments, is not to be explained by the diffusion of the salt, but must be explained by the continued branching and subdivision of the capillary pores around the individual grains of the sand. The stream of electrolyte issuing from the salt well W will gradually broaden as it passes downstream, because each thread of it must divide and divide again and again as it meets with each succeeding grain of soil. If diffusion had much to do with its rate of spread, it would also make itself apparent by causing an upstream motion to the electrolyte against the current of ground water. As before stated, in no case did the electrolyte succeed in moving upstream a distance as great as 3 inches.

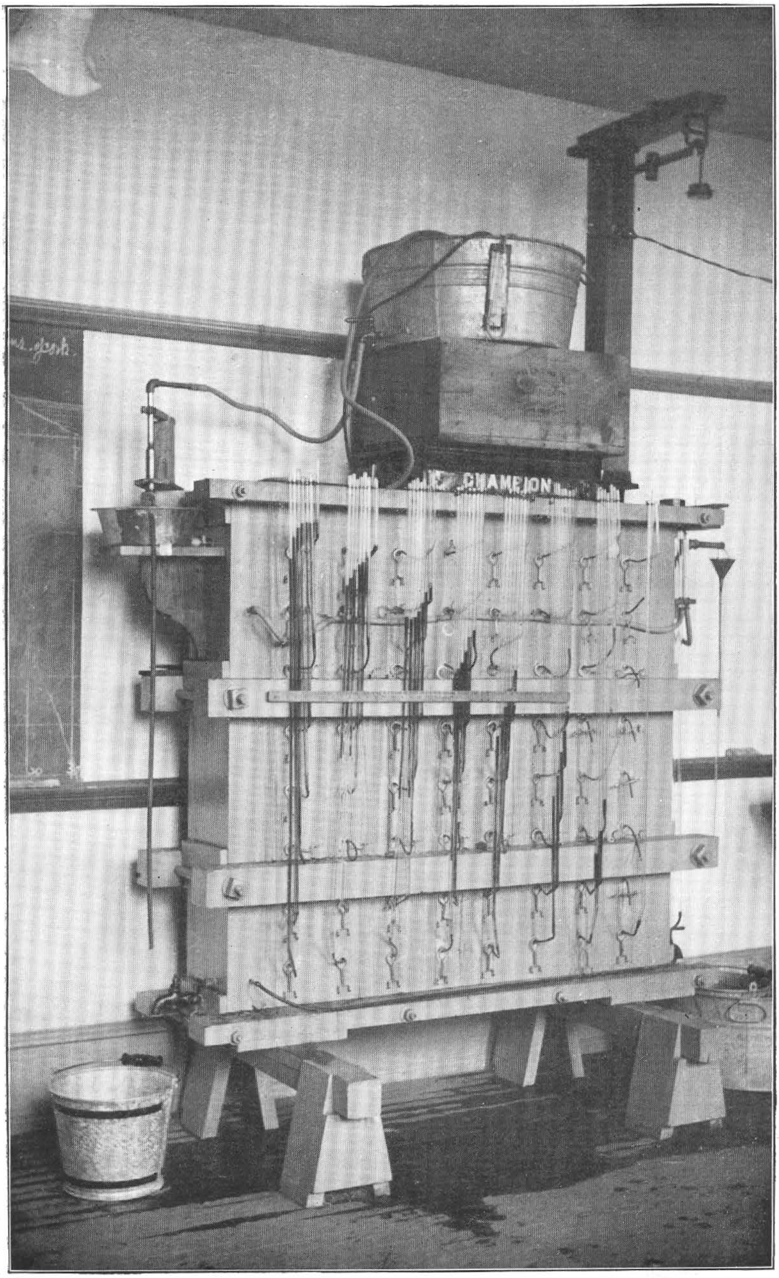
EXPERIMENTS IN THE VERTICAL TANK.

The experiments carried on in the winter of 1903–4 had as their object, in addition to those of the previous year, the determination of the law of distribution of the electrolyte in a vertical plane. For this purpose a tank was constructed of wood, as shown in fig. 21 and Pl. VIII. The inside dimensions of this tank were 4 feet high, 4 feet 6 inches long, and 8 inches wide. At each end of the tank chambers 3 inches wide were constructed of perforated brass, similar to those used in the horizontal tank, leaving a total length of 4 feet available for gravel. Horizontal tubes of slotted brass one-half inch in diameter extended through the side of the tank at the corners of squares 6 inches on a side, as shown by the small circles in the side elevation, fig. 21. These tubes of horizontal test wells were stuck through holes bored in the side of the tank and were supported at one end by a thumb tack soldered to the end of the tube and at the other end by the side of the tank, the tube being slightly longer than the inside width of the tank. A perforated rubber stopper containing a glass tube was placed in the hole, one end of the glass tube extending to the middle of the tank, the other end of the tube projecting outside of the rubber stopper to receive a small rubber tube, which was kept closed by means of a pinchcock. These tubes furnished ready means of drawing out samples of water from different positions in the tank. On top of the tank, in the reproduction of the photograph of the apparatus, Pl. VIII, can be seen the scales carrying the tubs of galvanized iron from which the water was run to a regulating apparatus consisting of a needle valve and float at the upper left-hand corner of the box similar to that used in the horizontal tank. The head of water in the two end chambers of the tank was measured by two glass gages placed about one-half inch apart, communicating with the chambers by large rubber tubes. The readings of the meniscus in the glass tubes of the gages could be readily estimated to one-half hundredth of an inch.

The gravel used in the experiments in the vertical tank was Madison glacial sand, the same as that used in experiments 16, 17, and 18 in the horizontal tank. Seven experiments were completed with this apparatus, the general results of which are tabulated in Table IX.

TABLE IX.—*Data obtained during experiments on flow of water through Madison glacial sand in the vertical tank.*

	Date.	Temperature.	Hydraulic gradient.		Discharge.		Area of cross section.	Velocity.	Velocity per unit head.
	1904.	*° C.*	*Per cent.*	*Feet per mile.*	*Pounds per hour.*	*Cubic feet per minute.*	*Square feet.*	*Feet per diem.*	*Feet per diem.*
1	Feb. 22	17.8	3.10	164	36.25	0.00965	2.34	16.90	0.10
2	Mar. 2	19.2	2.08	110	26.53	.00706	2.54	11.42	.10
3	Mar. 3	14.0	5.41	286	56.00	.0149	2.50	24.50	.09
4	Mar. 5	18.4	1.00	53	9.94	.002645	2.56	4.28	.08
5	Mar. 12	16.0	2.10	112	23.36	.00622	2.54	10.10	.09
6	Apr. 18	14.9	11.91	630	129.66	.0346	2.42	58.80	.09
7	Apr. 19	17.0	5.58	295	51.68	.0138	2.50	22.70	.08



VERTICAL TANK USED IN LABORATORY EXPERIMENTS.

The small test wells from which samples were drawn are equipped with glass gauges containing colored water, indicating distribution of pressure while right chamber of tank is kept empty.

The electrolyte was introduced into the well marked W, shown in fig. 21, and the samples from the various test wells were drawn out at stated intervals into test tubes and analyzed. The results of the

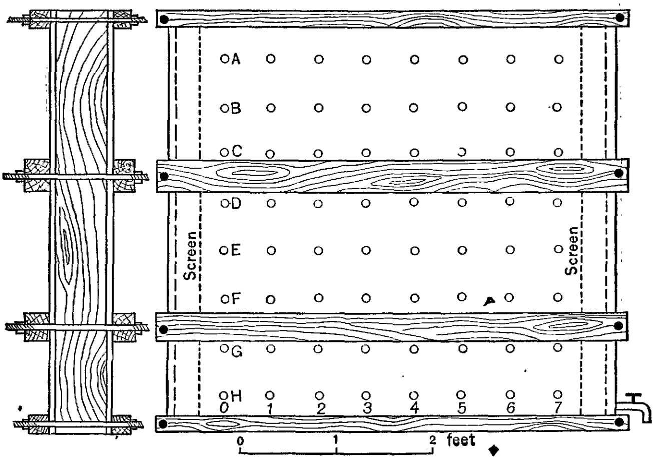


FIG. 21.—Diagram showing construction and dimensions of vertical tank used in laboratory experiments on the flow of ground water. The small circles indicate the position of the test wells.

experiments on the vertical distribution of the electrolyte are best shown by the diagrams, a series of which are given in figs. 22 to 29.

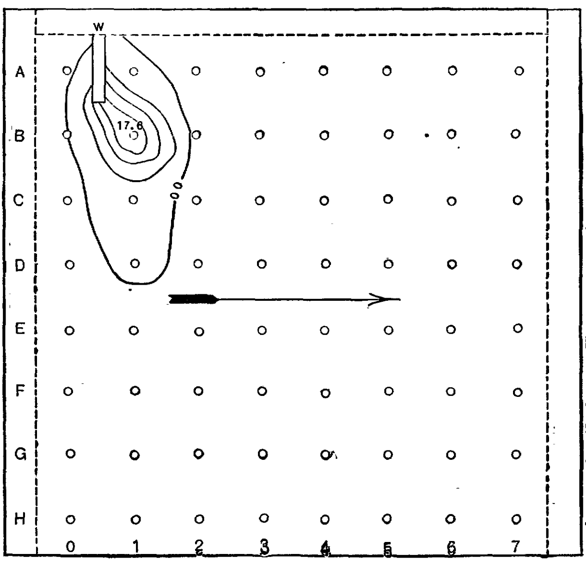


FIG. 22.—Diagram showing results of vertical-tank experiment 1, February 22, 1904. Well W was salted at 11.40 a. m. with sal ammoniac; velocity of the ground water was 17.06 feet a day, head, 1⅛ inches. The contours show the distribution of salt at 12.10 p. m.

In the series of six diagrams for experiment 1 the distribution of the electrolyte is shown by the contour curves for each one-half hour period after the beginning of the experiment. A single dose of 2 ounces of sal ammoniac was introduced into the well W at 11.40 a. m.,

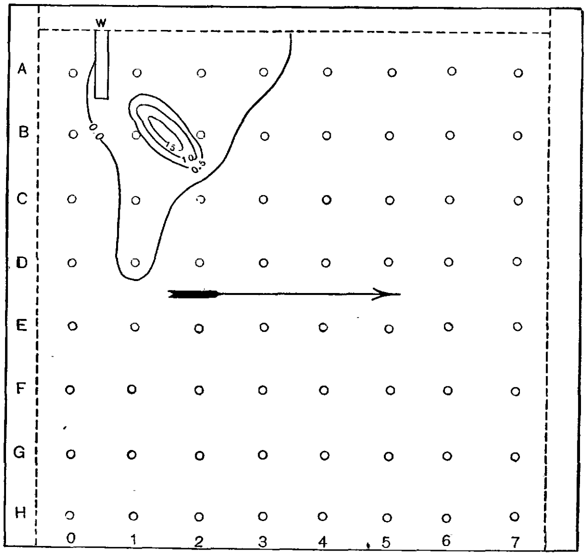


FIG. 23.—Diagram showing results of vertical-tank experiment 1, February 22, 1904. Well W was salted at 11.40 a. m. with sal ammoniac; velocity of the ground water was 17.06 feet a day: head, 1½ inches. The contours show the distribution of salt at 12.40 p. m.

on February 22, 1904. As will be observed by consulting the diagrams, the dissolved salt entered the ground water and passed to the

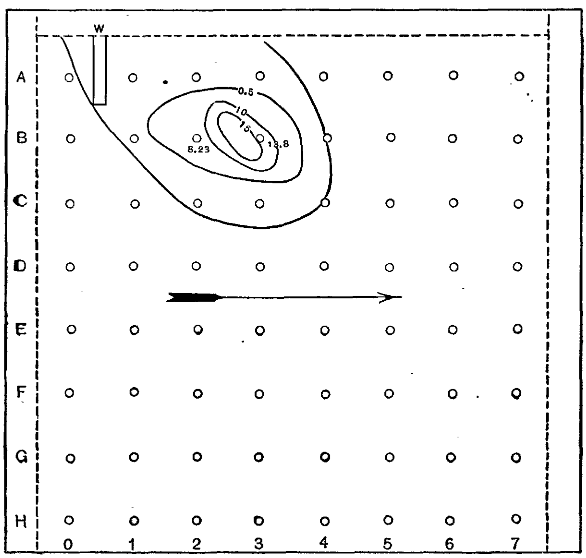


FIG. 24.—Diagram showing results of vertical-tank experiment 1, February 22, 1904. Well W was salted at 11.40 a. m. with sal ammoniac, velocity of the ground water was 17.06 feet a day; head, 1½ inches. The contours show the distribution of salt at 1.40 p. m.

right with the moving stream, at the same time moving slightly downward, as shown by the contour curves. The velocity of water through the gravel during this experiment was about 17 feet for twenty-four hours. The elliptical outline of the contour curves is due to the two

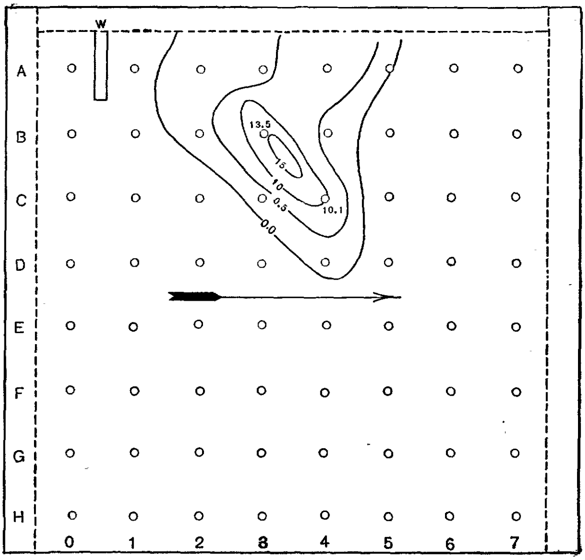


FIG. 25.—Diagram showing results of vertical-tank experiment 1, February 22, 1904. Well W was salted at 11.40 a. m. with sal ammoniac; velocity of the ground water was 17.06 feet a day; head, 1¼ inches. The contours show the distribution of salt at 2.40 p. m.

components of motion, one component being the velocity of ground water to the right, and the other being the downward motion, due to

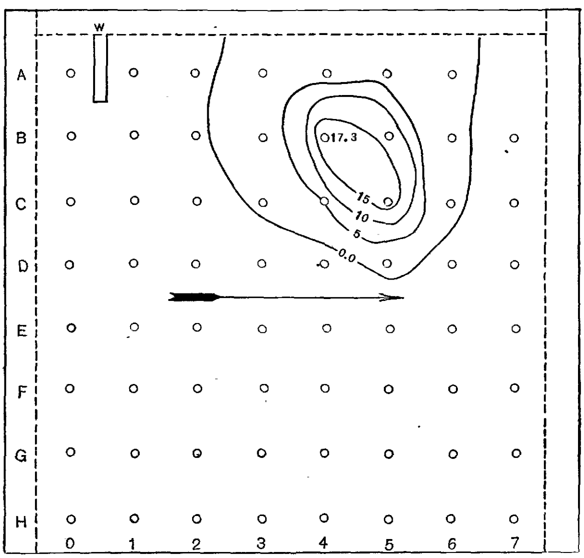


FIG. 26.—Diagram showing results of vertical-tank experiment 1, February 22, 1904. Well W was salted at 11.40 a. m. with sal ammoniac; velocity of the ground water was 17.06 feet a day; head, 1¼ inches. The contours show the distribution of salt at 3.40 p. m.

the high density of the solution of sal ammoniac. It will be noticed that the elliptical contour lines have their longest dimension sloping downward to the right, as they should if they represent the resultant of these two motions. It should also be noted (consult the diagrams)

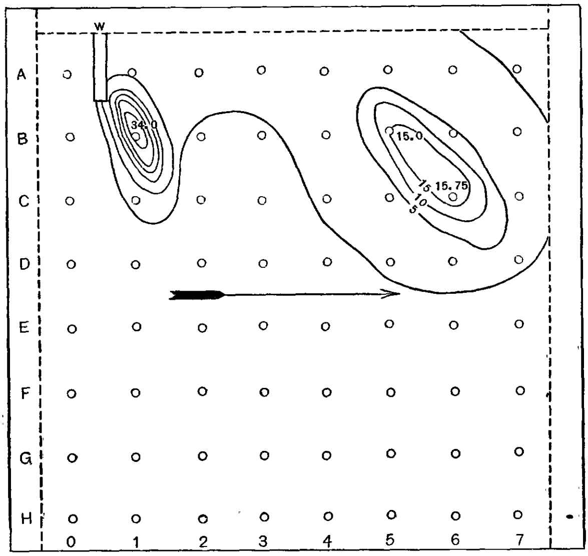


FIG. 27.—Diagram showing results of vertical-tank experiment 1, February 22, 1904. Well W was salted at 11.40 a. m. with sal ammoniac; velocity of the ground water was 17.06 feet a day; head, 1¼ inches. The contours show the distribution of the salt at 4.40 p. m. A second dose of salt was placed in well W at 4 p. m., and the diagram represents the two masses of electrolyte passing forward with the ground water.

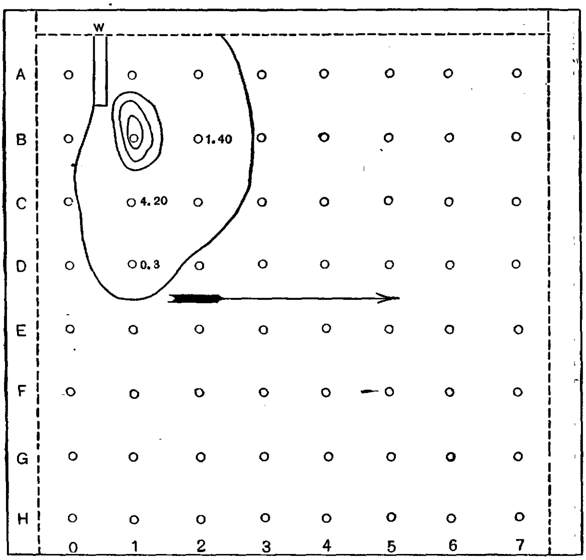


FIG. 28.—Diagram showing results of vertical-tank experiment 2, March 2, 1904. Well W was salted at 2.25 p. m. The velocity of ground water was 11.42 feet a day; head, 1 inch. The salt used was sal ammoniac. Contours show the distribution of salt at 2.55 p. m.

that after an interval of an hour nearly all of the electrolyte had left well W, and the water in the well had become fresh again. At 4 p. m.

an additional dose of sal ammoniac was placed in well W, the effect of which is clearly shown in the contour curves for 4.40 p. m. Here two masses of dissolved electrolytes can be observed traveling simultaneously through the sand. It should also be noted in these diagrams that the electrolyte does not pass upstream, or against the current of ground water more than 1 or 2 inches.

Two sets of contour curves are also given for the second experiment, that of March 2, 1904, in which the same electrolyte was used, but the velocity of the ground water was reduced to 11.42 feet for twenty-four hours. The well W was salted at 2.25 p. m., contours being given for 2.25 and 7.25 p. m. It will be observed that for the lower velocity of ground water the electrolyte sinks to a greater depth than in the case

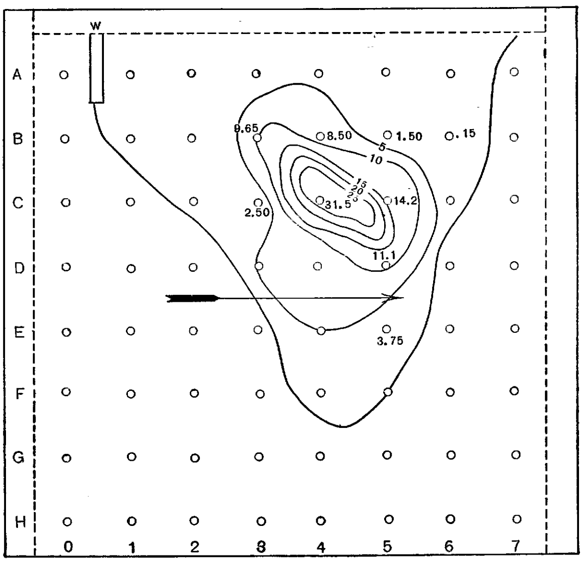


FIG. 29.—Diagram showing results of vertical-tank experiment 2, March 2, 1904. Well W was salted at 2.25 p. m. The velocity of ground water was 11.42 feet a day; head, 1 inch. The salt used was sal ammoniac. The contours show the distribution of salt at 7.25 p. m. A comparison of figs. 28 and 29 with 22 to 27 shows the larger vertical motion of the electrolyte, in the case of the lower velocity of experiment 2, as compared with the higher velocity prevailing during experiment 1.

of the higher velocities of the first experiment. Experiments were also carried out with common lye as electrolyte. This salt is very much heavier than sal ammoniac, and it was noted that it sank much faster than the solution of sal ammoniac for similar velocities of ground water.

One of the most interesting experiments with the vertical tank was made for the purpose of determining the amount of diffusion of the electrolyte. For this purpose the electrolyte was introduced into the well W and the ground water was permitted to remain stationary, no water being run into or out of the tank during the eight hours covered by the experiment. The well W is placed exactly midway between columns 0 and 1 of the small test wells, as can be seen from the diagram. For the purpose of the "still" experiment the uppermost test well of column 2 was removed and well W was placed directly over column 2. A charge of salt was introduced into the well W at 9 a. m., and samples were taken at the end of one-half hour and at the end of each hour thereafter until 5 p. m. The salt was found to drop vertically with a rapidity equal to the vertical component of motion noted in the experiments in which flow took place. In the eight hours of the test no portion of the charge could be detected in the test wells of columns 1 or 3. This experiment showed that the electrolyte had not

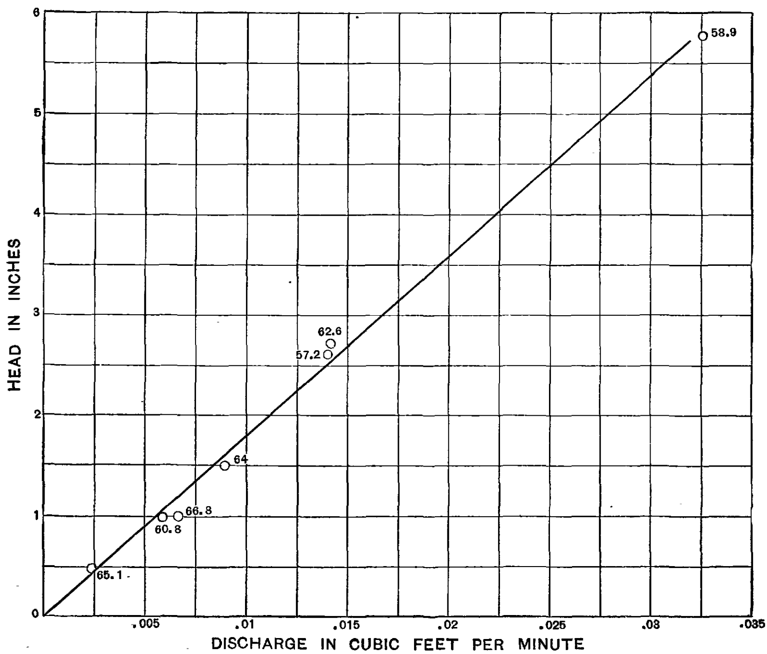


FIG. 30.—Diagram illustrating the variation in the rate of flow of ground water with the variation in head or hydraulic gradient, as observed in the experiments in the vertical tank. The figures attached to the small circles in the diagram designate the temperature, Fahrenheit, of the ground water during the experiment. The straight line represents the theoretical law of flow if the rate of flow varies directly as the head.

diffused sufficiently to reach the wells of columns 1 and 3, while dropping a vertical distance of about 3 feet.

The law of direct variation of the flow of ground waters with the head under which the flow takes place are verified by the experiments in the tank. The results are represented graphically in fig. 30. Exact agreement with this law would require all of the plotted points in this diagram to lie upon the straight line, provided the temperatures were the same. The larger departures from the straight line are not due to temperature differences, but to the high viscosity of the lye solutions used in those particular experiments.

INVESTIGATION OF THE ACCURACY OF THE ELECTRIC METHOD OF DETERMINING THE VELOCITY OF THE FLOW OF GROUND WATERS.

The vertical tank offered a ready means of checking the accuracy of the method of measuring the velocity of ground waters with the electric underflow meter. For this purpose the chambers of perforated brass at the upper and lower ends of the tank served as the upstream and downstream wells, respectively, and an electrode was sunk in the sand 2 inches from the lower partition, which answered the purpose of the electrode usually placed inside the downstream well. The apparatus was then connected in accordance with the method used in actual field work. A solution of sal ammoniac was placed in the upper chamber. The water running through the tank was weighed before it entered and after it left the apparatus, and observations were made of the electric current every fifteen minutes and sometimes oftener. Two experiments were made, one with a head of water of 2.68 inches and one with a head of 5.75 inches. From the weight of water discharged the computed velocity during the former was 23.15 feet a day, and during the latter the velocity was 58 feet a day. From the points of inflection of the two electrode curves the velocities were computed to be, respectively, 23.25 and 64.10 feet a day. This shows agreement in the case of the lower velocity within a very small fraction of 1 per cent, and in the case of the higher velocity within 10½ per cent of the actual rates. These results show that the electric method is sufficiently accurate for the purposes for which it is intended. It is very likely that if the tank in which these experiments were carried out had been wider the percentage agreement for the high velocity would be even closer than 10 per cent, for it must be remembered that the narrowness of the tank tended to bring the concentrated portion of the stream of electrolyte to a given downstream point more rapidly than if the tank had been wide enough to permit the electrolyte to spread in its natural way.

CHAPTER IV.

MEASUREMENTS OF THE UNDERFLOW AT THE NARROWS OF THE RIO HONDO AND SAN GABRIEL RIVER, CALIFORNIA.

The following underflow measurements were made during the summer of 1902 at the narrows of the Rio Hondo and the San Gabriel River, about 10 miles east of Los Angeles, Cal. The ultimate source of the streams referred to is found in the San Gabriel Mountains, a range which runs nearly east and west about 40 or 50 miles from the southern coast line of California. The main portion of the mountain drainage which supplies this particular stream is collected into one of the large canyons of the range, known as the San Gabriel Canyon. Like that of other streams that originate in these mountains, the water is not carried above ground much farther than the mouth of the canyon, except in times of extreme flood. The ordinary flow of the river sinks into an enormous alluvial delta cone of gravel and mountain débris, and passes underground in a broad, gently sloping valley until it is interrupted by a line of shale hills about 10 miles south of the mountain range. This line of hills acts as a dam to the underground waters, except for a break about 2 miles in width, where the drainage of the valley escapes to the sea. This break constitutes the so-called "Narrows" of the river. In consequence of the narrow outlet a large quantity of the ground water is brought to the surface, first showing itself about 2 miles above the narrows, and increasing in volume as it enters the contracted part of the pass. At the present time the surface waters appear as two distinct streams, the Rio Hondo on the west side and the San Gabriel River on the east side of the narrows.

In August, 1900, the flow of the Hondo at Old Mission bridge was 23 second-feet. The flow of the San Gabriel was somewhat larger. The Whitney electrolytic bridge indicates that the ground water and surface waters are substantially identical in character, containing 15 to 25 parts per 100,000 total solids.

The measurements of the rate of underflow were made by the electrical method as previously described in this paper. At the time of making these measurements the recording instruments had not been perfected for field use, so that all of the work was done with the hand apparatus. The test wells used were 2-inch drive wells, with 42-inch points and 48-inch well-point extensions. The wells were arranged as usual, one upstream, designed to receive the electrolyte, and the others downstream, 2 feet apart on an arc of a circle of 4-foot radius. In most instances the electrolyte moving with the ground water would show itself at but one of the downstream wells, but in one or two cases it reached two of the downstream wells, and in a few cases the first setting of the wells did not correspond to the actual direction of the motion, so that the lower wells were not touched at all by the dissolved electrolyte.

Measurements were made at four stations located within the narrows of the rivers named. The first and second stations were located under a wagon bridge over Rio Hondo near the Old Mission. Two groups of wells were driven, and the location and direction of these wells with reference to the bridge are shown in fig. 31. The electrical current was observed separately for a circuit between the casing of the upstream well and the casing of each of the downstream wells, and also for the circuit between the casing of each downstream well and the brass rod electrode contained within it, a direct-reading ammeter being used. The velocity at the first station was 3.8 feet per diem. The direction of flow departed slightly from the direction of the surface river, being 10 degrees west of south.

At the second station the electrolyte showed itself at both of the downstream wells, being stronger, however, in well F. The velocity here was 6.6 feet a day. Points of special interest are the several steps in which the ampere curves rise, as shown on the electrode circuits for both wells E and F. These indicate different velocities of ground water in the different strata penetrated by the wells. The well points and well-point extensions being covered with new bright brass gauze in these first tests, the different porous strata registered themselves on the brass gauze by blackened bands caused by the corroding influence of the electrolyte. In the present case there were three distinct zones marked off on the wells, of about 24, 20, and 8 inches each. The velocities in these strata undoubtedly differed from one another, and hence caused the steps in the ampere curve. At both stations 1 and 2 the ground water was artesian in character, rising in the wells about an inch for each additional foot increase in depth. The wells were 16 feet deep and showed about 15 inches of artesian head above the water in the flowing stream.

The third station was established on the San Gabriel River just below the wagon bridge on the Whittier road. A special point of interest at this location is the fact that the river totally disappears in its gravel bed a few rods below this bridge. We hoped to secure some facts concerning the direction and velocity of the disappearing water. A double row of wells was driven across the river bed in three groups about 33 feet apart, as shown in fig. 32. All of the wells, except a group near the left bank, pumped very poorly and were evidently in very tight material. The group of wells near the left

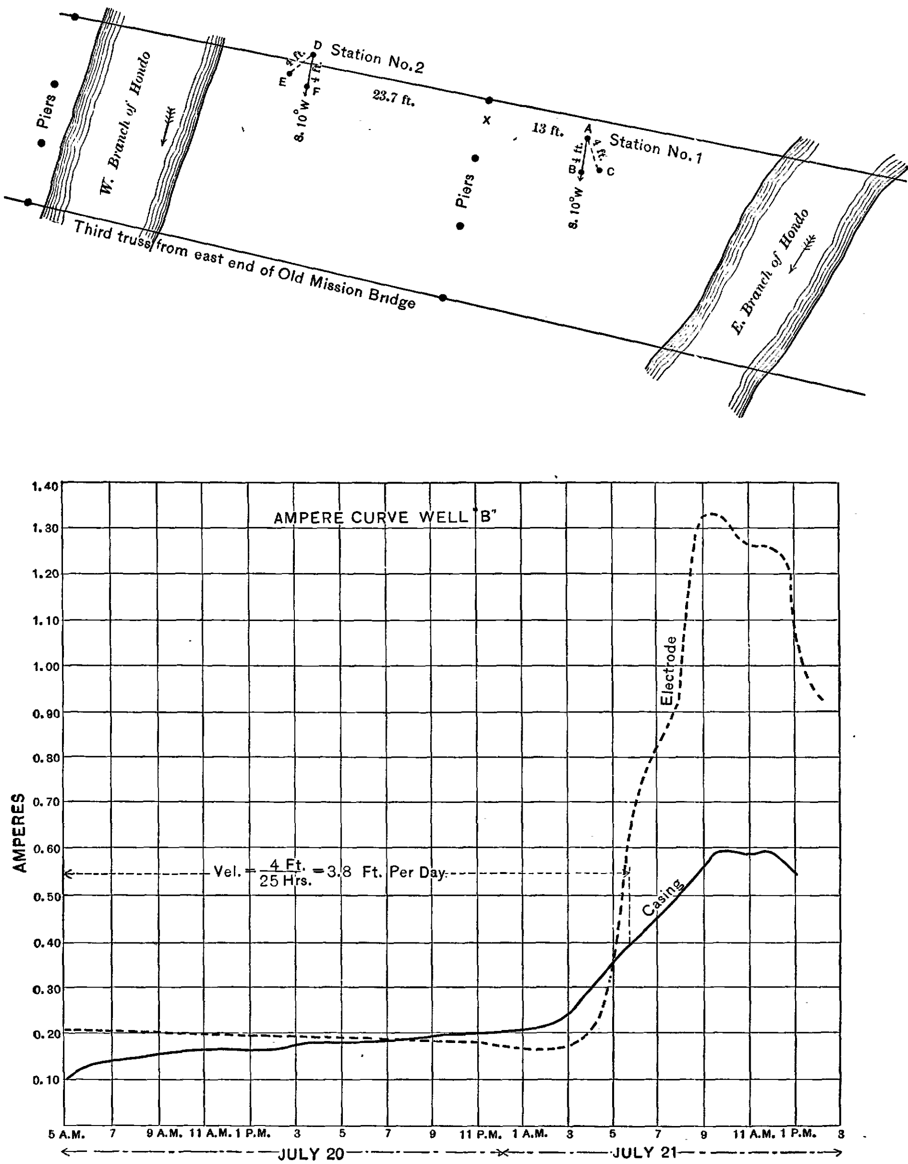
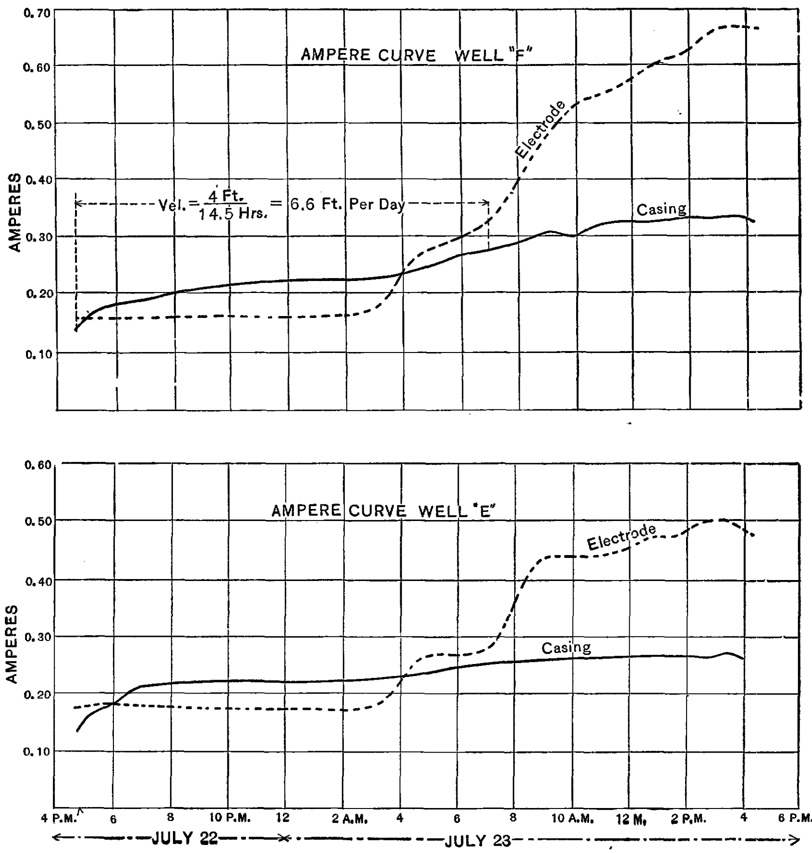


FIG. 31.—Diagrams showing the velocity and direction of flow of the

bank consisted of one upstream well, E, and two downstream wells, F and G. These wells evidently penetrated two different strata of water, as a velocity of 48 feet a day was observed between E and F, while a second result was strongly developed, indicating a velocity between E and G of 4.8 feet a day. This latter rate was due to the lower stratum of water, whose direction of motion crossed at an angle of 35° that of the upper current of disappearing river water. Further observations at this point were rendered impossible by the breaking of a dam some distance above the station, which completely flooded the wells after the above observations had been made.

The fourth station was established in a walnut grove on Temple's ranch, near the main road from El Monte to Downey. This location is about half way between the two bluffs of the narrows. The group consisted of four wells, and a velocity was found to be rather low, 14 inches a day. The direction of flow was due south.

The fifth station was on the bank of the San Gabriel River, just



underground water at the narrows of the Rio Hondo, stations 1 and 2.

above the head works of the Ranchita and Los Nietos ditches. The velocity determined was 5.3 feet a day, in a direction due south, making an angle, however, of about 45° with the direction of the surface stream at the same point. The direction of flow and ampere curve are shown in fig. 4.

The cross section of the alluvial deposits at the narrows of the Hondo and the San Gabriel is about 10,000 feet wide and probably does not exceed 600 feet in depth. If we assume that the porosity of the underflow gravel is 33 per cent and that the average velocity of the ground water is 10 feet a day, the resulting estimate of the amount of water which passes underground through the narrows is 230 second-feet, or nearly four times the flow of the surface streams. This is undoubtedly a maximum estimate, as there is no indication that the average velocity is as high as 10 feet a day. Four feet a day may be assumed as a fair minimum value of the average velocity. This would correspond to a total underflow of 92 second-feet.

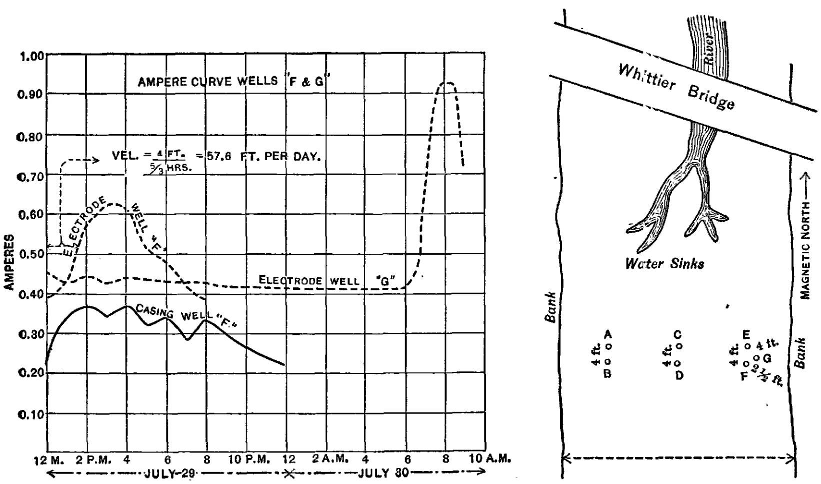


FIG. 32.—Diagram of velocity and direction of flow of underground water at the narrows of the San Gabriel River; station 3.

The measurements established the existence of a distinct underflow of moderate velocity through the alluvial deposits of the narrows. In low stages of the surface streams the underflow probably represents a drainage from the upper valley in excess of that discharged by the surface streams. The substantial identity of the water of the underflow and the water of the surface streams is proved by tests with the Whitney bridge, so that we may conclude that the original mountain stream appears at the narrows as a composite river, consisting of surface streams bordering both the east and the west bluffs of the narrows, together with a very wide and deep but slowly moving underflow occupying the entire major trough of the valley.

CHAPTER V.

MEASUREMENTS OF THE UNDERFLOW AT THE NARROWS OF THE MOHAVE RIVER NEAR VICTORVILLE, CAL.

CONDITIONS AT THE STATION.

The Mohave River rises on the slope of the Sierra Madre Mountains in San Bernardino County, Cal., its headwaters flowing from elevations of 5,000 to 8,000 feet. After following a general northerly course the stream disappears in the Mohave Desert a short distance below Barstow, Cal. After leaving its mountainous canyon the stream gradually loses water, and for a large portion of the summer its bed is dry for a greater part of its course on the plains. At a point about 16 miles north of its source the river passes through a narrow gorge called the "Narrows" of the river. The granite uplift which forms this gorge constitutes a dam that raises the underflow to the surface, so that within an area that extends from a point a mile and a half above the gorge to a point a considerably greater distance below the gorge the stream is of perennial flow. A view of the narrows of the river is shown in Pl. IX. This gorge is just south of the village of Victorville, Cal., a station on the Santa Fe Railway. The place had been under investigation as a possible site for a dam by the United States Geological Survey during the season of 1899 and previously. Reports on this subject will be found in the Eighteenth Annual Report, United States Geological Survey, Part IV, page 708, and the Twenty-first Annual Report, United States Geological Survey, Part IV, page 471. The permanent dry-season flow of the river at the gorge varies from about 30 to 60 second-feet. On August 15, 1902, the discharge, as measured by J. B. Lippincott, was 33 second-feet. Soundings have been made to bed rock at three different lines across the narrow part of the gorge by the United States Geological Survey. The positions of these cross sections are shown in fig. 33. The river-gage rod of the United States Geological Survey is located on the right bank of the river at the end of line 3. This line was selected as the location for the underflow measurements. The maximum depth to bed rock at this point is 46 feet, as is shown in the approximate cross section given in fig. 34. The material filling the gorge and constituting the bed of it is a coarse angular granite débris of a size somewhat larger than buckwheat. Mechanical analysis of the gravel filling the gorge is given in Table VI (p. 30). Determinations of the effective size of the gravel by King's aspirator showed a mean diameter of 0.72 mm. The samples of gravel were taken from the

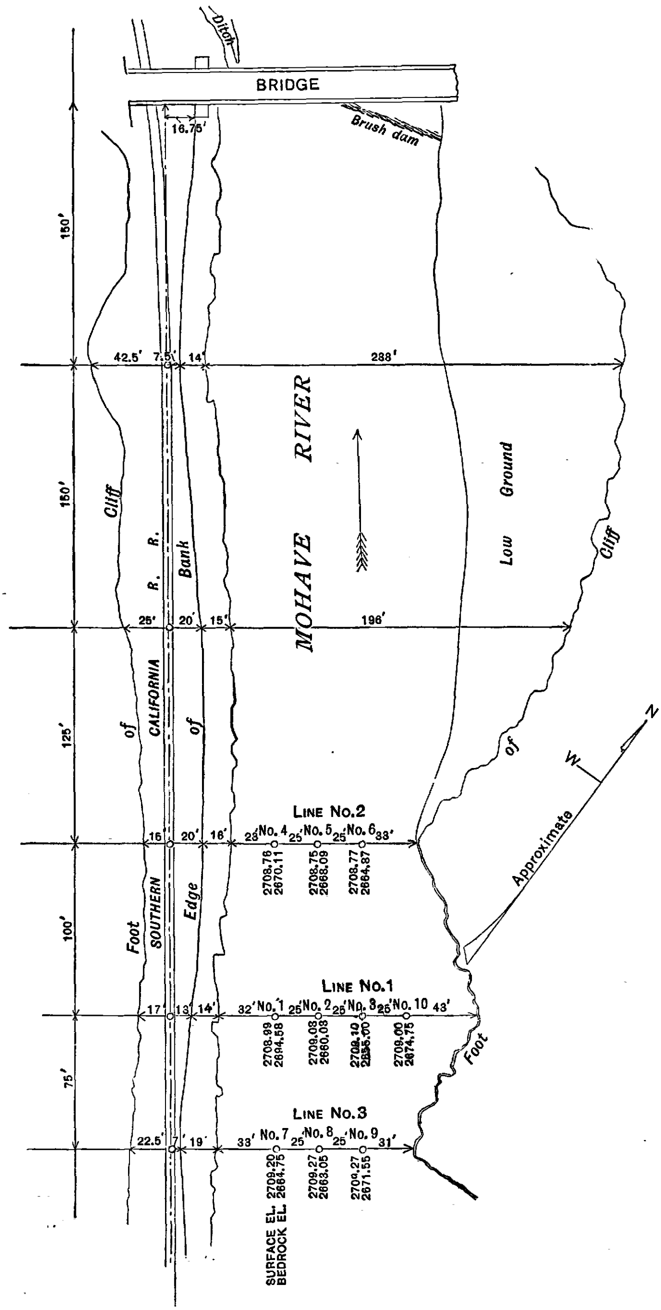
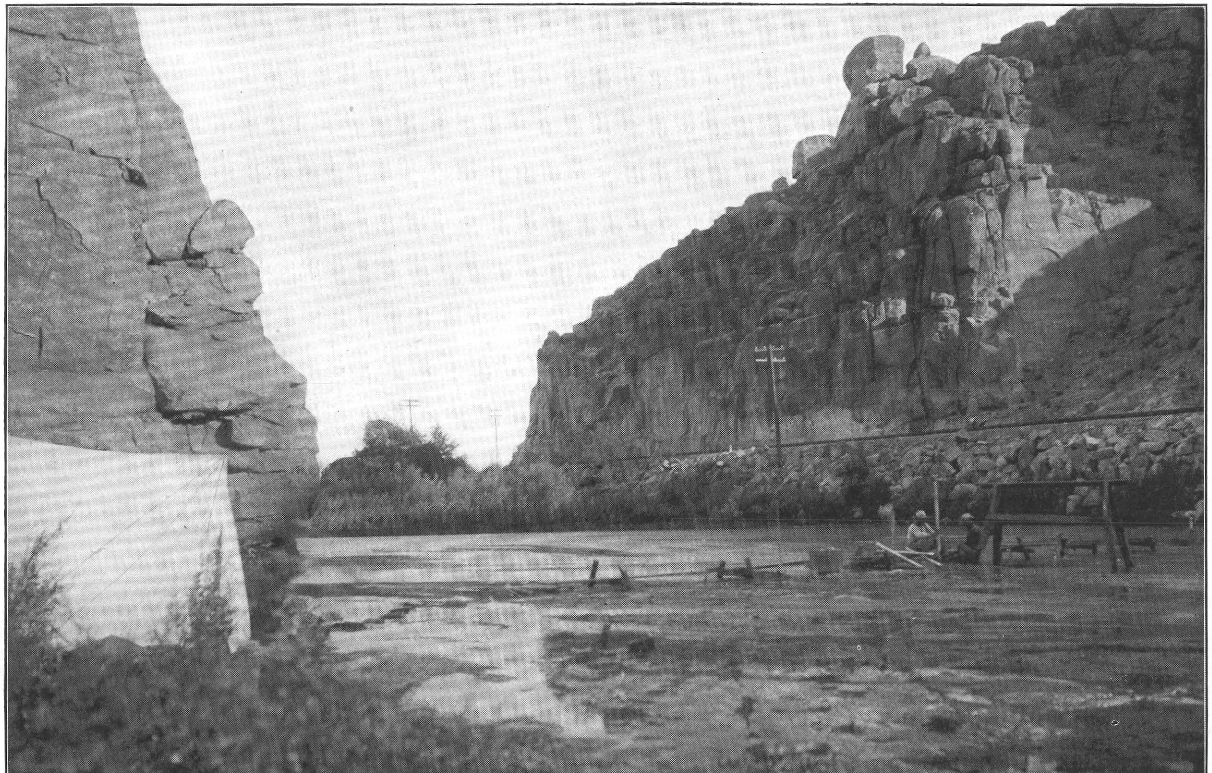


FIG. 33.—Map of the narrows of the Mohave River above Victorville, Cal., showing three lines of test borings made to bed rock by the United States Geological Survey in 1900. Line 3 of these borings coincides with the cross section at which the underflow measurements were made.

surface material. High velocities of the underflow determined at certain depths indicate that there are some streaks of coarser material.



NARROWS OF MOHAVE RIVER.

At time of the underflow investigation; instruments are located in tent at side.

DESCRIPTION OF EXPERIMENTS.

The site selected for the measurement of the underflow at the upper narrows of the river was in a line extending across the river at right angles to its main course, as shown in the plan given in fig. 33. The water in the river at this point hardly exceeded a foot in depth, but the water spread over the greater portion of the space between the banks, necessitating the construction of a small foot bridge, shown in

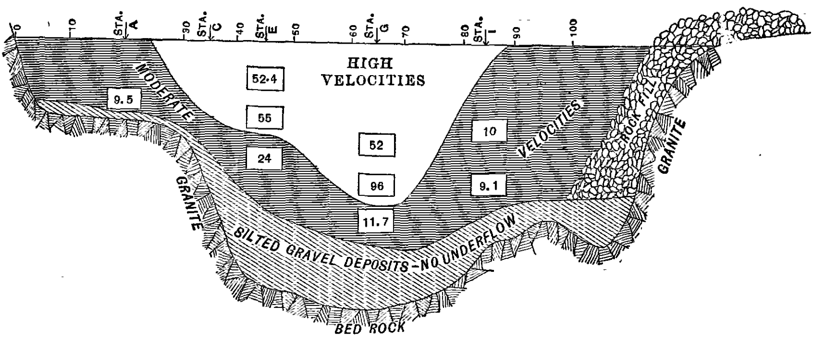


FIG. 34.—Cross section of the narrows of the Mohave River at which the underflow was measured. This line of cross section corresponds to line 3 in the preceding diagram. The rectangles inclosing the figures represent the position and depth at which the underflow was measured. The figures inclosed in the rectangles represent the velocity in feet per day at that point in the cross section.

Pl. X. Another view, Pl. XI, illustrates the method used in putting down the test wells. The double row of test wells, A, B, C, D, E, F, G, H, I, were driven across the river at this point as located on the plan shown in fig. 35. The gorge at this place is only 120 feet wide, and it was at first thought unnecessary to drive more than a single downstream well for each measurement, as it was believed that the

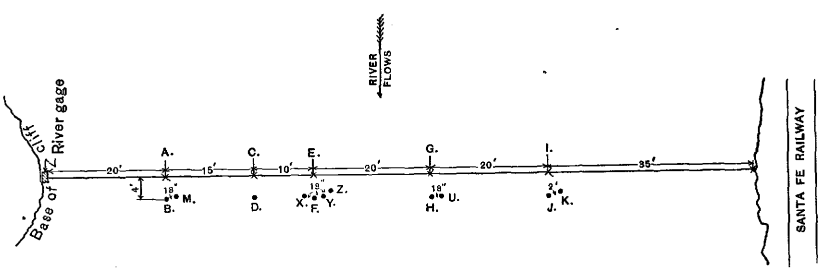


FIG. 35.—This plan shows the position of the various test wells used in the underflow investigation. The principal line of test wells corresponds to line 3 of fig. 33.

underflow must move through the gorge in a very direct course. It was determined, however, after first salting the upstream wells, that the ground waters must be moving through the gorge at this point at a slightly different direction from that of the surface waters, as absolutely no results could be obtained from the wells as first arranged. Accordingly, directional wells M, X, Y, Z, U, K were driven as

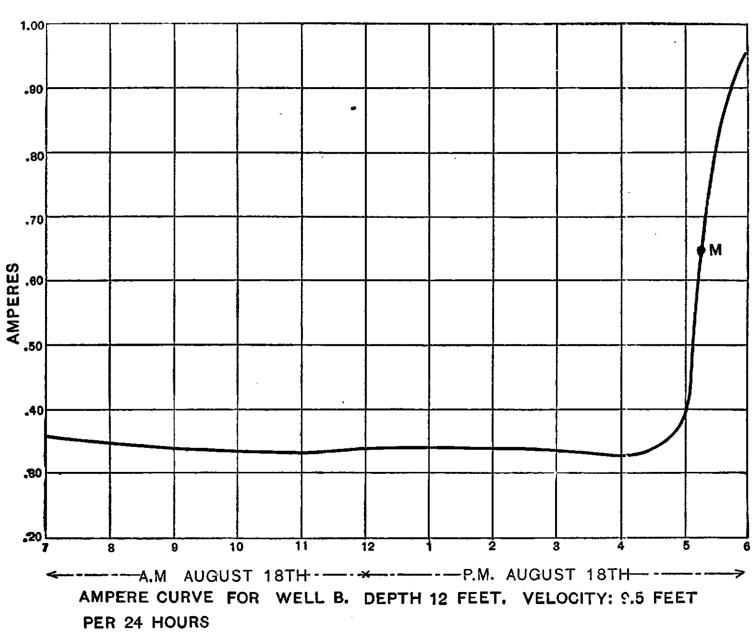


FIG. 36.—Diagram showing the velocity of underflow at narrows of Mohave River, Station A.

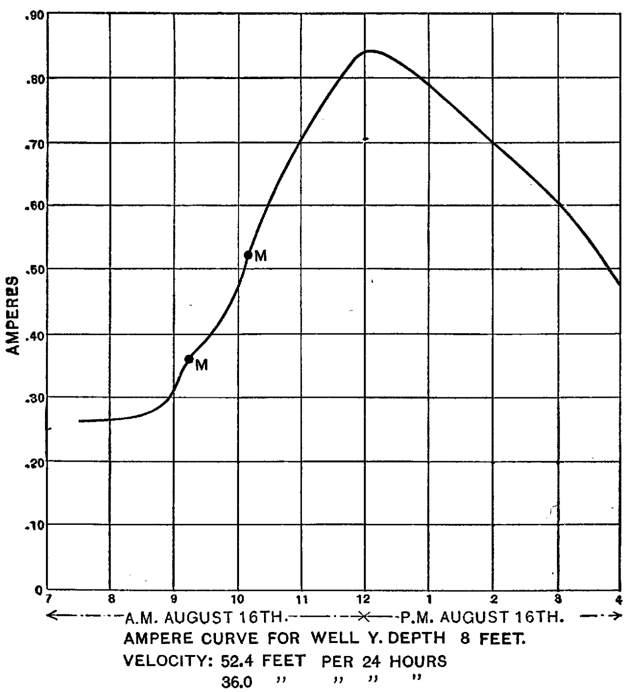
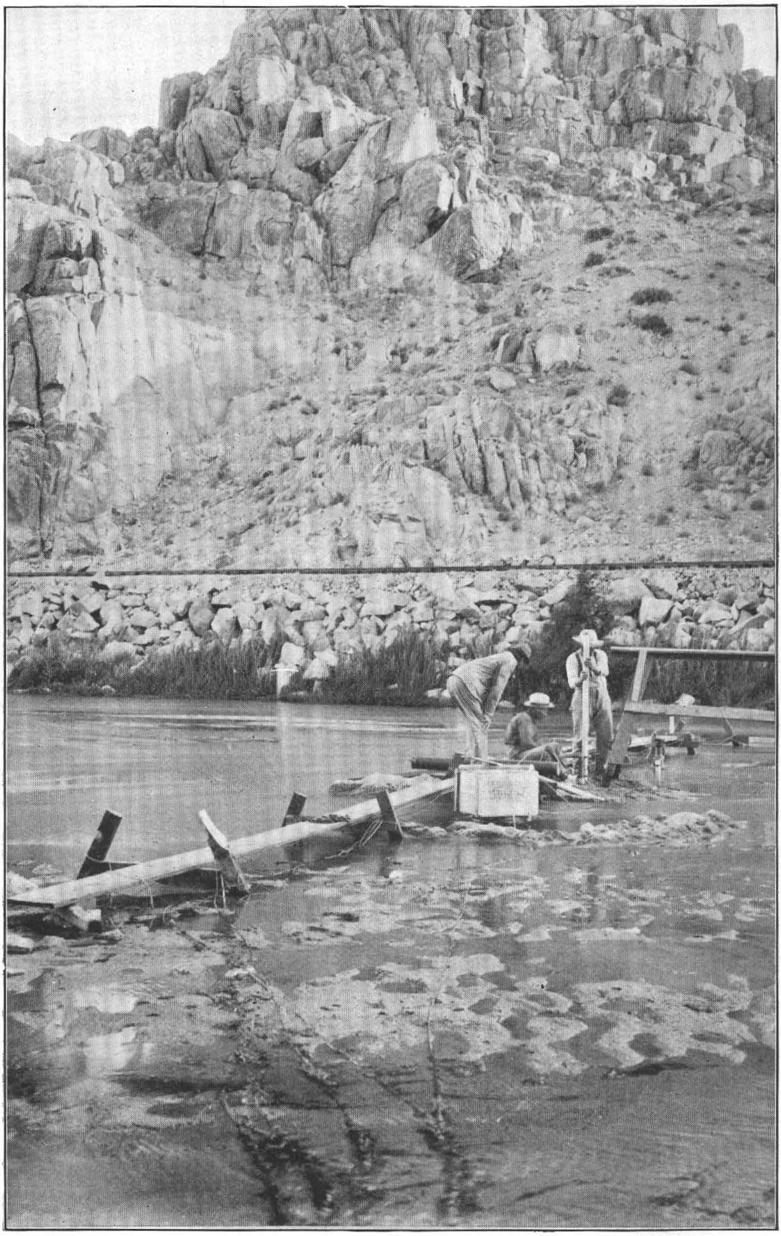
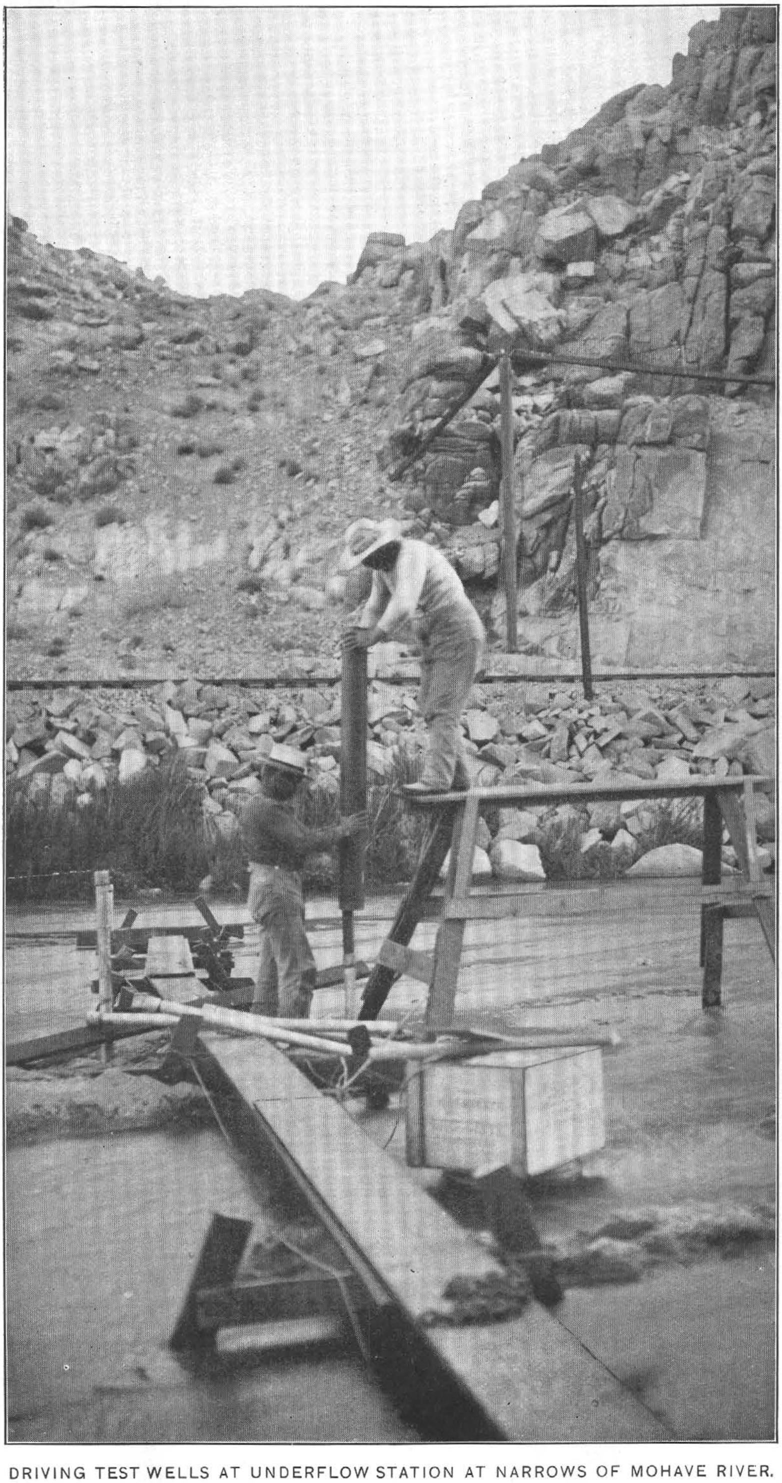


FIG. 37.—Diagram showing velocity of underflow at narrows of Mohave River, station E.



DRIVING WELL G AT UNDERFLOW STATION AT NARROWS OF MOHAVE RIVER.

Showing shallow character of river at this place during dry season.



DRIVING TEST WELLS AT UNDERFLOW STATION AT NARROWS OF MOHAVE RIVER.

The wooden ram used weighed about 60 pounds.

shown in fig. 35. In order to determine whether a variation in the direction was the cause of the failure to measure the underflow, some preliminary experiments were carried out at the position lettered E, test wells X and Y being driven 18 inches from the well F. After these wells were put in place, the well E was salted. This test turned out to be unsatisfactory also, but a slight rise in the electric current in well Y was noticed, which encouraged the belief that the direction

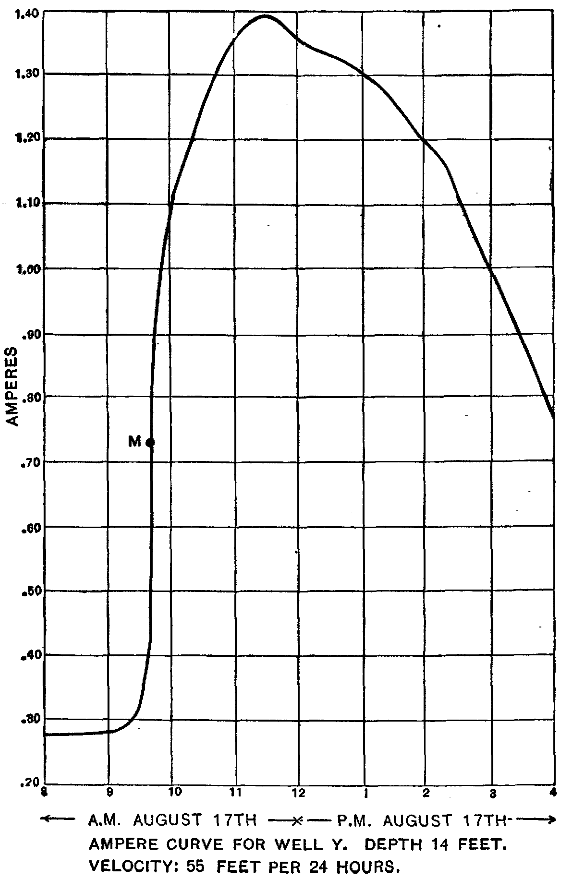


FIG. 38.—Diagram showing the velocity of underflow at narrows of Mohave River, station E.

of flow had been missed in the first test. It was surmised that the ground water might be moving so rapidly as not to give time for the electrolyte to spread sufficiently, and hence was able to pass between two downstream wells 18 inches apart. It was also possible that the direction of the flow was to the left of the new well Y. In order to provide for this contingency, the well X was pulled and redriven in the position indicated by the letter Z, 18 inches from Y.

If it were true that the motion of the ground water of the underflow might be so great that the electrolyte used in well E would not have time to spread sufficiently so as to be certain of coming in contact with one of two downstream wells 18 inches apart, it would be necessary to modify the method of salting E so as to cause, if possible, a wider path to be traversed by the electrolyte. This was finally accomplished by introducing into the well E, along with the dry sal ammoniac, about 10 per cent caustic soda, or common soda lye. This, of course, brought about a reaction between the two salts in solution, ammonia

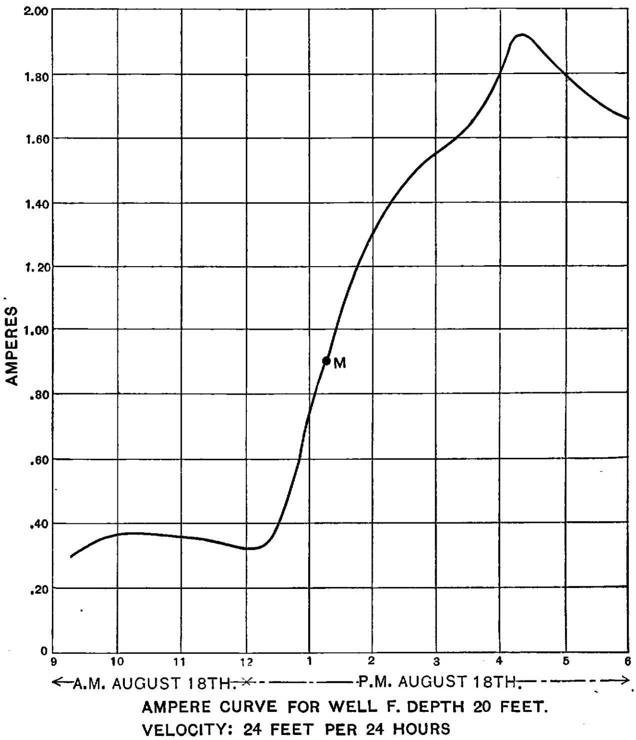


FIG. 39.—Diagram showing the velocity of underflow at narrows of Mohave River, station E.

gas being liberated. It was believed that the liberation of the gas would cause the mixed chemicals to spread more rapidly in the ground waters. This later seemed to be the case, for, carrying out the experiment in this way, it was found that the electrolyte reached well Y, where it showed itself very strongly and just grazed well F. The electrode curve for well Y is shown in fig. 40, which indicated a velocity of ground water of about 52.4 feet for twenty-four hours. This velocity was several times greater than any previously determined, which accounted for the difficulties encountered in interpreting the first failure and in getting the direction of flow. After this experience all of the upstream wells were salted with the same mixture of sal ammoniac and caustic soda, and no further difficulties were experienced in getting the velocity and direction of flow. At the various stations, A, E, G, I, determinations of velocity were made at various depths, as is shown by numbers inclosed in rectangular lines at appropriate points in the cross section, fig. 34. The pipe casing of well D

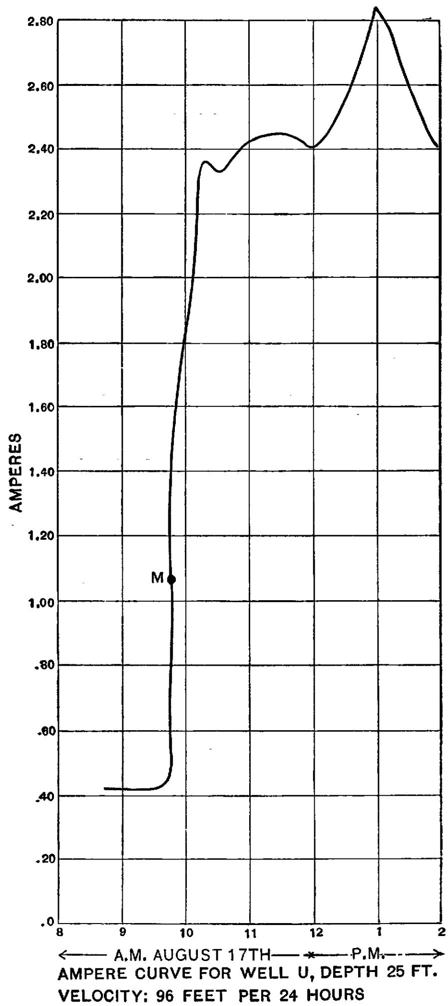


FIG. 40.—Diagram showing velocity of underflow at narrows of Mohave River, station G.

was found to be broken below the ground, and station C was on that account not used.

At depths below the surface not exceeding 25 or 30 feet the gravel of the gorge is completely silted with fine material deposited by the river and is, of course, impervious. At stations E, G, and I, after the well points were driven a few feet below the point at which the deepest measurements were made the points were completely embedded

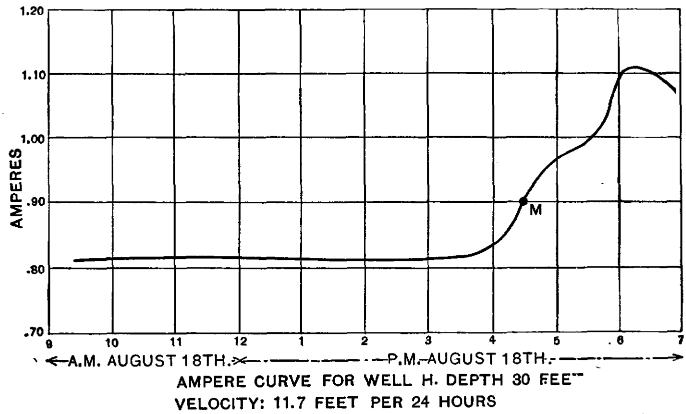


FIG. 41.—Diagram showing the velocity of underflow at the narrows of Mohave River, station G.

in the silted gravel and no water could be drawn from the wells with an ordinary pump. It was therefore very plain that the underflow of

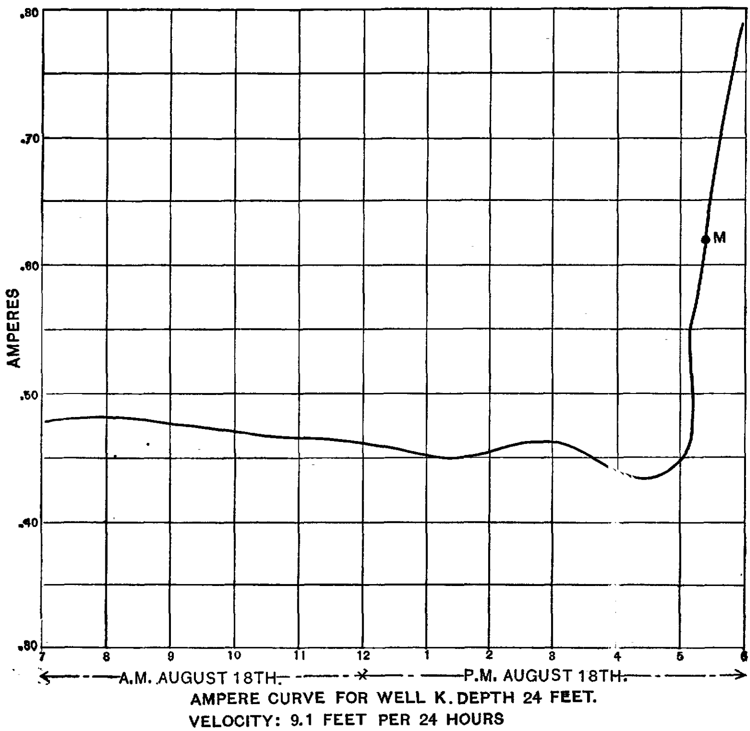


FIG. 42.—Diagram showing the velocity of underflow at the narrows of Mohave River, station I.

the gorge was confined to a depth not exceeding about 30 feet. All of the velocities determined in the clear gravel of the gorge ran very high, three of them exceeding a velocity of 50 feet for twenty-four hours. Taking Schuyler's figures for the area of the cross section of the gorge, 4,160 square feet, and assuming a mean velocity of ground water in the entire section of 50 feet for twenty-four hours, and estimating the porosity of the gravel at 33⅓ per cent, the total underflow in the gorge will be found to be less than 1 second-foot. This must be understood to be a maximum estimate. The underflow probably does not exceed 300,000 gallons for twenty-four hours. The gradient of the water plane at and above the gorge is almost exactly 20 feet to the mile.

The reproductions of photographs shown herewith illustrate the method of driving the wells used and show the small footbridge and the test wells that were put in place during the investigation. The tent appearing at the left of the cut contained the instruments from which wires were led to the various test wells (Pl. IX).

QUALITY OF THE WATER.

The quality of the water in the surface stream and in the underflow of the Mohave River at the narrows was determined by tests with the Whitney electrolytic bridge, and the amount of chlorine in the water was determined by titration. The water is remarkable as a desert water for its unusual softness, being very much softer than the usual water found in southern California, as at Los Angeles and neighboring points. This softness is undoubtedly due to the insoluble character of the granitic deposit through which the water flows after leaving its mountain source. It should be remembered that both the surface water in the stream and the underground waters at the location of the narrows of the Mohave River has been flowing in a ground-water stream for 10 or 12 miles of its course. As all of this water reaches the narrows by passing underground for a considerable distance, the results of the few tests made, given herewith in Table X, are of considerable interest.

TABLE X.—*Quality of the water in the river and in test wells at the narrows of the Mohave River.*

[Total solids were determined with the Whitney electrolytic bridge.]

Well.	Date (August, 1902).	Depth in feet.	Temperature, ° F.	Resistance in ohms.	Chlorine, pts. per 100,000.	Total solids, pts. per 100,000.
A	10	8	72	1,125	....	14
B	19	12	67	1,150	2.51	15
C	10	16	71	1,275	....	12
F	10	7	72	1,150	1.77	13
G	10	20	70	1,300	....	12
H	10	20	70	1,300	1.25	12
H	15	25	67	1,460	....	11
J	10	14	72	1,250	1.77	12
Z	15	8	72	1,200	....	12.5
River water	(a)	....	67	1,200	2.01	13.5

a Aug. 10, 7 a. m.

It will be noticed that the temperature of the water from the deeper wells was somewhat lower than that near the surface, and the deeper water also appeared to be somewhat softer. The temperature of the ground waters remained nearly constant at the various depths, but the stream water showed very marked fluctuations in temperature, as would be expected in a shallow desert stream. The temperature of the stream water taken in the morning was always low. The temperature at 7 a. m. August 10 was 67° F., which was the usual morning temperature. During the day the temperature would rise, the extent of the rise depending upon the character of the day, temperatures as high as 82° being not uncommon. On cloudy days the temperature remained low. It will be noted from the table that the temperature of the surface stream was lower than the temperature of the upper underflow waters at night, and warmer than these waters during the daytime. This is already accounted for by the fact that the surface waters rise from the underflow but a mile or so above the narrows, the surface stream, of course, representing merely the surplus of underflow waters as the ground water approaches the narrows.

CHAPTER VI.

MEASUREMENTS OF THE RATE OF UNDERFLOW ON LONG ISLAND, NEW YORK.

CONDITIONS EXISTING AT THE STATIONS.

The following determinations of ground-water velocities were made along the south side of Long Island, between the villages of Freeport and Massapequa. These places are located about 6 miles apart, on the Montauk division of the Long Island Railroad, which between these points runs nearly east and west and is about 1 mile north of the edge of the extensive salt marshes which border the Atlantic Ocean.

Freeport is about 24 miles from Brooklyn Bridge, and Massapequa, 6 miles east of Freeport, is within 2 miles of the western line of Suffolk County.

Within the 6-mile stretch above mentioned the city of Brooklyn has five pumping stations, drawing water from extensive batteries of driven wells. The names of these stations, from the west, are: Agawam, Merrick, Matowa, Wantagh, and Massapequa. There is a brick conduit on the north side of the right of way of the Long Island Railroad, into which the water from the pumping station is discharged, carrying the water by gravity to a pumping station at Milburn, just west of Freeport, where an additional lift sends the water into the city of Brooklyn. The five driven-well plants above mentioned are used for auxiliary supply in the summer months, the period of use extending usually from July to December, but varying with the rainfall and other climatic conditions.

Within the 6 miles from Freeport to Massapequa the conduit crosses several small surface streams, four of which have been ponded and their waters gated into the conduit. These surface waters flow into the conduit the year round, the driven wells constituting the auxiliary supply.

The particular district under discussion was selected as the object of study because, in the first place, the region seemed typical of conditions on the southern side of the island, and, secondly, because the ground water was substantially in normal condition, owing to the fact that the driven-well plants had not been operated since the previous December. The purpose of this work was to determine the principal facts concerning the underground drainage of the island, so that a preliminary basis could be secured for an estimate of the amount of ground water available for municipal supply.

The determination of ground-water velocities was made at certain selected stations or localities, following, in general, an east-west line. These stations were confined, for the most part, to the highways or other public lands. This restriction did not interfere materially with the selection of the best sites for the work. One set of stations was placed south of the railroad and just north of the line of wells of the driven-well stations, it being considered of importance to measure velocities in the immediate neighborhood of the pumping plants both before and after pumping had commenced. Other stations were located north of the railroad and conduit, out of range of an extensive influence of the pumping plants.

The 6-mile line from Freeport to Massapequa is, as has been stated, about 1 mile distant from the edge of the tidal marshes bordering the Atlantic Ocean. North of this line for a distance of 9 or 10 miles the natural surface drainage of the land is toward the south, the slope for nearly 8 miles of the distance being very uniform and in amount almost exactly 15 feet to the mile. This drainage plain is not only very flat and unbroken, but the surface conditions are exceedingly favorable for the absorption of a large percentage of the rainfall. The soil for the most part is coarse and sandy and very porous. The slope of the water plain is somewhat less than that of the surface of the land, being approximately 10 or 12 feet to the mile. The underground drainage is in general toward the south, the main east-west underground watershed probably coinciding within a mile or two with the surface watershed. The average rainfall is about 44 inches, a very large portion of which enters the ground.

In the localities where the test wells were bored the material was, for the first 30 to 40 feet, yellow sand and gravel, quite clean and uniform, but growing finer with the depth. The first 20 feet below the water plane seemed in every case to be of high transmission capacity, and the material below this level was usually of increasing fineness, finally changing into a fine, dark-colored, micaceous sand. At a depth of 40 to 60 feet a compact layer of clayey and bog-like material was often met, and in driving the test wells into and through this layer the water rose continuously in the wells until a marked artesian head was developed. Immediately below this compact layer good sands were again encountered.

In the report on New York's water supply made by John R. Freeman in the year 1900, it is stated as probable that this layer of clayey material referred to above is distributed as a wide and practically unbroken sheet lying 40 to 60 feet beneath the surface of the south-sloping drainage plain of the island.

One of the objects of the measurement for ground-water velocities was to determine whether or not there was a considerable southerly movement to this water in the sands and gravels above the supposed clay sheet, and to determine the order of magnitude of such a movement if it existed. Whenever there exists in any drainage area a body of ground water which does not escape into the beds of surface streams as seepage water, but continues a seaward course through the sands and gravels quite independent of the surface streams, this moving sheet of water is known as the "underflow." One of the problems was, therefore, to determine whether or not a true underflow existed in this part of Long Island, and to learn something of its magnitude if it was found to exist. Another problem was to discover, if practicable, if any part of the underground drainage existed below the bed of clay; in other words, it was sought to determine whether the underground drainage consisted only of a surface zone of flow, or whether a deeper zone, or possibly several deeper zones of flow, were also present.

In respect to the first problem above mentioned—the existence of an underflow—there can be no question that a true underflow of considerable importance exists within a depth below the surface of 40 to 50 feet. In practically all of the stations established a good movement was found to exist, having a strong southerly component, and surprisingly free, in many cases, from the influence of neighboring surface streams. The velocity near the surface, 16 to 24 feet below the water plane, ran as high as 5 to 12 feet per day. At greater depths of 30 and 42 feet, respectively, the velocities were in each case about 15 inches per day. At station 9 the sand was so fine at a depth of 45 feet that it could not be prevented from running into the bottom of the well above the top of the well strainer so that the wells could not be used.

The existence of a deep zone of flow was also established. At station 15 clay was encountered at a depth of about 44 feet. These wells were driven to a depth of about 62 feet, when an artesian head of about 30 inches developed. A measurement was then made, the screens on the wells being just below the impervious layer. A velocity of 6 feet a day was found to exist in a direction about 10° west of south. The rate of flow at the same point just above the clay was only 18 inches a day, so that a true "deep zone of flow" undoubtedly exists at this point. This result, although very important, was not surprising, as it had already been well established by the work of Mr. A. C. Veatch and others, of the United States Geological Survey, that the clay layer, formerly supposed to be of wide expanse and quite unbroken, is, as a matter of fact, absent over considerable areas of the island, so that no reason exists why a part of the underground drainage should not exist below this impervious bed. It is strongly urged that further measurements below the clay be made. Measurements made some distance to the east of the present work, say, in Suffolk County, would be of especial value in indicating the areal extent of this deep zone of flow.

The surface zone of flow of the underground waters is probably divided into a number of drainage areas, although it is exceedingly doubtful if the underground drainage basins coincide very closely with the drainage areas of the surface streams. In general, the velocities seemed to increase from west to east, the lowest velocities, however, corresponding to a middle area, where the yellow gravels contained a quantity of fine, clay-like silt. The Wantagh area seemed to have the largest underflow. It would be exceedingly interesting to have series of measurements extending eastward into Suffolk County. By increasing somewhat the number of stations in

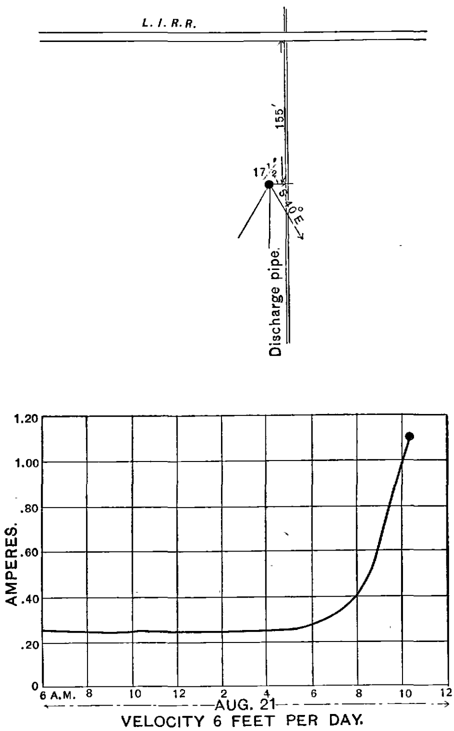


FIG. 43.—Diagram showing velocity and direction of the flow of underground water at Wantagh pumping station (station 2 X). Velocity, 6 feet a day, S. 40° E. This velocity was determined while pumps were drawing water from the wells of the driven well plant at a rate of 4,366,000 gallons per twenty-four hours. No velocity detected when not pumping.

the area already covered and comparing with results from drainage areas in Suffolk County, a comparative study of underground drainage systems would result which ought to have much value in planning sources of supply for Brooklyn.

The details of the measurements are given in the reports on individual stations contained in Table XI. The locations of the stations are shown in fig 57, and the curves of electrical current for the various stations are given in figs. 5 and 43 to 56.

TABLE XI.—*Underflow measurements on Long Island.*

Number of station.	Velocity of ground water; feet a day.	Direction.	Date, 1903.	Depth of wells in feet.	Kind of point.	No. of text figure.
1	5.5	S. 10° E	June 21	22	Perforated pipe.	5
2	2	....	June 24	22	Do.	....
2 X	6	S. 40° E	Aug. 21	22	Do.	43
3	2	....	June 26	22	Do.	....
4	2	....	June 27	22	Do.	....
5	6.4	S. 8° W	June 29	22	Common point.	44
5 X	5.4	S. 8° W	July 3, 4	22	Do.	44
5 Y	8.0	S. 22° E	Aug. 19	22	Do.	44
6	5.0	S. 8° W	July 1, 2	34	Do.	45
7	2.6	S	July 5, 6	20	Do.	46
8	0.0	S	July 9, 10, 11	21.6	Open-end point.	....
8	3.1	N. 34° W	July 14, 15, 16, 17.	21.6	Do.	47
10	2.6	S. 37° E	July 17, 18, 19, 20.	28	Common point.	48
11	0.0	....	July 27–Aug. 8.	22	Do.	....
12	1.07	S. 3° E	July 27–Aug. 1.	27	Open-end point.	49
13	96.	S	Aug. 3, 4	16	Common point.	53
13	6.9	S	Aug. 3, 4	16	Do.	53
14	9.3	S	Aug. 5, 6	17	Do.	50
15	1.53	S	Aug. 6, 7, 8, 9, 10.	42	Open-end point.	51
15 X	6.00	S. 15° W	Aug. 17, 18, 19.	62.5	Do.	52
16	0.	S. 30° E	Aug. 10, 11	16	Common point.	....
16 X	77	S. 60° E	Aug. 13, 14	16	Do.	54
16 X	11.6	S. 60° E	Aug. 13, 14	16	Do.	54
17	10.6	S. 30° W	Aug. 12, 13	20	Do.	55
18	1	S	Aug. 15–21	62	Open-end point.	....
21	21.3	S. 50° E	Aug. 18, 19	16.5	Common point.	56
22	5.6(?)	S. 30° E	Aug. 20, 21	16	Do.	....

INFLUENCE OF THE RAINFALL UPON THE RATE OF MOTION OF GROUND WATERS.

An excellent opportunity was presented at one of the stations for noting the influence of a heavy rain upon the velocity of ground waters.

At station 5, Agawam pumping station (see figs. 58 and 44), the upstream well, A, was salted at 9.45 a. m., June 29, 1903. Between

9 a. m. and 1 p. m. nearly 3 inches of rain fell, so that the heavy precipitation coincided with the early part of the ground-water measurements. The velocity found was 6.4 feet a day. On July 3 the experiment was repeated, there being no rain in the intervening time. The velocity found in the second trial was 5.3 feet a day. The change in velocity was undoubtedly due to the enormous rainfall during the first experiment. Part of the high velocity during the rain storm may be attributed to the low barometer accompanying the storm, but part

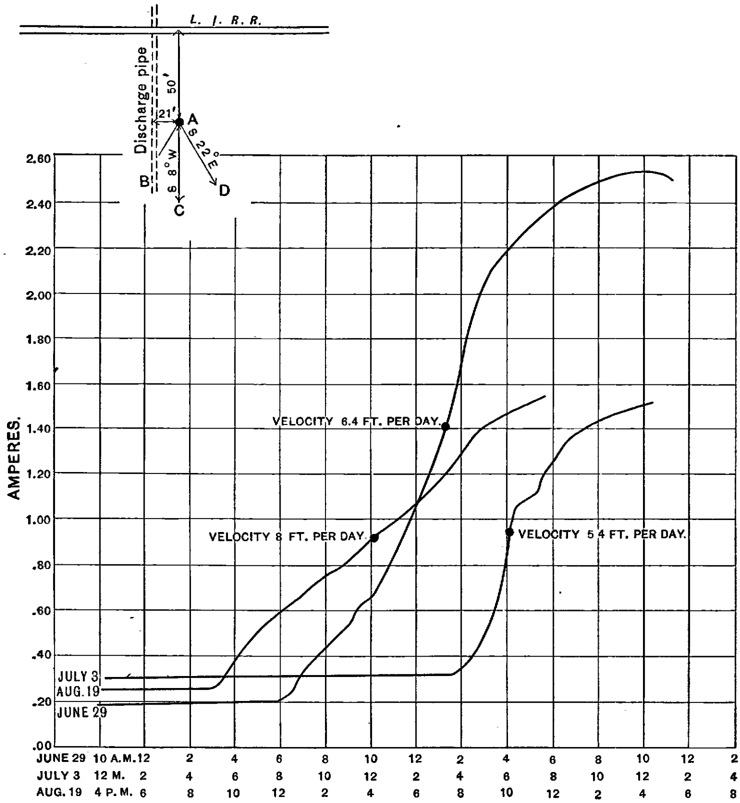


FIG. 44.—Diagram showing three determinations of velocity and direction of flow of underground water at Agawam pumping station (station 5). Normal velocity of ground water, 5.4 feet a day, S. 8° W. Velocity during heavy rain, 6.4 feet a day, S. 22° E. Velocity while pumping from the lines of driven wells, 8 feet a day, S. 22° E.

of it should be assigned to the increased head of ground-water pressure and to increased load carried by the soil, caused by the heavy rainfall upon the receiving area.

As is shown in another place[a] ground waters move very much as electricity is conducted in a good conductor, the most striking quality being an almost complete absence of true inertia in ground-water motions. The motion of a mass of ground water, even for the highest

[a] Nineteenth Ann. Rept. U. S. Geol. Survey, pt. 2, 1899, p. 331.

velocities, is so slow that the resistance to an accelerating force represented by the inertia of the ground water is almost nothing when compared with the component of the retarding force due to the capillary resistance in the small pores of the sand or gravel. Actual computation will show that in a uniform sand of diameter of grain of one-half millimeter, the ground water will reach within 1 per cent of its final maximum velocity due to a sudden application of pressure, or head, in approximately thirty seconds of time. This surprising result of the theory of ground-water motions receives a very striking verification in the increase in velocity noted during the rainstorm as described above.

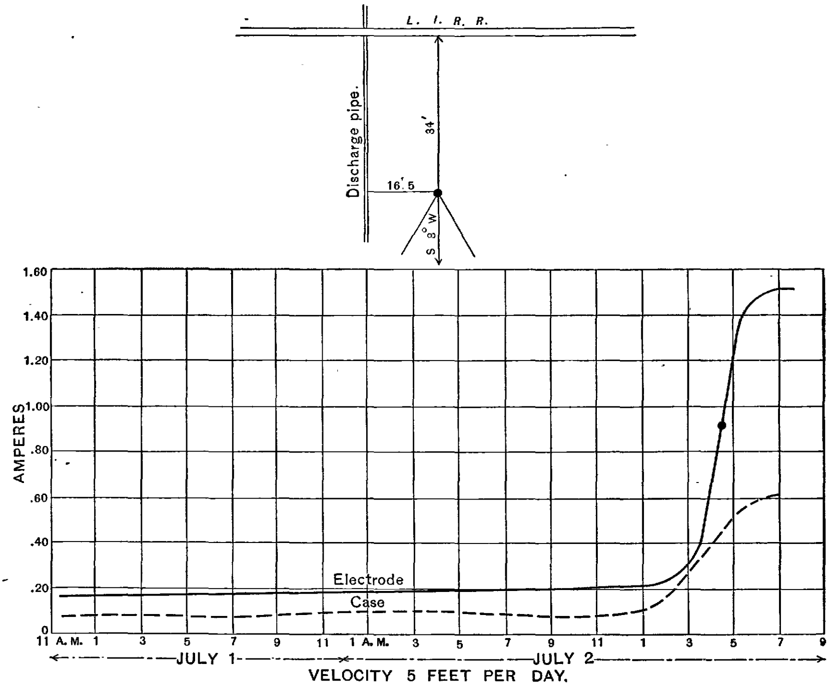


FIG. 45.—Diagram showing velocity and direction of flow of underground water at Agawam pumping station (station 6). This station is located near station 5, but wells were 12 feet deeper.

These results have important bearings on our knowledge of ground-water phenomena in the neighborhood of a well. They indicate that the velocity of the ground waters in the neighborhood of a well reaches a maximum value soon after pumping is commenced. The gradual formation of the cone of depression near the well shows that there must be a progressive augmentation of the initial velocity of the ground waters toward the well. Nevertheless, the rate of depression of the water table is so slow that the ground-water motion established soon after the pumping has begun is substantially the same as its value after prolonged pumping. These remarks have their most important bearing upon the phenomena of the mutual interference of wells. The interference of one well with the supply of a neighboring well is thus seen to come into existence almost instantaneously and need not wait for the establishment of a cone of depression of large area. The phenomenon of the cone of depression has much to do with the permanent supply of the well, but has slight bearing upon the proper spacing of the wells or the percentage of interference of one well with another.

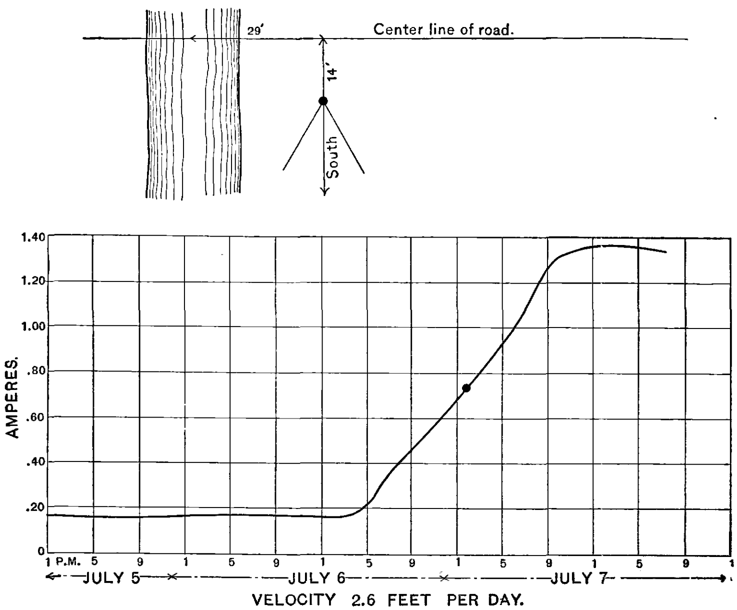


FIG. 46.—Diagram showing velocity and direction of flow of underground water at East Meadow Brook and Babylon Road (station 7). This station is a short distance above Agawam Pond, and the velocity is reduced by the flat water plane due to the presence of the pond. Velocity, 2.6 feet a day, south.

SEEPAGE WATERS FROM PONDS AND RESERVOIRS.

The work on Long Island afforded some unusually good opportunities of determining the rate of seepage below the impounding dams of some of the storage ponds which the Brooklyn Water Works has established north of the conduit line referred to in the opening pages of this chapter. The batteries of driven wells, which have been placed a few hundred feet south of nearly all of these ponds, were not used during the summer of 1903, as the heavy rains furnished a sufficient quantity of surface water, and the auxiliary supply from the wells was not drawn upon, as usual, during July and August. Station 5 is below the Agawam Pond and somewhat within the line of seepage from the pond, as can be seen by consulting fig. 58. The normal velocity of ground water at this station is 5.3 feet a day. At station 7, just north of the pond, the velocity was 2.6 feet a day. It seems clear that the natural velocity at these points, if the influence of the dam and pond were removed, would be about 4 feet a day. The velocity at station 6, located but a few feet from station 5, was 5 feet a day at a depth of 34 feet, as compared with 5.3 feet a day at a depth of 22 feet. The dam has the effect of making the water table nearly level in the immediate neighborhood of the pond, and also of greatly augmenting the slope of the water table for a short distance below the pond. The lower velocity above the pond and the higher velocity below the pond correspond

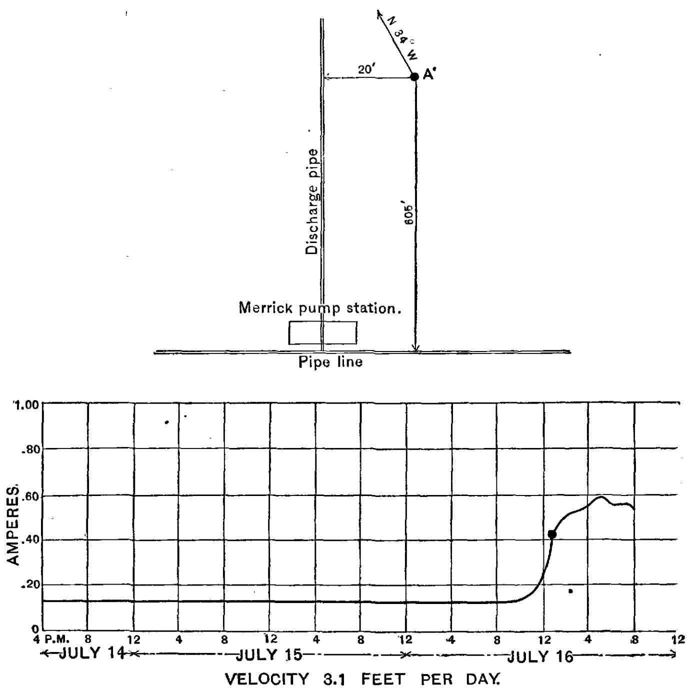


FIG. 47.—Diagram showing velocity and direction of flow of underground water near Merrick pumping station (station 8). The ground water at this point slopes in a northerly direction toward the brick conduit north of the Long Island Railroad. The velocity found was 3.1 feet a day, N. 34° W. The northerly flow at this point is undoubtedly due to seepage into the conduit.

with these facts. When there was no flow over the waste weir of the dam, the flow of the small stream which rises below the dam was measured at the bridge marked A in fig. 58. On July 10 this flow was 1.2 second-feet, practically all of which represented seepage water from the reservoir.

A flow of 1.2 second-feet or 103,000 cubic feet a day represents an amount of water flowing through a bed of sand 30 feet deep and 1,000 feet wide, at a velocity of 1 foot a day, the porosity of the sand supposedly being equal to one-third. The normal velocity of the ground water is augmented, as shown by the measurement quoted above, by somewhat more than 1 foot a day. The width of the lower end of this pond, or the length of the earthen dam, is about 1,400 feet, so, basing the estimate on this minimum length and on a minimum depth of 30 feet, an augmented velocity of 1 foot a day would give a minimum estimate of the seepage from the dam of 1.6 second-feet. Since 1.2 second-feet are known to actually come to the surface to feed the stream below the dam, it is evident that this estimate of seepage is a minimum. It seems evident that a considerable volume of

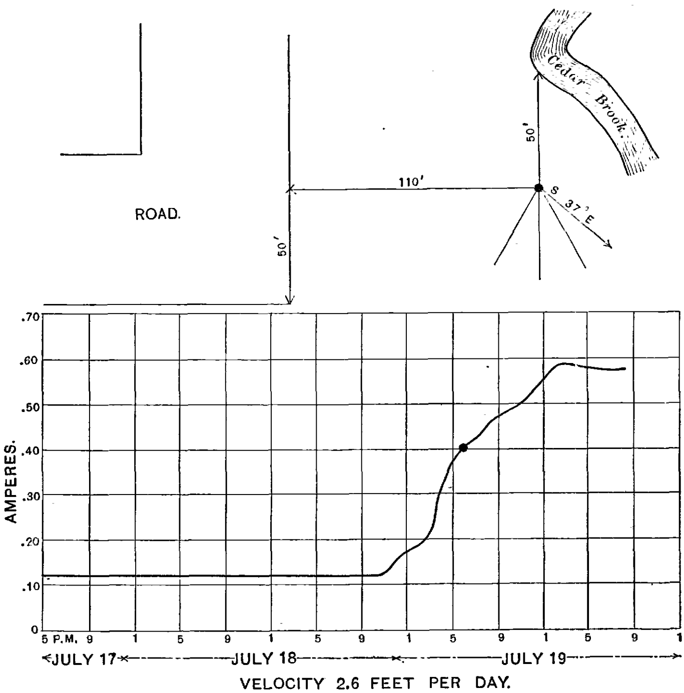


FIG. 48.—Diagram showing velocity and direction of flow of underground water at Cedar Brook (station 10). This station is above Cedar Brook Pond. The velocity is 2.6 feet a day, S. 37° E.

seepage water could be recovered by extending the line of driven wells of the Agawam pumping station to the east of the present terminus, a distance of 600 or 700 feet, without serious lowering of the water plane.

A test well was driven in the lower south end of Agawam Pond to a depth of 10 feet to determine the pressure gradient of ground water beneath the surface of the pond. The water in this test well stood about 1 foot lower than the water in the pond itself, showing a slope of the water plane or a hydraulic gradient of 7 feet to a mile.

The gradient of the water plane below the dam—that is, between the dam and station 5—was 17 feet to the mile, so that the velocities to be compared are:

Station 7 above pond; gradient, 7 feet per mile; velocity, 2.6 feet a day.
Station 5 below pond; gradient, 17 feet per mile; velocity, 5 feet a day.

These results check very favorably, especially when it be considered that the gradient above or north of station 7 was probably 10 or 12 feet per mile, which would make the effective gradient at this station somewhat greater than 7 feet per mile.

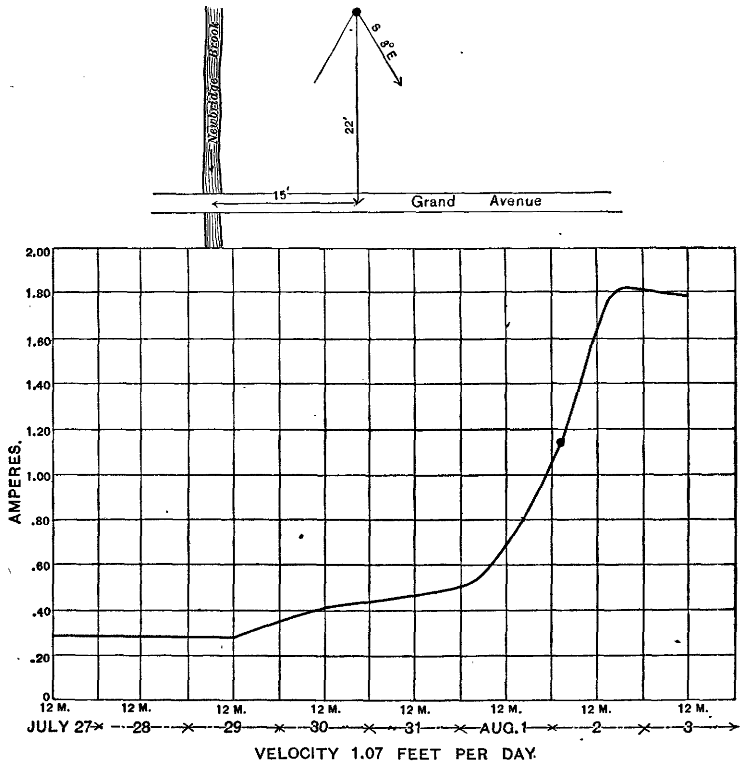


FIG. 49.—Diagram showing velocity and direction of the flow of underground water at Grand Avenue and Newbridge Brook (station 12). Velocity, 1.07 feet a day, S. 3° E. This is the lowest velocity determined on Long Island.

Very striking results were obtained below the dam at the Wantagh Pond, where measurements were undertaken to determine the rate of seepage. The dam of Wantagh Pond runs parallel to the right of way of the Long Island Railroad, about 75 feet north of the road, and has an extreme length of 500 or 600 feet. About 150 feet south of the railroad, downstream from the reservoir, the city of Brooklyn began in 1903 the construction of an infiltration gallery, consisting of a line of 36-inch double-strength tile, laid at a depth of 16 feet below the

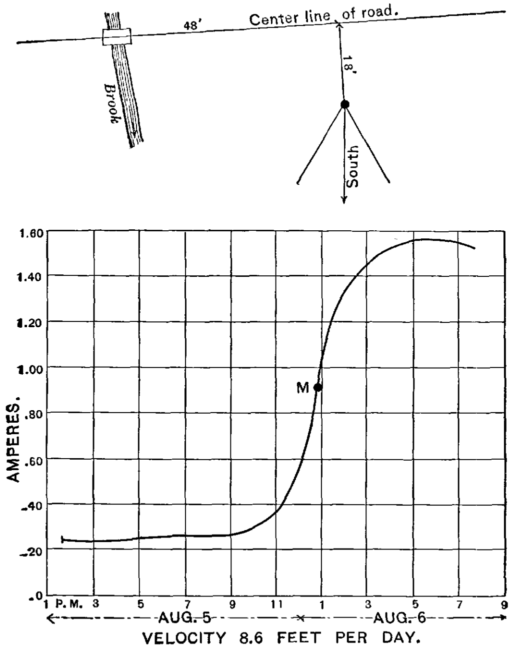


FIG. 50.—Diagram showing velocity and direction of flow of underground water at Bellevue road (station 14). Velocity, 8.6 feet a day, south.

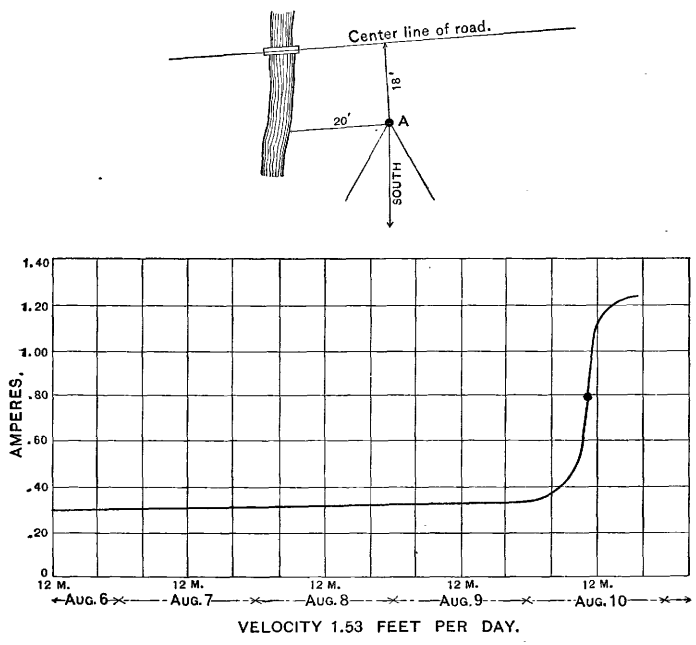


FIG. 51.—Diagram showing velocity and direction of the flow of underground water at Bellevue road (station 15). Velocity, 1.53 feet a day, south.

water plane. It is proposed to extend this gallery for a mile east and west from the Wantagh pumping station. Stations 13, 16, and 17 were established for the purpose of measuring the normal ground-water velocities at the depth (16 feet) of the proposed gallery. Two of these stations are immediately south of the pond and in the apparent direct line of seepage, while station 17 is located slightly east of the edge of the pond and, as seems evident from fig. 59, just on the edge of the main influence of seepage from the ponds. The seepage velocities at stations 13 and 16 turned out to be enormous, the velocity at station 13 being 96 feet a day, south, while at station 16 the velocity was 77 feet a day, the direction being about 30° east of south, the deflection being toward the neighboring stream, as shown in fig. 59. These

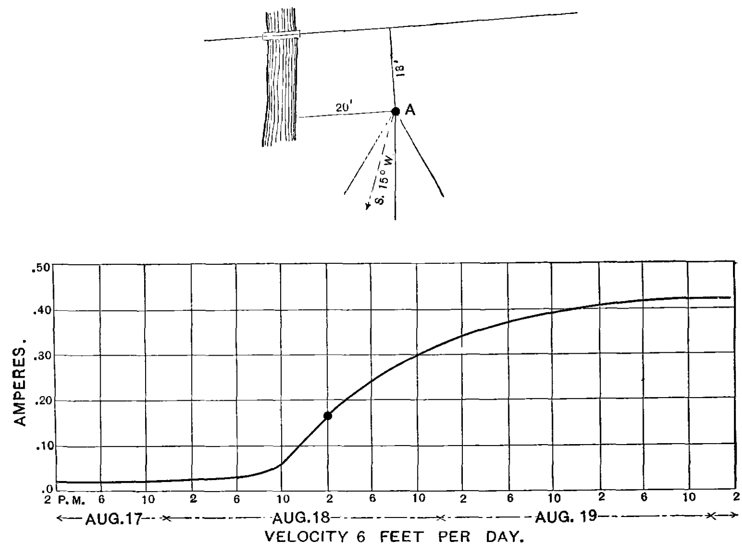


FIG. 52.—Diagram showing velocity and direction of the flow of underground water at Bellevue road (station 15 X). Velocity, 6 feet a day, S. 15° W. This station is the same as station 15, but measurement of velocity was made below a stratum of clay or bog material at a depth of 62.5 feet, 20 feet deeper than the measurement shown in fig. 51.

velocities are the highest the writer has determined. They may be regarded as record-making rates for the horizontal motion of ground waters. Both measurements were made with the recording instruments, and by consulting the curves in figs. 53 and 54 it will be noted that each curve has two maximum points, which must correspond to the velocities in two distinct layers of gravel. The secondary velocity for station 13 was 7.4 feet a day and for station 16, 11.3 feet a day. A very striking verification of the fact that the high movements here found were due to the escape of water from the pond will be noted when the temperatures of the waters in the wells of these stations are compared with the temperatures of the water in the pond and the water in wells outside of the influence of seepage from the pond. Practically all well water taken from wells on Long Island have temperatures lying between 58° F. and 60° F. In the present case the temperature of water drawn from H. A. Russell's well, 22 feet deep, just west of Wantagh Pond, was 59° F. on August 8, 1903. The temperature of water from well D of station 17, just east and slightly below the pond, was 61.2° F. on August 11, 1903. This well was 20 feet deep, the bottom being at the same depth as the wells of stations 13 and 16. The

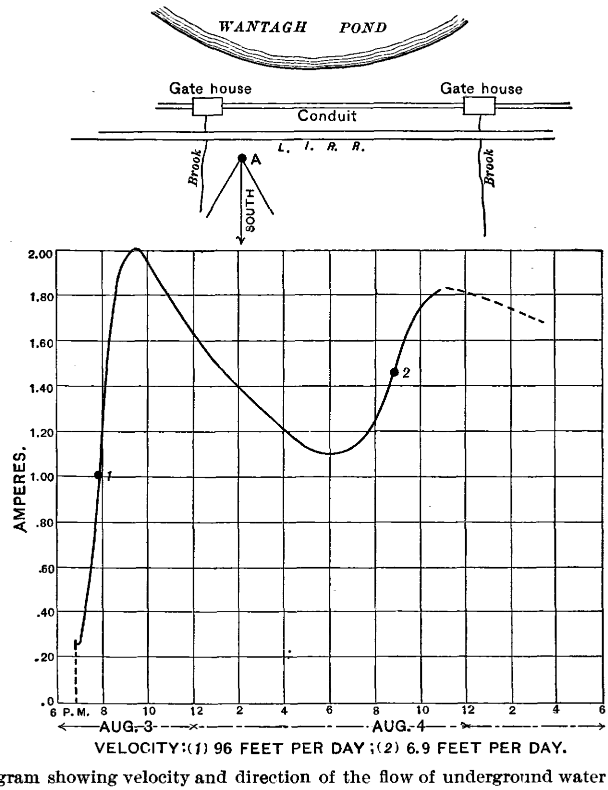


FIG. 53.—Diagram showing velocity and direction of the flow of underground water south of Wantagh Pond (station 13). Two velocities are shown, two different depths. The high velocity, 96 feet a day, is the highest yet determined. Seepage from the pond accounts for the high velocities, 96 and 6.9 feet a day, south. Ammeter chart for this station is shown in fig. 12.

temperature of water in the pond varies more or less, especially the temperature of the surface layer. The temperature of the pond water on August 8, a cloudy day, was 72.5° F., and on July 30, a sunny day, it was 80° F. The temperature of water from the wells of station 13 was 65.8° F. on July 30, and from the wells of station 16 on August 8 was 69.5° F. These high temperatures at stations 13 and 16 show that a large portion of the moving ground water must come directly from the pond, and the rate of motion is so great that the ground water has not time to be reduced to the normal temperature of the ground.

The velocity at station 17 was 10.6 feet a day in a direction 30° west of south. The temperature of the water was 61.5° F. The ground water at this point is probably not entirely free from the seepage water from the pond. The direction of flow, the velocity, and the temperature of the water all indicate, however, that a considerable

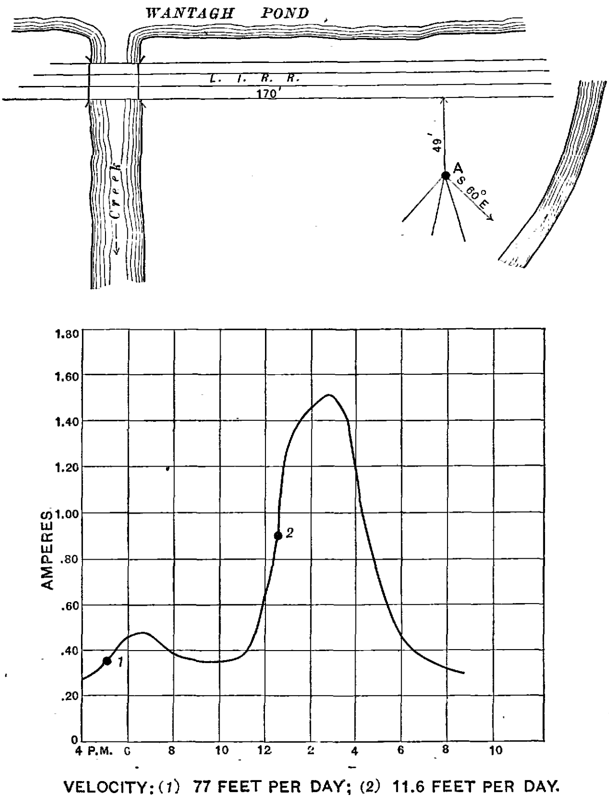


FIG. 54.—Diagram showing velocity and direction of flow of underground water at Wantagh Pond (station 16 X). This station is near station 13, and the curve shows two distinct velocities in different strata. Velocities, 77 and 11.6 feet a day, S. 60° E. The stream just east of the station seems to deflect the direction of flow toward itself.

part of the water is the natural underflow, which at this point is diverted toward the lowland occupied by the streams below the pond.

There can be no doubt but that the proposed infiltration gallery will intercept a large amount of seepage water from the pond, which at the present time runs entirely to waste. The amount of seepage in the first 16 feet in depth is probably somewhat less than 3 second-feet per 1,000 feet of length of cross section, or about 2,000,000 gallons per twenty-four hours.

At station 21, located just above Wantagh Pond, the velocity at a depth of 17 feet was 21.3 feet a day in a direction 60° east of south. This station is near the west bank of the main brook that feeds the pond, and the greater portion of the ground-water at this point percolates into the bed of the stream. The true underflow at this point can be found by taking the southerly component of this velocity, which gives 10.6 feet a day. The temperature of the ground water at this point was 58° F.

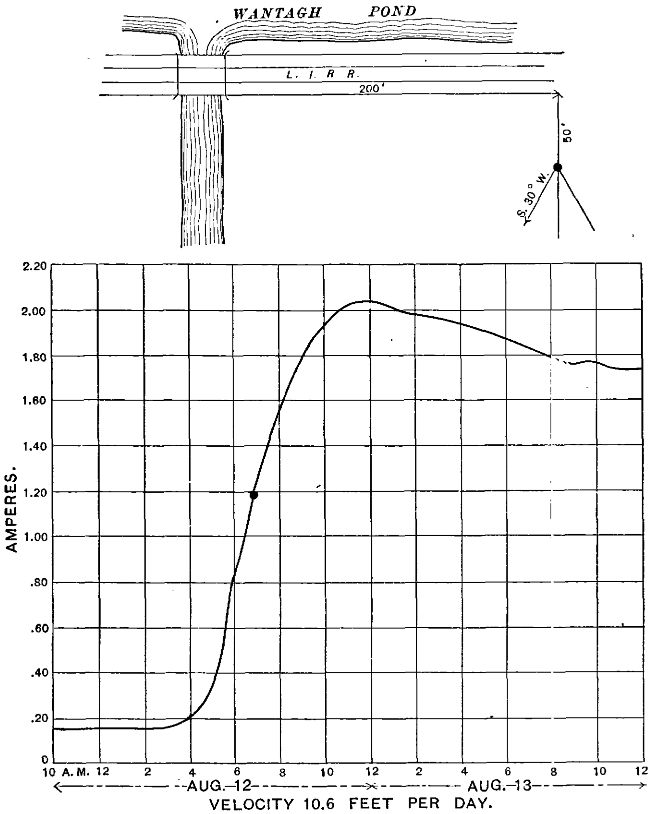


FIG. 55.—Diagram showing velocity and direction of the flow of underground water at Wantagh Pond (station 17). Velocity, 10.6 feet a day, S. 30° W.

The increase of underflow rate at the Wantagh Pond from 10.6 feet a day above the pond to 96 and 77 feet a day below the pond, as compared with velocities above and below Agawam Pond, 2.6 and 5.3 feet a day, respectively, is easily understood when the material constituting the bottom of the ponds is inspected. The material at Agawam is good, the soil being fine and compact, while at Wantagh the bottom of the pond is very sandy, in some places having a closer resemblance to a filter bed than to a puddled floor.

INFLUENCE OF PUMPING UPON THE RATE OF MOTION OF GROUND WATERS NEAR SOME OF THE BROOKLYN DRIVEN-WELL STATIONS.

Through the courtesy of Mr. I. de Verona an excellent opportunity was furnished the writer of making some observations on the influence of pumping upon the normal rate of motion of ground waters in the neighborhood of some of the Brooklyn driven-well stations. For this special purpose the pumping stations at Agawam and Wantagh, which had been idle since December, 1902, were started up for two days each in August, 1903. Agawam was operated continuously from 7 a. m.,

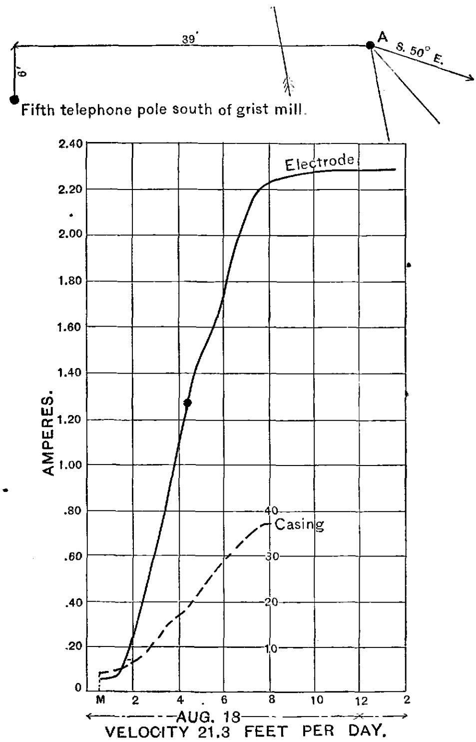


FIG. 56.—Diagram showing velocity and direction of the flow of underground water (station 21). Velocity, 21.3 feet a day, S. 50° E.

August 19, to 7 a. m., August 20. At the Agawam station observations were made at station 5 by means of the recording instrument. Well A was charged at 4 p. m., August 19, or after nine hours of continuous pumping. After this length of time it was expected that the maximum rate of flow of ground water would be established, although, of course, the cone of depression near the wells would still be changing quite rapidly.

Station 5 is 30 feet north of the intersection of the chief suction mains communicating with the line of driven wells and 12 feet east of the central discharge main (see fig. 58). The depth of the test wells is 22 feet, while the depth of the 30 wells of the Agawam station system varies from 30 to 105 feet.

The rate of pumping during the forty-eight-hour test was very uniform, at an average rate of 2,250,000 gallons per twenty-four hours. The vacuum at the pump was maintained at 24 inches, while that at the first well east of the engine-house was 23.2 inches. The charge of the centrifugal pump was dropped from 4 p. m. to 4.40 p. m.,

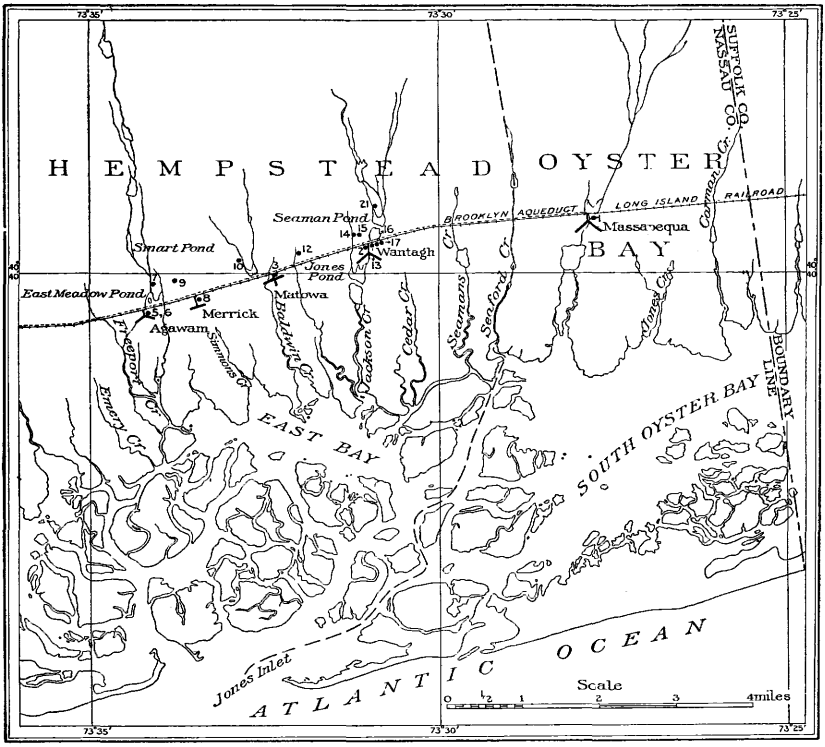


FIG. 57.—Map showing location of overflow stations, at which determinations of the rate of flow of underground water were made on Long Island. The Brooklyn driven-well pumping stations are located on the south side of the railroad and are named, from east to west, Massapequa, Wantagh, Matowa, Merrick, and Agawam.

August 19, during which time the vacuum fell to 7 inches. This was the only interruption during the test.

The velocity determined at station 5 during the test was 8 feet a day in a direction S. 22° E. The normal velocity at this station is 5.4 feet a day, S. 8° W., so that the influence of the pumping was to increase the velocity by 2.6 feet a day, or an increase of about 50 per cent (fig. 44). The actual velocity found and the percentage of increase are both very moderate, and indicate that the pumping station is not making an unreasonable draft upon the ground-water supply at this point.

The 30 wells of the Agawam supply station have screens each 10 feet long, or, altogether about 730 square feet of screen. The maximum velocity of the ground water as it enters these screens must be 1,230 feet a day, since the actual pumpage was 2,250,000 gallons or 300,000 cubic feet per twenty-four hours. The mean velocity in the area (10 by 1,500 feet cross section) immediately drawn upon by the wells was about 30 feet a day. The reduction of this rate to 2.7 feet a day represents a ratio of reduction of 11, which could be taken care of by a depth of 110 feet in the water-bearing gravels, without going outside of the 1,500 foot east and west line of the driven wells.

To put this in another way: the daily pumpage of 300,000 cubic feet of water could be supplied by the normal rate of motion of the ground

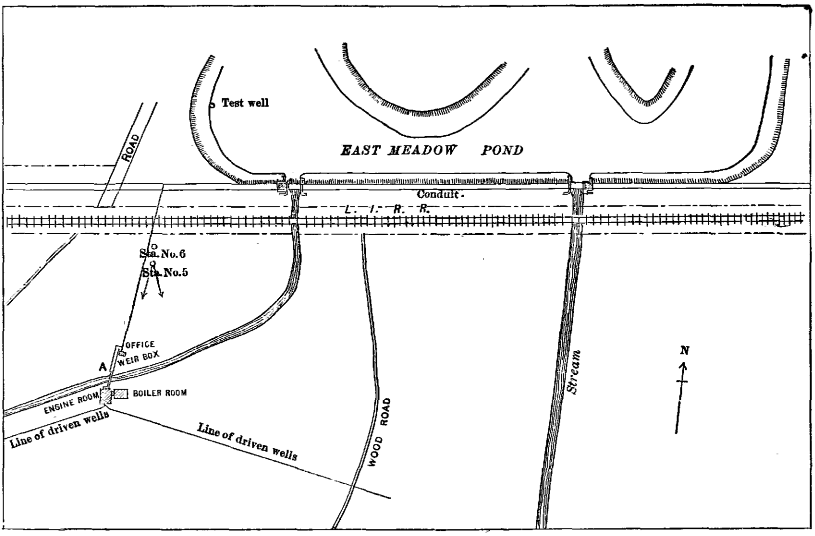


FIG. 58.—Map showing location of stations 5 and 6 with reference to Agawam pumping station and East Meadow Brook Pond. The surface stream was gaged at the bridge marked A. The normal direction of ground-water motion at station 5 was S. 8° W. During a heavy rain, and also when the pumps were drawing water from the lines of driven wells, the direction of flow changed to S. 22° E., as shown by the arrows drawn from station 5.

water at this point (5.4 feet a day) through a cross section of 510,000 square feet, or, say, 100 feet deep by 1 mile wide. To supply this amount of water, if removed from the ground on each of the three hundred and sixty-five days in a year would utilize 1 foot of rainfall on 12 square miles of catchment area. These amounts are not excessive. The rate of removal of ground water at the Agawam station must therefore be regarded as exceedingly moderate.

The observations at Wantagh pumping station were made on August 21 and 22. The pumping at this station began at 7 a. m., August 21, and continued forty-eight hours at the uniform rate of 4,366,000 gallons per twenty-four hours. The water at this station is drawn from 48 driven wells, arranged on three lines of suction mains as shown in fig. 59. The east and west expanse of the two chief lines of wells is about 1,500 feet. The wells of this station are of two different types, shallow wells of depth of about 24 feet and deeper wells, extending below an impervious bed to depths of from 60 to 112 feet. These latter wells have an artesian head of 3 or 4 feet, and when the pumping plant is idle the water from the deep wells flows into the suction main and into the shallow wells, whence the water escapes into the sands and gravels of the upper zone of flow. An attempt was made on June 24 to measure the rate of motion of the ground water at station 2, situated 17 feet west of the chief discharge pipe and 300 feet north of the intersection of the main suction pipes from the driven wells, as shown in fig. 59. The attempted measurement was a failure, it not being

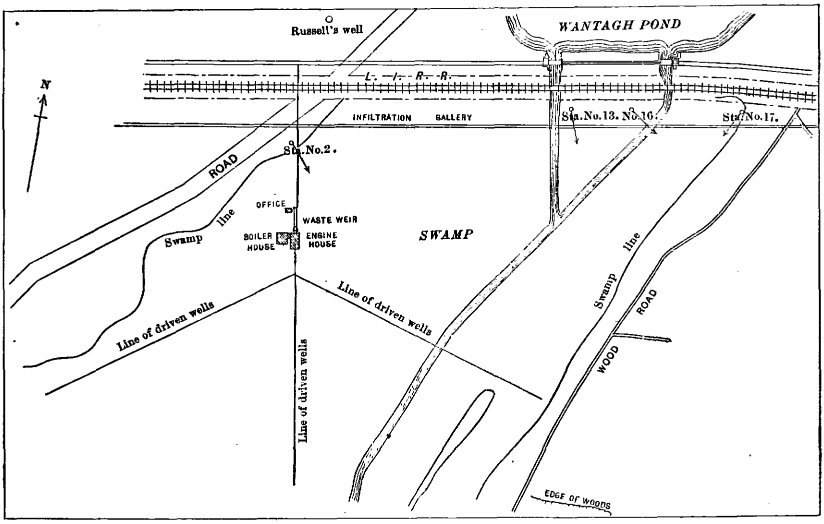


FIG. 59.—Map showing location of stations 2, 13, 16, and 17 near Wantagh pumping station and Wantagh Pond. The arrows indicate the directfon of flow of ground water. The flow at station 2 was observed while pumps were drawing water from the three lines of driven wells.

known at that time that the discharge from the numerous artesian wells was entering the surface layers of gravels and hence interfering with the normal flow in these gravels. The ground water at station 2 was, on account of this situation, either entirely stationary or moving slightly toward the north. On August 21 well A of station 2 was charged at 6 p. m., or after eleven hours of continuous pumping from the driven wells. The velocity of the ground waters observed was at the rate of 6 feet a day in a direction 40° east of south. As this station is distant only 300 feet from the lines of driven wells, it is evident that the withdrawal of 4,366,000 gallons, or 582,000 cubic feet, per twenty-four hours has not an excessive influence on the normal rate of motion of the ground waters. The results at Wantagh compare very well with the results at Agawam, and indicate that the driven-well plants have not exhausted the possibilities of ground-water developments.

CONCLUSION.

The very evident conclusion from observations on Long Island is that large amounts of ground water can still be obtained along the south shore of the island, especially if deep wells of large diameter can be successfully bored. The writer has already called attention to the possibility of constructing 12-inch wells of the California or "stovepipe" type in the unconsolidated material which extends from the surface to considerable depths on Long Island. Such wells, several hundred feet in depth, with perforations opposite the best water-bearing material, would utilize a large part of the underflow which now escapes to the sea. The practicability and success of such wells in this locality seems very probable, but the only way to arrive at an entirely satisfactory conclusion is to actually construct a test well.

CHAPTER VII.

THE SPECIFIC CAPACITY OF WELLS.

GENERAL PRINCIPLES.

The amount of water discharged or obtained from a tubular well is a quantity which is as rigidly dependent upon certain definite and measurable factors as the total horsepower of a steam engine is dependent upon the elements in its design and the pressure of steam furnished to the engine. Very few persons realize, however, the closeness and intimacy of the dependence of the yield of a well upon the various causes represented by the character of the water-bearing material in which it is constructed and the size and shape of the well itself. In fact, the available published data containing the results of actual tests of the capacity of wells are usually incomplete in some important particular, so that no laws or general principles are discernible even where they exist. With every well, no matter what its size or method of construction, there can be associated a perfectly definite quantity which expresses the capacity of that well to furnish water. In order to add definiteness to well construction and well data, such a quantity should be applied to every well whose capacity is measured. It can conveniently be designated by the term "specific capacity." By "specific capacity" of a well is meant the amount of water furnished under a standard unit head, or the amount of water furnished under unit lowering of the surface of the water in the well by pumping. This number can be made definite by agreeing upon the unit of measure of quantity of water and on the unit in which the head is to be measured. If the unit of yield be the "second-foot," or cubic foot of water per second of time, and if the hydraulic head be measured in feet of water, then the specific capacity of any well is found by dividing the number of second-feet by the hydraulic head. For example, if an artesian well flows 2 second-feet, and if the static head in the well when the water is not permitted to flow is equivalent to a head of 20 feet of water, then the specific capacity of the well is 2 divided by 20, or 0.1 second-foot. We describe the specific capacity by saying that the specific capacity of the well is 0.1 second-foot. Likewise, if we desire to speak of the specific capacity of a common tubular well which is not artesian in character, we can proceed in a similar way. For example, if the well yields 2 second-feet when the water in the well is lowered 20 feet below its normal position, the specific capacity is found by dividing 2 second-feet by 20, giving a specific capacity of 0.1 second-foot.

For the purpose of expressing the capacity of wells, the second-foot will be found to be a large unit of capacity, so that it will often be convenient to express the yield in gallons per minute, rather than in second-feet. One second-foot is equivalent to about 450 gallons per minute, so that the specific capacity of the wells above given might be stated as "45 gallons per minute." Another convenient unit of measure for the capacity of the well is the miner's inch, the California miner's inch being one-fiftieth of a second-foot, and hence of a very convenient size for the measurement of well capacity. However, the different values of the miner's inch prevalent in various sections of the country make this unit of measure undesirable for general use.

The importance of accurate knowledge of the specific capacity of the wells of a locality can not be overestimated. To the owner of a well it is very important that he know whether or not his well is better or poorer than neighboring wells, and whether the difference is due to a diversity in pumping machinery or to a difference in the well itself. To one who contemplates the construction of a well it is of the first importance that he know how much water he may expect to obtain, and in what manner it can best be obtained. In spite of striking examples of irregularity, it is usually true that the same water-bearing material is very uniform in a given locality, and by properly designing a well one should be able to estimate in advance of construction the capacity of a well with a very small per cent of error. However, tests on existing wells and all data concerning them will have to be obtained and recorded with much greater accuracy and completeness than heretofore if this desirable result is to be realized.

It does not count against the above statements concerning the ability to determine in advance the probable yield of a well, to find that neighboring wells, similarly constructed, yield very different amounts of water, or that water can not be obtained a short distance from a good well. Such a discovery always causes considerable comment, while the numerous cases in which ground water is found at very uniform depths and in nearly identical material call forth no comment whatever.

The amount of water yielded by a common open well or by a non-flowing tubular well is dependent first of all upon the degree of fineness of the material in the various strata from which the water is obtained. The size of the soil grains not only controls the rate at which water can be transmitted to the well under a given head, but it also determines the proportion of contained water which the soil will freely part with. The fine-grained soils retain a considerable proportion of the water of saturation as capillary water even after free means of drainage are established, so that fine-grained material will not only deliver water slowly, but will furnish only a small total amount. Some quicksand is so fine that the water can be pulled away from the fine grains with the greatest difficulty, while silt with a diameter of grain of about one one-thousandth of an inch (not at all an unusual size) will part with its water very slowly even when it is placed on a piece of blotting paper.

The above factor in the specific capacity of the well can be expressed by means of the transmission constant, k, of the material furnishing the water. Other things being equal, the yield of the well will vary directly with the transmission constant.

Another cause effecting the yield of the well is the thickness of the water-bearing stratum. If the transmission constants of all water-bearing strata are the same, the amount of water available is directly dependent upon the thickness of strata penetrated, provided, of course, that only such material is counted as is in contact with a suitable well screen or strainer.

An important factor in determining the yield of a well is the diameter of the well. By the diameter is meant the diameter of the well where it penetrates the water-bearing stratum. The diameter of the well is a factor which determines the rate at which the water must move in the water-bearing material as it enters the well. A well having a large casing will permit a given amount of water to enter under a low velocity, and hence with little friction in the pores of the water-bearing medium. The dependence of the yield upon the diameter of the well is not expressible in a very simple way. In fine material, the dependence of the yield upon the diameter of the well is very much less than is commonly supposed. Only in material that is very coarse is it usual that any great advantage is obtained by using casing as large as 16 to 24 inches in diameter.

The friction of the water as it flows upward in the casing of a well, a factor which is often very large in the case of an artesian well, is usually small or negligible in common tubular wells from which the water is pumped with a suction pipe much smaller than the diameter of the well itself. This statement must not be understood to imply that the amount of water discharged by the pump is not influenced by the size of the suction and discharge pipes. What is meant is that, with a given lowering of the water in the well the yield of water will not be dependent upon the friction in the casing to the upward-moving water, while of course the amount of power applied to the pump will be greatly influenced by the size of the suction and discharge pipe and upon the manner in which these pipes are installed.

Finally, the specific capacity, if the well be not too shallow, varies directly as the distance the surface of the water in the well is lowered by pumping. Thus, if the water in a well is lowered 2 feet below the natural level by pumping from it at the rate of 20 gallons a minute, the same well may be expected to yield approximately 40 gallons a minute if the water is lowered 4 feet below the natural level. For shallow wells the yield will not increase in this direct ratio, but will be considerably less on account of the decrease in percolating surface due to the lowering of the water plane in the neighborhood of the well. Besides the advantages just mentioned, tubular wells, owing to their greater depth, are much more likely to strike a vein of coarse material, a small stratum of which may be expected to furnish much more water than a considerable depth of fine material. This accounts for the well-known superiority of deep tubular wells over common dug wells.

If a well be cased through the water-bearing medium, the character of the screen or perforations in the casing will of course influence the yield of the well. If a screen is clogged, or if the perforations are not ample, the capacity of the well will be cut down because of this imperfect casing.

All of the factors named above influence the yield of a flowing artesian well, except that in place of the distance the water is lowered by pumping we must substitute the static head at the point of discharge of the flowing water. By the static head is meant the pressure when the well is closed at the point at which the flow is measured. This static head is conveniently expressed in terms of feet of water. For example, instead of giving the static head in pounds per square inch we can state it in feet of water. The flow of water from the porous medium into the well will vary directly as the static head, but the total yield of the well will not vary in this simple way on account of the frictional resistance which the water suffers in flowing through the casing and drill hole of the well. This last component of the specific capacity while usually small in a well that is pumped is often of the very first importance in the case of a flowing well. To the friction in the casing and discharge pipe should be added the influence of all turns and bends and reductions in size and the like. This factor is often a very large one in the determination of the amount of water yielded by an artesian well. The resistance due to friction increases very greatly with a decrease in the size of pipe and also with an increase in the length of the pipe, and is materially influenced by the curves and variations in size of the pipe and by the rivets and joints in the well casing or discharge pipes. The friction in pipes does not vary directly with the hydraulic head, but approximately as the square root of the head at which the flow takes place.

As stated before, complete data concerning tubular wells are very difficult to obtain. Complete data concerning an artesian well should consist of the following: First, exact dimensions of all casing and sizes of the bore hole, including, of course, total depth; second, the static head of the well measured at a point a known distance above the surface of the ground; third, an accurate measurement of the amount of water yielded by the well when freely flowing under the measured static head; fourth, the thickness of the various water-bearing strata furnishing water to the well. The data for common tubular wells should include the following facts: First, the diameter of the well casing; second, the depth to water; third, the depth of the well; fourth, the length of screen or perforations in the well; fifth, the character of the perforations; sixth, the amount of water obtained from the well under continuous pumping; seventh, the amount that the water in the well is lowered below its normal level during such pumping. From these facts the specific capacity of the well can be computed and many important facts can be determined. Additional data of considerable importance would be the following: Eighth, the distance the water is raised by the pumps; ninth, the cost or expense of pumping.

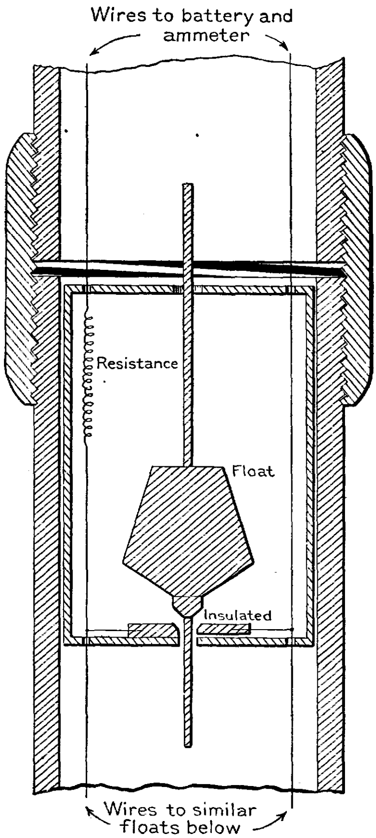


FIG. 60.—Apparatus for measuring the rate of rise of water in wells. A number of floats, as shown in the figure, are placed a foot apart in a 1-inch brass tube. The rising water in the well raises the several floats in turn and registers the time on an ammeter above.

Complete estimate of the specific capacity of a tubular well can be made if the following data can be obtained: First, the amount that the water in the well is lowered below the undisturbed water plane; second, the rate at which the water rises in the well after pumping ceases; third, diameter of casing and of suction pipe. The determination of the rate at which the water rises in the well casing requires some special appliances, a stop watch being usually a necessity. Additional apparatus for this purpose has been constructed and is shown in fig. 60. The apparatus consists of a brass tube 1 inch in diameter containing some small floats placed at distances of about 1 foot apart. The apparatus is lowered into the well until its lower end reaches the level of water in the well when it is being pumped. When pumping ceases water in the well rises and raises in succession each float from its seat, which in turn is indicated to the observer by the deflection of a needle that is controlled by electric circuit running to the several floats. By use of a stop watch the rate at which water rises in the well can be determined. The manner of using the apparatus will be easily understood from the diagram.

The rate of rise of the water surface in the well after it has been depressed by pumping should furnish a very smooth and regular curve when plotted on cross-section paper. The law of this curve is such that if at the end of a certain period of time (say fifteen minutes) the depression of the water surface in the well is half of the original amount of depression just before pumping ceased, then at the end of twice that period of time (thirty minutes) the depression will be one-fourth of the original amount; at the end of thrice that period of time (forty-five minutes) it will be one-eighth of the original amount, etc. Four curves of rise of water in wells are given in fig. 61. Curves 3 and 4 are from the same well, but during the rise shown by 4 a neighboring well 20 feet distant was being pumped.

The theoretical law of rise of water in a well can also be expressed by a formula, as follows:

$$t = \frac{17.25\ A}{c} \log \frac{h}{H}$$

In this formula A is the area in square feet of the cross section of the well casing, counting out the area of the pump rod, suction pipe, or other obstruction. H is the amount in feet that the surface of the water in the well was depressed below its natural level just before pumping stopped; c is the specific capacity of the well expressed in gallons per minute; h is the amount in feet of depression of the water surface below the natural level at any time t (in minutes) after pumping ceased. By taking two corresponding values of h and t from the curve of rise of water surface, the specific capacity of the well (c) can easily be computed from the formula

$$c = 17.25 \frac{A}{t} \log \frac{h}{H} \text{ gallons per minute.}$$

Examples of use of this formula will be given below (p. 93). The logarithm indicated by "log" is the common or Briggs logarithm.

The following reports of tests on small wells used for irrigation illustrate the importance of accurate tests of this kind and indicate the sort of information that it is desirable to secure. The first test shows a well-constructed plant giving fair service. The second plant shows a well-constructed plant, but indicates not only an inefficient style of pump, but showed an expensive waste of gasoline through a hidden leak in the feed pipe.

TESTS.

TEST I. ON WELL AND GASOLINE PUMPING PLANT OF D. H. LOGAN, GARDEN, KANS.

This plant is located on the northeast corner of sec. 13, T. 24 S., R. 33 W., and is in the northwest corner of the city of Garden. The outfit consists of a 6-horsepower Fairbanks, Morse & Co., horizontal gasoline engine connected by a belt to a No. 3 centrifugal pump. The well is constructed of a 20-inch galvanized-iron casing 32 feet long, perforated 10 feet up from the bottom, inside of which are two 4-inch feeders 28 feet long, perforated their entire length and extending 26 feet below the bottom of the 20-inch casing, making a total depth of 38 feet. The pump has been in operation since April, 1902, and the engine since April, 1903. The water was measured by the use of a fully contracted weir with a length of crest of 0.66 feet.

The engine was started at 9 o'clock, and the weir was ready for water at about 10.30. The water was turned on weir and the head read until it became constant at 1 p. m., then height was read every five minutes until 2.30 p. m. In order to determine the expense of pumping, all of the gasoline in the reservoir was used, then 1 gallon was poured in and the length of the run noted to be one hour and thirty-two minutes, or two-thirds gallon per hour. As the engine is 6 horsepower, this equals 0.111 gallon, or 0.445 quart of gasoline per horsepower hour.

The average corrected head on the weir was found to be 0.440 feet. Using the weir formula

$$q=c\ 2/3\ \sqrt{2\,g}\ b\,\mathrm{H}^{3/2}$$

where b=.66, and c=.592, the discharge is found to be

$q=$ 9.6045 second-feet.
= 272 gallons per minute.
=16,320 gallons per hour.

	Feet.
Average depth to water while pumping	18.6
Elevation of well platform, 2,835.26 feet.	
Normal depth to water	11.75
Amount lowered by pumping	6.85
Distance water was raised above platform	3.5
Total distance water was raised	22.1

Cost of pumping was therefore 0.9 cent per 1,000 gallons, or 0.0406 cent per 1,000 foot-gallons (1,000 gallons raised 1 foot).

The engine ran at a rate of 350 revolutions per minute, exploding 143 times per minute. The diameter of engine pulley is 16 inches and of pump pulley 10 inches. This gives a speed somewhat less than 560 revolutions per minute to the pump.

SEEPAGE AND EVAPORATION.

The size of the pond was 40 by 60 feet, mostly covered with a green scum, which would decrease evaporation. As to seepage, the pond falls 8 inches in twelve hours at night. The pond being 2,400 square feet in area, the observed seepage represents a loss of 16.68 gallons per minute, which should be added to the capacity of pump and well, but not to the effective capacity for Mr. Logan.

There is a windmill 20 feet north of the well pumped by the engine, a 12-foot aermotor connected to a 10-inch pump of 12-inch stroke. After the weir measurements were completed the windmill was thrown into gear. There was a brisk wind from the south and the pump threw a good quantity of water, but no appreciable lowering of the water was detected in the well being tested 20 feet away. The rise of the water in the well was obtained twice.

Below are the two sets of observations:

First trial; windmill not running.			Second trial; windmill running.		
Minutes.	Seconds.	Stopped pumping.	Minutes.	Seconds.	Stopped pumping.
0	55	18.60	24	30	....
1	05	16.05	....	35	18.0
1	20	14.55	....	45	16.5
1	37	12.95	....	48	14.35
1	55	12.50	25	10	13.10
2	8	12.35	....	26	12.90
....	22	12.35	....	38	12.55
....	33	12.25	....	48	12.55
....	48	12.15	26	00	12.45
			....	23	12.25
			....	47	12.25
			....	58	12.25
			27	15	12.25
			....	30	12.25

The curves showing the rate of rise of water in the Logan well after pumping ceased are given by curves 3 and 4 in fig. 61. The curve 4 is the one which was produced when the windmill was pumping from a well 20 feet from the one for which the curve is drawn. The comparison of this curve with curve 3, which was produced when the neighboring well was not used, is very interesting, showing as it does a less rapid rise when the neighboring well was in use. To find the specific capacity for the Logan well from these curves we must substitute the values of the various constants in the formula

$$c=17.25 \frac{A}{t} \log. \frac{H}{h} \text{ gallons per minute.}$$

The value of A, the area of cross section of the well casing, is 2.17 square feet, and of H, the amount the water is lowered by the pump, 6.85 feet. The amount of depression h of the water level below the natural level at any time can then be selected from the curve and the specific capacity readily computed. If t be taken to be forty seconds, or two-thirds minute, h will be found from the curve to equal $6.85 - 5.5 = 1.35$ feet, hence

$$c = 17.25 \times \frac{3}{2} \times 2.17 \times \log\left(\frac{6.85}{1.35}\right) \text{ gallons per minute.}$$
$$= 39.5 \text{ gallons per minute.}$$

The yield of the well for the maximum depression, 6.85 feet, must then be

$$6.85 \times 39.5 = 270 \text{ gallons per minute.}$$

The curve of rise of water forms one of the best methods of determining the yield of a well. Such curves can readily be obtained.

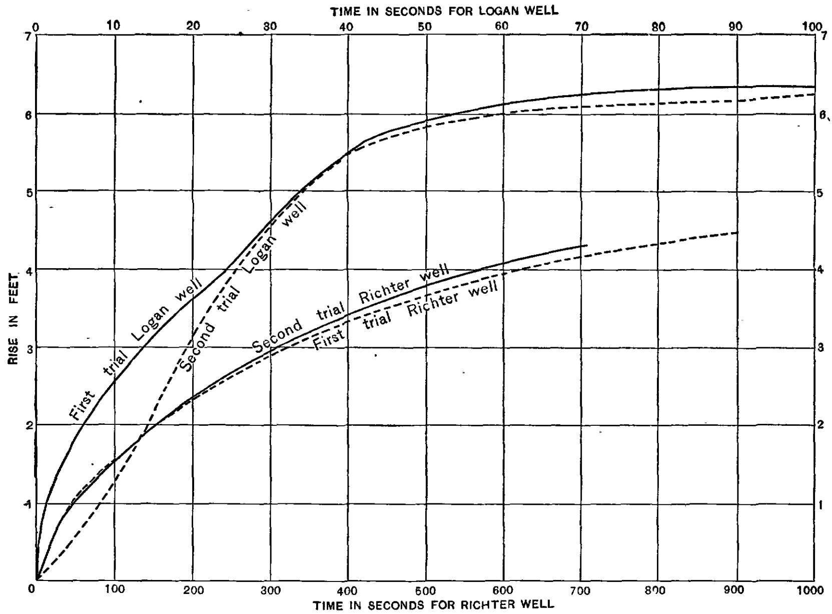


FIG. 61. Curves showing the rate of rise of water in the Richter and Logan wells near Garden, Kans. Curve 1 (dotted), first trial of Richter well; curve 2 (solid), second trial of Richter well; curve 3 (solid), first trial of Logan well; curve 4 (dotted), second trial of Logan well.

Well data should always include measurements of the amount of lowering of the water surface by the pumps, and it is only necessary to continue these measurements after the pumps have stopped to secure sufficient data to estimate the specific capacity and total yield of the well. This avoids the necessity of constructing a weir or other method of measuring the water discharged. The accuracy is sufficient for the purpose for which such data are used.

TEST II. ON WELL AND GASOLINE PUMPING PLANT OWNED BY MINNIE RICHTER, FINNEY COUNTY, KANS.

This plant is located in the northwest corner of the SW. $\frac{1}{4}$ sec. 14, T. 24 S., R. 33 W. The upper part of this well is cased with part of an old standpipe from the city of Garden. The casing is 10 feet in diameter and extends down 20 feet. In the bottom of this part of the well are placed four 8-inch galvanized-iron feeders, arranged symmetrically about the center. Each feeder is 25 feet long, perforated its entire length, and extends about $2\frac{1}{2}$ feet above the bottom of the large part of the well.

The pump used operates on the principle of a screw propeller of a steamship. It bores the water out and up a square wooden penstock or pump shaft. There are two of these propellers, mounted one above the other on a vertical iron shaft inside the penstock. The top of the iron shaft carries the belt pulley and has a shoulder bearing which takes the thrust of the pump. This pump (called the Menge) is made in New Orleans. The pump is run by a 10-horsepower Otto gasoline engine, which runs at a speed of 300 revolutions per minute. The circumference of the drive pulley is 5.25 feet and of the driven pulley 2.65 feet, making the pump run at 595 revolutions per minute. The screws are under water when the pump is not in operation. A small pond was constructed at the end of the discharge trough, and a fully contracted rectangular weir of length of crest of 1.2 feet was used to measure the discharge. The measurements for head were taken 6 feet away from the weir, and boards were interposed between the discharge trough and weir to cut down the velocity which might tend to give erroneous results. The average corrected head on the weir was 0.371 feet. Using the weir formula

$$q=c\tfrac{2}{3}\sqrt{2g}\,b\,H^{\frac{3}{2}},$$

and, taking c from Merriman's tables as 0.603,

$$q=0.876 \text{ second-feet,}$$
$$=394 \text{ gallons per minute,}$$

or using Francis formula

$$q=3.33\,(b-0.2\,H)\,H^{\frac{3}{2}},$$
$$=314 \text{ gallons per minute.}$$

Using a small Price acoustic water meter in the discharge trough, by measuring the velocity at different places, and also by integrating, the discharge was found to be 0.76 second-feet=342 gallons per minute. By putting chips in the discharge trough and catching the time with a stop watch, the surface velocity was found to be 1.565 feet per second. This multiplied by 0.8 gives an average velocity of 1.25 feet per second and a discharge of 0.884 second-feet=397 gallons per minute.

An attempt was made to determine the amount of gasoline used. The reservoir was filled full and the engine run for one hour and thirty-six minutes, or 1.6 hours. All the gasoline we had, $9\frac{1}{4}$ quarts, did not then fill the tank. This was at noon, July 6. On the morning of July 7, 9½ quarts were required to completely fill the reservoir, a total of 18¾ quarts or 37½ pints for the run of 1.6 hours for a 10-horsepower engine. The makers claim that their engines use 1 pint per horsepower hour. This would require in this case 16 pints, or less than half of what was actually measured, if the engine developed its full horsepower. A leak in the tank or feed pipe is clearly indicated. This fact, while being of value to the owner of the plant, shows the record to be worthless as far as comparative cost of pumping is concerned.

Two observations of the rising curve were obtained which agree very well. The lower part of the curve is not accurate because the water in the penstock drops back into the well when pumping ceases.

	Feet.
The elevation of the ground at well is	2,846.0
Average elevation of water in well	2,836.6
Average elevation of water in well when pumping	2,831.5
Elevation of discharge from penstock	2,847.0
Lift	15.5
Average amount water is lowered	5.3
Number of explosions of engine, 126.5 per minute.	

The curves of rise for this well were obtained on two different occasions, and are shown as curves 1 and 2 in fig. 61. They agree very well. To find the specific capacity of the well from the curve, we note the following values of the constants in the formula for specific capacity:

$$c = 17.25 \frac{A}{t} \log \frac{H}{h} \text{ gallons per minute.}$$

The area, A, of cross section of the well casing is 76.79 square feet. The amount, H, that the water is lowered by the pump is 5.3 feet. The amount of depression, h, of the water surface below the natural level at any time can be selected from the curve. From the curve, at the close of ten minutes, h equals $5.3 - 4 = 1.3$ foot. Hence the specific capacity,

$$c = 17.25 \times \frac{76.79}{10} \log \frac{5.3}{1.3} = 81 \text{ gallons per minute.}$$

Multiplying by 5.1, the head under which pumping took place, the total yield of the well is $81 \times 5.3 = 429.3$ gallons a minute.

The above determination of the specific capacity is inaccurate, since the first portion of the rising curve does not show the true rate of rise of water in the well. The penstock of the propeller pump holds 37.7 cubic feet of water, which immediately returns to the well when the pump is stopped. This amount of water is sufficient itself to raise the level in the well by 0.465 foot. For this reason only that portion of the rising curve should be used which is uninfluenced by the returning water from the penstock. Thus, if we use that part of the curve from $t=100$ seconds to $t=600$ seconds, we will eliminate the inaccurate portion. By this modification the data are changed to H=3.75 feet; $h=1.30$ feet; $t=\frac{5}{6}$ minute. Computing the specific capacity on this basis we obtain $c=73$ gallons per minute. This multiplied by 5.3 gives the total estimated yield 388 gallons per minute, which checks more nearly with the 394 gallons per minute previously obtained.

The area of the surface of the strainers and the bottom of the well is 266.5 square feet. The above specific capacity divided by 266.5 gives .341 gallon per minute as the specific capacity per square foot of percolating surface.

The engine ran at a speed of 300 revolutions per minute and exploded 125 times per minute. This would indicate that it was working at about 83 per cent of its rated capacity. Assuming that such was the case, and that it would then use 83 per cent of the fuel necessary to run it at is full rated power (10 horsepower), we have 8.3 pints as the probable amount of gasoline used per hour by the engine during the test. This, at 20 cents per gallon, would make a cost of 21 cents per hour. This assumption makes the cost of water 0.89 cent per 1,000 gallons, $2.90 per acre-foot, and one-seventeenth cent per 1,000 foot-gallons.

CHAPTER VIII.

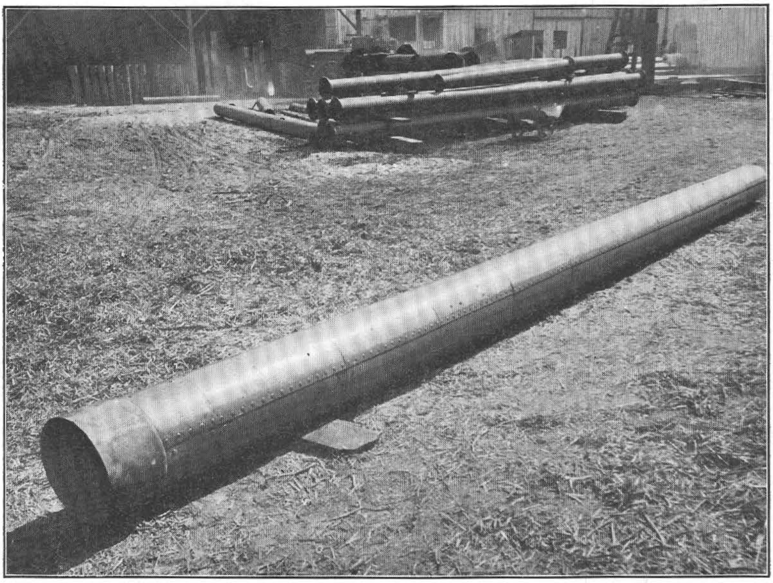
THE CALIFORNIA OR "STOVEPIPE" METHOD OF WELL CONSTRUCTION FOR WATER SUPPLY.

MODE OF CONSTRUCTION.

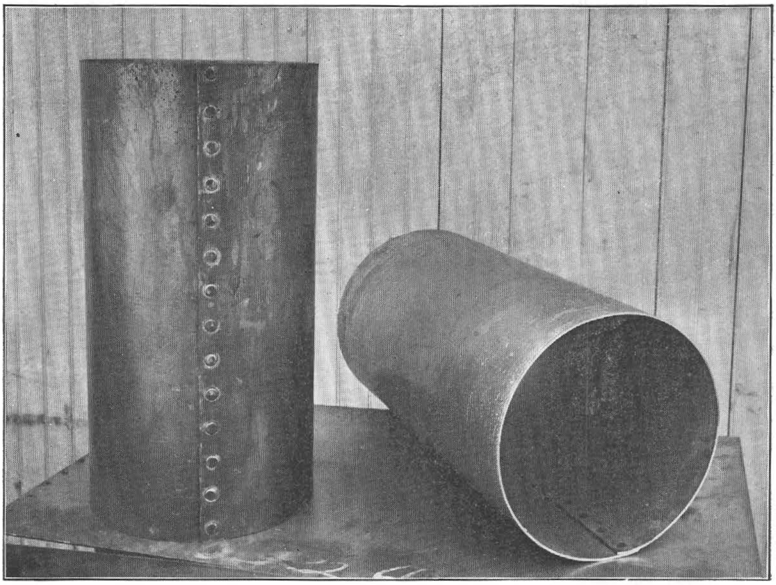
The peculiar conditions of water supply existing in southern California have led to the development of a special type of well, which the writer believes to be admirably adapted to conditions found in many places in the various parts of the United States. It is hoped that the following account will call the attention of those interested in recovering ground water in large quantities to the many points of excellence of the California type of well and method of well construction.

The valleys of southern California are filled with deposits of mountain débris, gravels, sands, bowlders, clays, etc., to a depth of several hundred feet, into which a considerable part of the run-off of the mountains sink. The development of irrigation upon these valleys soon became so extensive that it was necessary to supplement more and more the perennial flow of the canyon streams by ground water drawn from wells in the gravels. This necessity was greatly accentuated by a series of dry years, so that ground waters became a most valuable source of auxiliary supply for irrigation in the important citrus areas in southern California. The type of well that came to the front and developed under these circumstances is locally known as the "stovepipe" well. It seems to suit admirably the conditions prevailing in southern California. In developing water supply for irrigation the item of cost is of course much more strongly emphasized than in developments for municipal supply. The drillers of wells in California were confronted not only with a material which is almost everywhere full of bowlders and like kinds of mountain débris, but also with a high cost of labor and of well casings. It was undoubtedly these difficulties that led to the very general adoption in California of the stovepipe well.

The wells are put down in the gravel and bowlder mountain outwash, or other unconsolidated material, to any of the depths common in other localities. One string of casing, in a favorable location, has been put down over 1,300 feet. The usual sizes of casings are 8, 10, 12, 14 inches, and even larger. A common size is 12 inches. The well casing consists of: First, a riveted sheet steel "starter" 15 to



A. TWELVE-INCH STOVEPIPE STARTER.



B. TWO LENGTHS OF STOVEPIPE CASING.

25 feet long, made of two or three thicknesses of No. 10 sheet steel, with a forged steel shoe at the lower end. Pl. XII, *A*, shows a starter 21 feet long, made of double No. 10 sheet steel, with a $\frac{3}{4}$- by 8- by 12-inch steel shoe riveted on the bottom. In ground where large bowlders are encountered the starters are made heavier, the shoe is 1 inch thick and 12 inches long, and three-ply instead of two-ply No. 10 sheet steel body is used.

Above the starter, the rest of the well casing consists of two thicknesses of No. 12 sheet steel made into riveted lengths, each 2 feet long. One set of sections is made just enough smaller than the other so that one length will telescope snugly inside of the other. Each outside section overlaps the inside section 1 foot, so that a smooth surface results both outside and inside of the well when the casing is in place, and so that the break in the joints is always opposite the middle of a 2-foot length. It is these short, overlapping sections which are popularly known as "stovepiping." A pile of this casing ready for use is shown in Pl. XIII, *A*, and two lengths are shown on a larger scale in Pl. XII, *B*. The sheets of steel can be taken to the field flat and the riveting done during the process of well construction.

The casing is sunk by large steam machinery of the usual oil-well type, but with certain very important modifications. The well rig shown in Pl. XIII has a derrick with mast 40 feet high. When ready to move, the mast swings backward on hinges with the top resting on upright at the rear end of the rig, as shown in fig. 63. Jackscrews are placed under the sills and the whole machine is raised sufficiently to allow wheels to be placed on two axles bolted to the sills. The photograph reproduced in Pl. XIII also shows a 25-horsepower boiler mounted on separate trucks. The 10-inch sand pump and jars are shown just as they have been pulled out of a 12-inch well.

In ordinary material the "sand pump" or "sand bucket" is relied upon to loosen and remove the material from the inside of the casing. The casing itself is forced down, length by length, by two or more hydraulic jacks, buried in the ground and anchored to two timbers 14 inches square and 16 feet long, planked over and buried in 9 or 10 feet of soil. These jacks press upon the upper sections of the stovepiping by means of a suitable head. In Pl. XIII, *B*, the clevises of the pistons of the hydraulic jacks can be seen hooked over the ears of the well cap. The jacks, whose clevises appear in the cuts, have 8-inch piston and $4\frac{1}{2}$-foot stroke, and a combined pull of about 120 tons. The driller, who stands at the front of the rig, has complete control of the engine, hydraulic pump, and valves by which pistons are moved up or down, and also of the lever which controls two clutches which cause tools to work up and down or to be hoisted. The hydraulic pump is mounted upon the main frame of derrick, as shown in Pl. XIV, *B*. The one shown is a Marsh pump with a steam cylinder of 8-inch diameter, and water cylinder of $1\frac{5}{8}$-inch diameter with 12-inch stroke. It is coupled to the jacks with extra strong $\frac{3}{4}$-inch hydraulic pipe and fittings. Smaller rigs use a pump with $6\frac{1}{8}$-inch steam by $1\frac{1}{8}$-inch water cylinders, 10-inch stroke, and coupled to jacks with $\frac{1}{2}$-inch pipe. A boiler pressure of 100 pounds puts nearly a limiting stress on the $\frac{1}{2}$-inch pipe and it sometimes breaks.

The sand pumps used are unusually large and heavy. For 12-inch work they will vary in length from 12 to 16 feet, $10\frac{5}{8}$ inches in diameter, and will weigh, with lower half of jars, from 1,100 to 1,400 pounds.

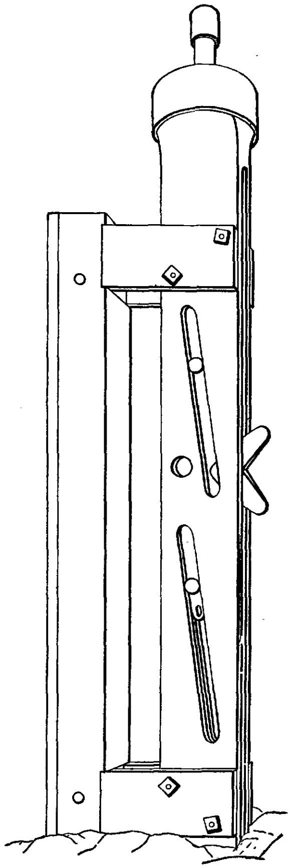


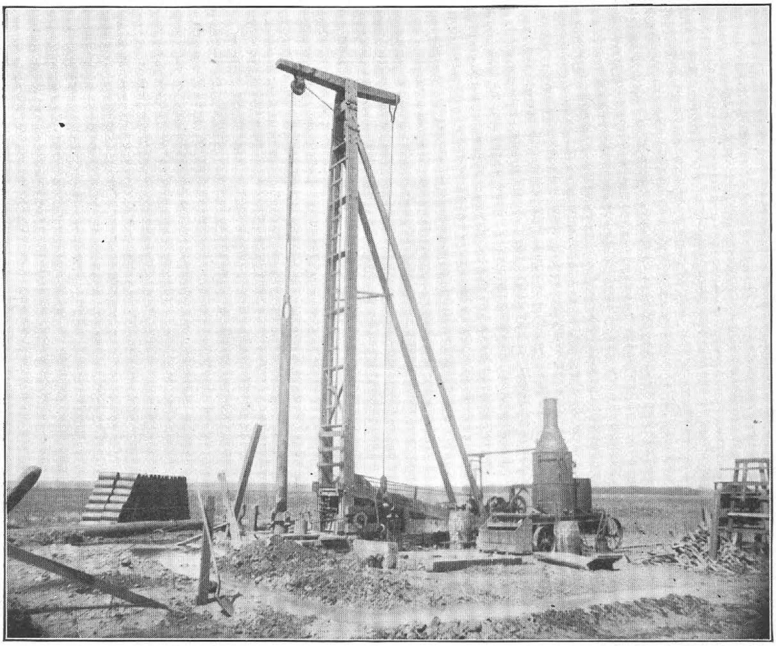
FIG. 62.—Roller type of perforators for slitting stovepipe wells. This perforator was used for cutting 60 feet of screen in the wells shown in Pl. XV.

After the well has been forced to the required depth, a cutting knife is lowered into the well and vertical slits are cut in the casing where desired. A record of material encountered in digging the well is kept, and the perforations are made opposite such water-bearing strata as may be most advantageously drawn upon. A well 500 feet deep may possess 400 feet or more of screen if circumstances justify it.

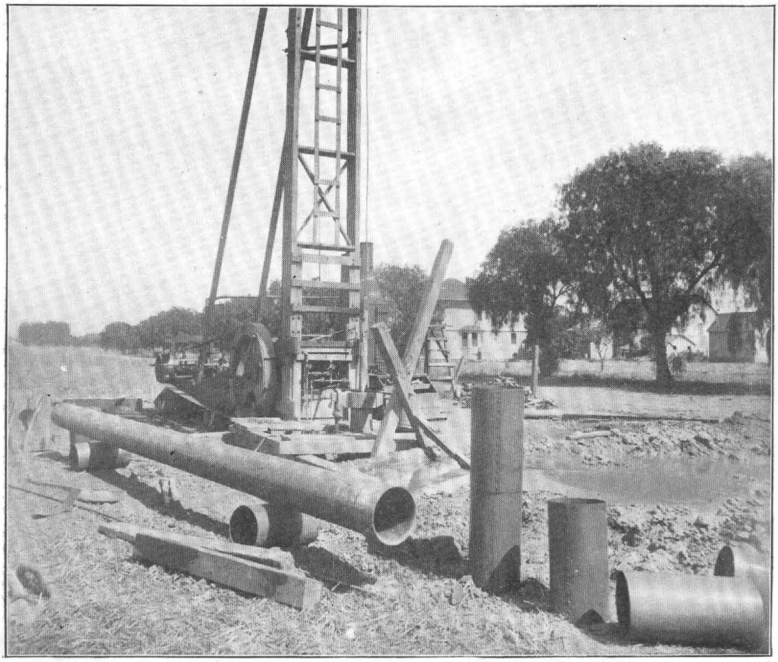
Pl. XIV, *A* shows the perforator for slitting stovepipe casing. It is handled with a 3-inch standard pipe with $\frac{3}{4}$-inch standard pipe on the inside. The perforator is shown in cutting position with knife extended. In going down or in coming out of the well the weight of $\frac{3}{4}$-inch line holds point of knife up. When ready to "stick" the $\frac{3}{4}$-inch line is raised. By raising slowly on 2-inch line with hydraulic jacks, cuts are made three-eighths inch to three-fourths inch wide and 6 to 12 inches long, according to the material at that particular depth.

Fig. 62 shows another type of perforating knife. The revolving cutter punches five holes at each revolution of the wheel. This style of perforator is called a "rolling knife." By means of this tool 60 feet of perforations were cut in the well shown in Pl. XV.

A great many different kinds of perforators are in use in California; in fact, the perforator is a favorite hobby of local inventors. The different patterns in use seem to work well. Those shown in the illustrations are very good.



A



B

CALIFORNIA WELL RIG.

A, Side view; *B*, Front view, showing clevises of hydraulic jacks hooked over ears of well gap.

ADVANTAGES OF "STOVEPIPE" CONSTRUCTION.

The advantages of this method of well construction are quite obvious. For wells in unconsolidated material the California type is undoubtedly the best yet devised. It is believed that wells of this type would be highly successful in the unconsolidated deposits in other localities. The absence of bowlders and very coarse gravels in some deposits may possibly make it more advantageous to use the hydraulic jet instead of the ponderous sand bucket in soft material, but this is the only modification that these conditions seem to suggest.[a]

Among the special advantages in the stovepipe construction may be enumerated the following:

1. The absence of screw joints liable to break and give out.

2. The flush outer surface of the casing without couplings to catch on bowlders or hang in clay.

3. The elastic character of the casing, permitting it to adjust itself in direction and otherwise to dangerous stresses, to obstacles, etc.

4. The absence of screen or perforation in any part of the casing when first put down, permitting the easy use of sand pump and the penetration of quicksand, etc., without loss of well.

5. The cheapness of large-size casings because made of riveted sheet steel.

6. The advantage of short sections, permitting use of hydraulic jacks in forcing casing into the ground.

7. The ability to perforate the casing at any level at pleasure is a decided advantage over other construction. Deep wells with much screen may thus be heavily drawn upon with little loss of suction head.

8. The character of the perforations made by the cutting knife are the best possible for the delivery of water and avoidance of clogging. The large side of the perforation is inward, so that the casing is not likely to clog with silt and débris.

9. The large size of casing possible in this system permits a well to be put down in bowlder wash where a common well could not possibly be driven.

10. The uniform pressure exerted by the hydraulic jacks is a great advantage in safety and in convenience and speed over any system that relies upon the driving of the casing by a weight or ram.

11. The cost of construction is kept at a minimum by the limited amount of labor required to man the rig as well as by the good rate of progress possible in what would be considered in many places impossible material to drive in, and by the cheap form of casing.

COST OF CONSTRUCTION.

An idea of the cost of construction of these wells can best be given by quoting actual prices on some recent construction in California.

[a] A 12-inch stovepipe well was sunk to a depth of 2,800 feet on the Lanoria Mesa, 7 miles northeast of El Paso, Tex. The last 2,000 feet was drilled in dry clay by use of a powerful hydraulic jet.

According to contracts recently let near Los Angeles the cost of 12-inch wells was 50 cents per foot for the first 100 feet and 25 cents additional per foot for each succeeding 50 feet, casing to be furnished free. This makes the cost of a 500-foot well $700 in addition to casing. The usual type of 12-gage, double, stovepipe casing is about $1.05 a foot, with $40 for 12-foot starter with three-fourths by 8-inch steel ring or shoe. The pay of a good driller is $5 a day, of helpers $2.50 a day. The cost of drilling will run higher than that given above in localities where large and numerous bowlders are encountered.

WELL RIGS.

Pls. XIII and XIV, *B*, show a new rig of very excellent type owned by Mr. E. W. Riggle, Los Angeles, Cal. The drillers build their own

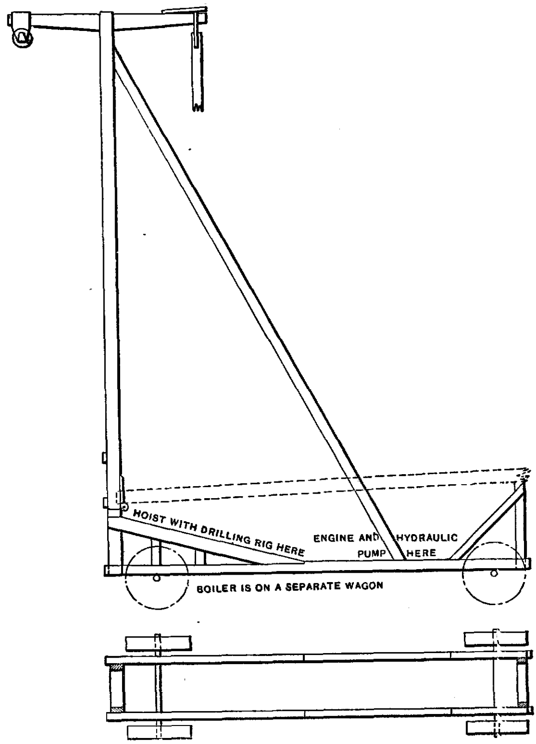
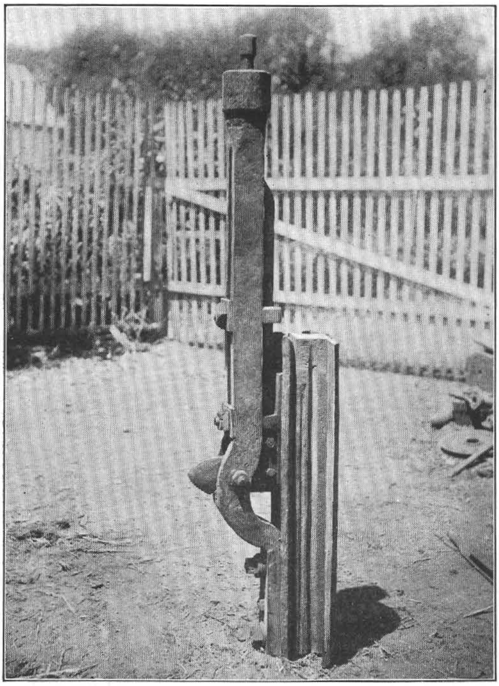


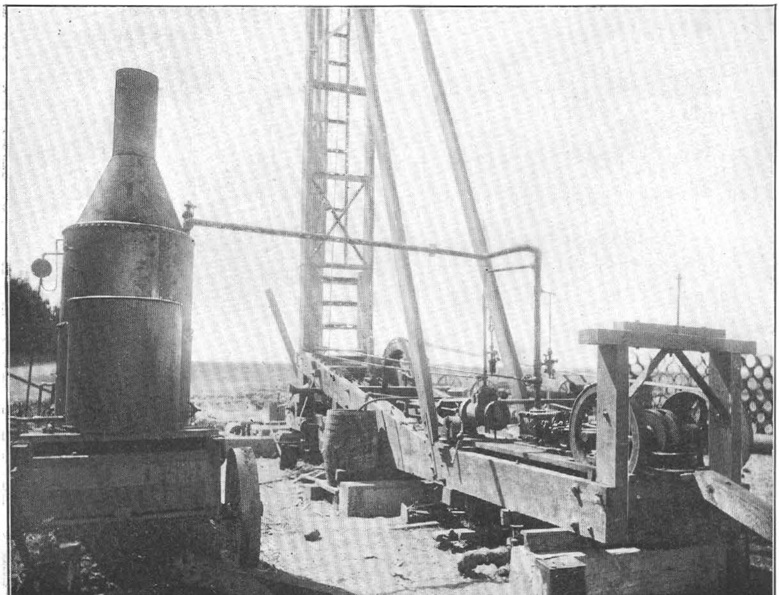
FIG. 63.—Plan and elevation of derrick for California well rig.

rigs according to their own ideas, so that no two rigs are exactly alike—that is, the drillers pick out the castings and working parts and mount them according to ideas that experience has taught them are the best for the wash formations in which they must work. A scale drawing of derrick is shown in fig. 63.

In Pl. XV is shown another excellent California rig owned by Mr. J. B. Proctor, of Compton, Los Angeles County. As it appears

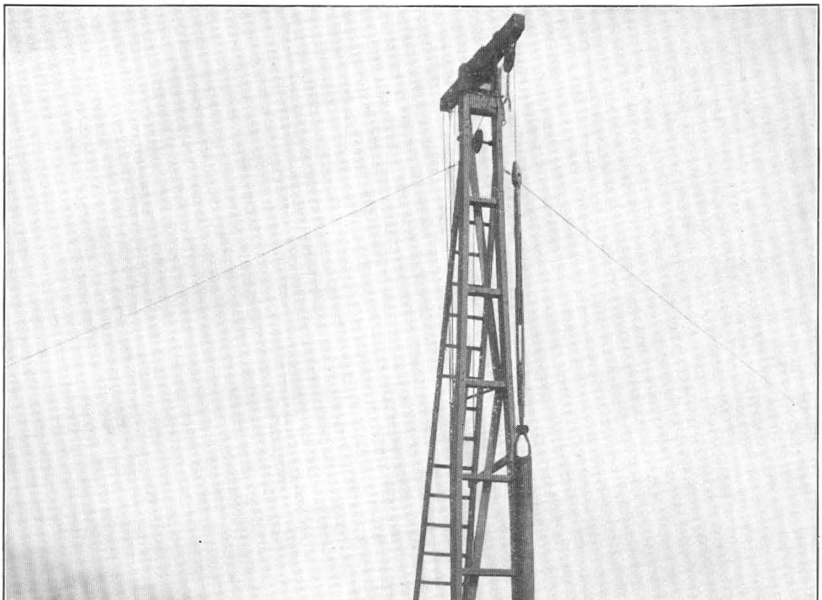


A. PERFORATOR FOR SLITTING STOVEPIPE CASING.



B. REAR VIEW OF CALIFORNIA WELL RIG.

Showing engine and hydraulic pump.



CALIFORNIA WELL RIG AFTER COMPLETING 12-INCH WELL FLOWING 5,250,000 GALLONS PER TWENTY-FOUR HOURS.

in the cut it has just finished a 12-inch well which flows 404 miner's inches, or about 5,250,000 gallons per twenty-four hours. This well is 848 feet deep and has about 60 feet of perforations. Mr. Proctor used four hydraulic jacks in sinking this well, developing a pressure of 160 to 200 tons.

YIELD OF WELLS.

It is not very profitable to name individual wells of this type and give their yield, since conditions vary so much from place to place. From the method of construction it must be evident that this type of well is designed to give the very maximum yield, as every water-bearing stratum can be drawn upon. The yield from a number of wells in California of average depth of about 250 feet, pumped by centrifugal pumps, varied from about 25 to 150 miner's inches, or from 300,000 to 2,000,000 gallons a day. These are actual measured yields of water used for irrigation.

Among the very best flowing wells in southern California are those near Long Beach. The Boughton well, the Bixby wells, and the wells of the Sea Side Water Company are 12-inch wells varying from 500 to 700 feet in depth and flowing about 250 miner's inches each, or over 3,000,000 gallons per twenty-four hours. The well shown in Pl. XV is located about 4 miles northeast of Long Beach and its flow is the greatest yet reported.

Among the records of depth are those of 1,360 feet for 10-inch well and 915 feet for 12-inch well. Mr. Proctor has bored a 14-inch well more than 704 feet in depth.

CHAPTER IX.

TESTS OF TYPICAL PUMPING PLANTS.

In connection with the general discussion of movement of underground waters it has been thought that a few descriptions of characteristic tests of pumping plants would be of interest and value. With this idea in view a number of typical plants, including several different classes, have been selected from the large number examined and descriptions of the tests prepared.

The Felix Martinez pumping plant is run by electric power and gives a good chance to see what can be done with combination of centrifugal pump and electric motor in the recovery of water for irrigation. The pumping plant of J. A. Smith is of special interest on account of a very low cost of power, due to the use of petroleum gas generated from crude oil. The test of Roualt's pumping plant is of great interest on account of the use of steam engine with wood as fuel. The wood was obtained at a very low price per cord, yet the showing in the cost per acre-foot will not compare with the plants that use gasoline engines with gasoline at 17 cents a gallon. The last pumping plant reported upon, that of the Horaco Ranch Company's well No. 1, is of special interest on account of the all-around excellence and efficiency of the plant. The table that is inclosed summarizes the results at all of the plants and gives items of cost.

TEST OF PUMPING PLANT OF FELIX MARTINEZ NEAR EL PASO, TEX.

The pumping plant on the ranch of Mr. Felix Martinez, of which a test was made, is located near the main county road east of El Paso, about 3 miles from the court-house. The plant consists of a No. 5 Byron Jackson horizontal-shaft centrifugal pump, run by a General Electric 10-horsepower direct-current motor, type C. E., class 4. The pump is located in a pit, and is connected to a 6-inch well. The well is 68 feet deep, measured from the surface of the ground, and has 10 feet of perforated or slotted galvanized-iron strainer at the bottom. The gravels were reached at a depth of 56 feet, and consisted of fairly large gravel, containing a large quantity of fine sand. The pump is connected with the well by a 5-inch suction pipe and discharges through a vertical and horizontal 5-inch discharge pipe into a rectangular flume. The discharge was measured by integrating with a Price acoustic current meter in the rectangular flume. The average depth of water at the cross section of flume where measurements were taken was 0.475 foot. The average width of flume was 0.992 foot, giving an area of 0.470 foot. The mean velocity of the water at the selected

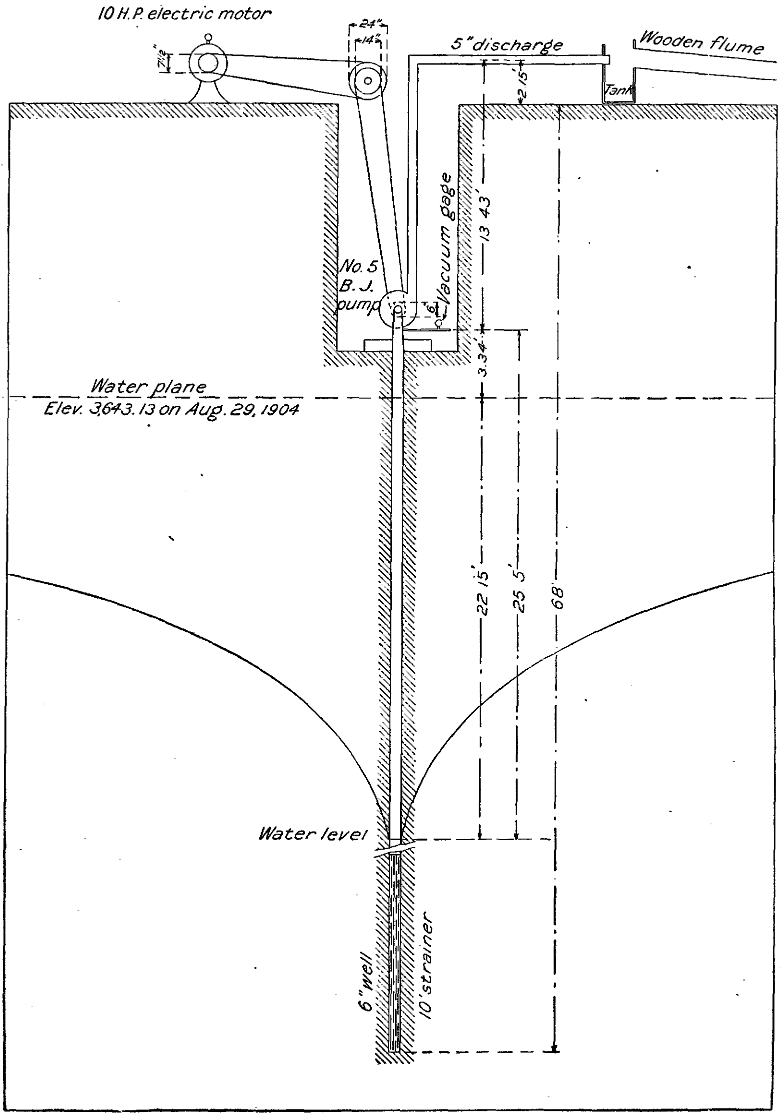


FIG. 64.—Conditions at pumping plant of Felix Martinez near El Paso, Tex.

cross section was 1.78 feet per second, giving total discharge of 0.838 cubic foot per second, or 378 gallons a minute.

The vacuum gage was attached to the goose neck of the certrifugal pump. The vacuum shown after a few minutes pumping was 18 inches, but it gradually fell to 24½ inches at the close of the first half hour, where it remained constant during the next hour. The vacuum, when corrected for altitude, is equivalent to 22.5 inches of mercury, or 25.5 feet of water.

The elevation of the water plane on August 29, 1904, was 3,643.13 feet above sea level. The elevation of tap of vacuum gage was 3,646.47 feet. The elevation of top of discharge pipe was 3,659.90 feet. The total lift is, therefore, 38.93 feet, and the amount the water level in the well was lowered by pumping was 22.16 feet. From this the specific capacity of the well can be determined to be 17.5 gallons a minute. The area of the well strainer is 14.4 square feet, from which we conclude that the specific capacity for each square foot of well screen was 1.21 gallons a minute.

The amount of electric current used during the pumping was determined by means of a Westinghouse watt meter. The current used in one hour's test (average speed of motor, 1,485 revolutions a minute) was 4,950 watts. The speed of the pump was 1,028 revolutions a minute. The pulley dimensions are as follows: Pulley on motor, 7½ inches diameter; driven pulley on countershaft, 24 inches; driving pulley on countershaft, 14 inches; pulley on pump shaft, 6 inches.

The horsepower actually used at the plant is the equivalent of 4,950 watts, or 6.64 horsepower. The power represented by the discharge of 0.838 second-foot of water lifted 38.93 feet, is equivalent to 2,030 foot-pounds per second, which is equal to 3.7 effective horsepower. Comparing the applied horsepower, 6.64, with the effective horsepower, 3.7, the total efficiency of the plant is found to be 55.5 per cent. The duty of the plant can be found by comparing 4,950 watts, the electrical energy consumed in one hour, with 655,200 foot-gallons, the work done by the pump in one hour. The resulting duty is 132,400 foot-gallons of water per kilowatt hour of electric current.

At 5 cents per kilowatt per hour, the cost of power for raising the water at the Martinez plant was one twenty-seventh of a cent for each 1,000 gallons of water raised 1 foot, or $3.43 for each acre-foot of water recovered. The labor cost being very small in an electrically driven plant, the total cost per acre-foot, including depreciation, interest, labor, etc., did not exceed $5.75 per acre-foot.

TEST OF PUMPING PLANTS OF J. A. SMITH, NEAR EL PASO, TEX.

The pumping plants of J. A. Smith are located 8 miles east of El Paso, Tex., near the right of way of the Southern Pacific Railroad. There are two plants on the same ranch. At the first or older plant there are three wells arranged in a row, 40 feet apart. The pump pit is over the middle well, which is an 8-inch well, 62 feet deep, measured from the top of the ground. Fine sand and quicksand were encountered in sinking this well until a depth of 50 feet was reached, where coarse gravel containing much fine material was encountered. There was only 12 feet of this coarse gravel. Ten feet of slotted galvanized-iron strainer with hit-and-miss slits was placed at the bottom of this well. The east well is 6 inches in diameter and 73 feet deep. The gravel at this point was found to be 22 feet deep. A 16-foot slotted strainer was used in this well. The west well is also a 6-inch well and is 61 feet deep. The gravel was found to be 11 feet deep, and a 10-foot slotted strainer was used in the well. All of the strainers have $\frac{3}{16}$-inch by $1\frac{1}{2}$-inch slots, or perforations. The horizontal 8-inch suction pipe, which extends from the central well to the east and west wells, is 14 feet below the top of the ground.

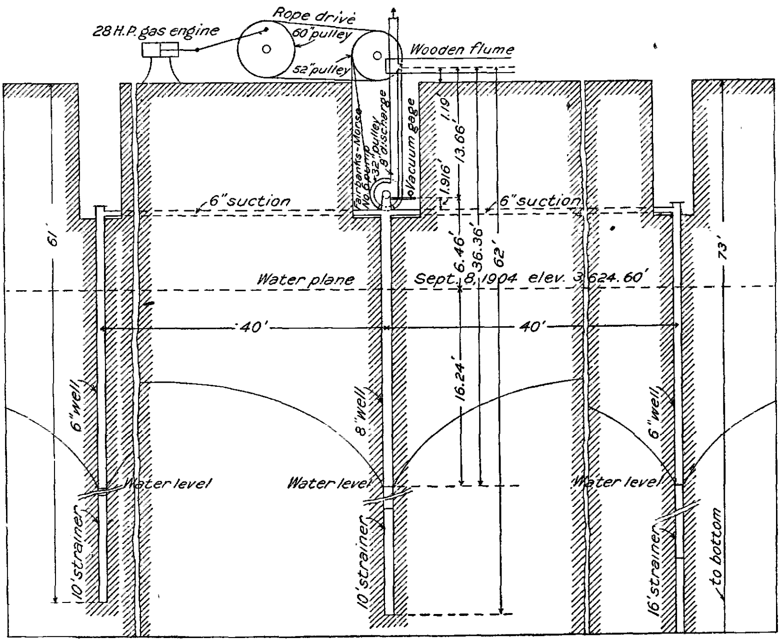


FIG. 65.—Conditions of pumping plant of J. A. Smith, near El Paso, Tex.

The water is pumped by a No. 6 Fairbanks-Morse horizontal-shaft centrifugal pump, connected with rope drive to a 28-horsepower gasoline engine, with crude oil gas generator attached. The fact that the engine is run by producer gas generated from Texas crude petroleum renders this plant of especial interest. The fuel cost relative to the amount of water recovered is the lowest that the writer has recorded for a small plant. The crude oil gas generator has been in operation several months, running continuously day and night, except for a cleaning each week or two. When the generator is kept clean there is little trouble from carbon passing from the generator into the cylinder of the engine and cutting out the cylinder and packing. The plant must be pronounced a decided success, as the further account to be given will show. The speed of the engine was 159, and of the pump 544 revolutions a minute.

The discharge was measured by integrating with a Price acoustic current meter in a rectangular flume. The average depth of the water at the selected cross section was 0.53 foot, and the average width was 1.87 feet, giving an effective cross section of 0.992 square foot. The average velocity of the water at this cross section was found to be 2.085 feet per second, giving a discharge of 2.075 second-feet or 934 gallons a minute. This measurement of discharge was made after three months of continuous pumping day and night. The elevation of the vacuum-gage tap was 3,631.06, and it was located 1.917 feet above the top of horizontal suction pipe. The elevation of the water plane on September 8, 1904, was 3,624.60, and the elevation of the middle of the 8-inch opening in the tee in the side of vertical discharge pipe, from which the water enters a horizontal wooden flume, was 3,645.05. The vacuum read 22 inches, or 20 inches of mercury when corrected for altitude, which is equivalent to 22.7 feet of water. The total lift is therefore 36.7 feet. The water is lowered in the wells 16.24 feet by pumping, which gives a specific capacity for the three wells of 57.4 gallons a minute. The total area of surface of the strainers in all of the wells is 56.7 square feet, from which we can deduce a specific capacity of 1.01 gallons a minute for each square foot of strainer.

Several accurate tests of the amount of fuel consumed at this plant have been made. One test was made by the manufacturers of the gas generator, and, consequently, the consumption of crude oil appears at a minimum in this test. This test lasted seventy-four hours and fifteen minutes. The amount of crude oil consumed was 241 gallons, or 3.24 gallons per hour. At 3 cents a gallon this makes the cost for oil $2.34 per day of twenty-four hours. The cost for each 1,000 gallons of water recovered was therefore 1¾ mills, or ten fifty-sevenths of a cent. This is at the rate of 57 cents per acre-foot of water. The lift being 37 feet, this makes the cost of 1,000 gallons lifted 1 foot (1,000 "foot-gallons") one two hundred and tenth of a cent.

Another experimental test of the plant was made when the engine was in charge of the regular help employed on the ranch. No effort was made to save oil or make a record, everything being managed exactly as it was during several months of pumping for irrigation. The test was for forty and one-half hours, extending over four consecutive days of about ten working hours each. The amount of crude oil used was 163.5 gallons, or 97 gallons per twenty-four hours, or 4.03 gallons per hour. This represents, therefore, the actual rate at which oil was consumed during the irrigation season. The cost is $2.90 per twenty-four hours, or 12 cents per hour. The cost of fuel for each 1,000 gallons of water delivered was ten forty-sixths of a cent, and the cost of 1,000 foot-gallons was one one hundred and seventy-first of a cent.

The cost of the water at the same plant, when pumped with gasoline, was also determined. A test of eleven hours' run with same engine, using gasoline instead of crude oil gas, consumed 40 gallons of gasoline, or 3.64 gallons per hour. At 14 cents a gallon, the hourly cost for gasoline was $0.51, which makes the cost of each 1,000 gallons of water pumped $0.0092. The cost per 1,000 foot-gallons was $0.000236, or one forty-second of a cent.

The above estimates do not represent, of course, the total cost of pumping, as no items have been included to cover interest, depreciation, labor, etc.

The 926 gallons a minute furnished by the above plant amounts to a little over 2 second-feet, or 4 acre-feet per twenty-four hours. The cost of fuel per acre-foot of water was, therefore, 73 cents when using crude oil, and $2.99 an acre-foot when using gasoline at 14 cents a gallon.

TEST OF ROUALT'S PUMPING PLANT NEAR LAS CRUCES, N. MEX.

A test was made at the pumping plant of Theodore Roualt, located on a ranch about 3 miles northwest of Las Cruces, N. Mex. Water is obtained from a 10-inch well, 48 feet deep, containing 10 feet of 9¾-inch slotted galvanized-iron strainer. Water is recovered by a No. 3 Van Wie vertical-shaft centrifugal pump, driven by a 10-horsepower Nagle steam engine, on 18-horsepower horizontal wood-burning boiler. The engine is directly belted to pump shaft by means of 30-inch driving and 12-inch driven pulley. The water is discharged through an 8-inch vertical discharge pipe into a rectangular flume.

The speed of engine was 205 revolutions per minute, and that of the pump was 525. The steam pressure varied between 81 and 83 pounds. The distance from vacuum-gage tap to the water plane was 3.64 feet. The distance of vacuum-gage tap to top of bottom plank of flume was 7.96 feet, and from tap to top of water jet the distance was 8.66 feet.

The vacuum gage read 24.25 inches, which is equivalent, when corrected for altitude, to 22.25 inches of mercury, or 25.5 feet of water, making the total lift 34.16 feet. The discharge was measured by integrating with a Price acoustic current meter in the rectangular flume. The width of flume was 1.19 feet and the average depth of water at the selected cross section was 0.35 foot, giving a cross section of 0.417 square foot.

The average velocity of the water at the selected cross section was 1.867 feet per second, which gives a discharge of 0.78 second-foot, or 351 gallons a minute. From this we deduce the specific capacity of the well to be 16.3 gallons a minute, and the specific capacity for each square foot of well strainer is 0.627 gallon a minute.

The cost of fuel used for pumping can be readily estimated from careful tests by Mr. Roualt. For one irrigation of a 70-acre field of tomatoes, twenty-eight days of twenty-four hours were required, and

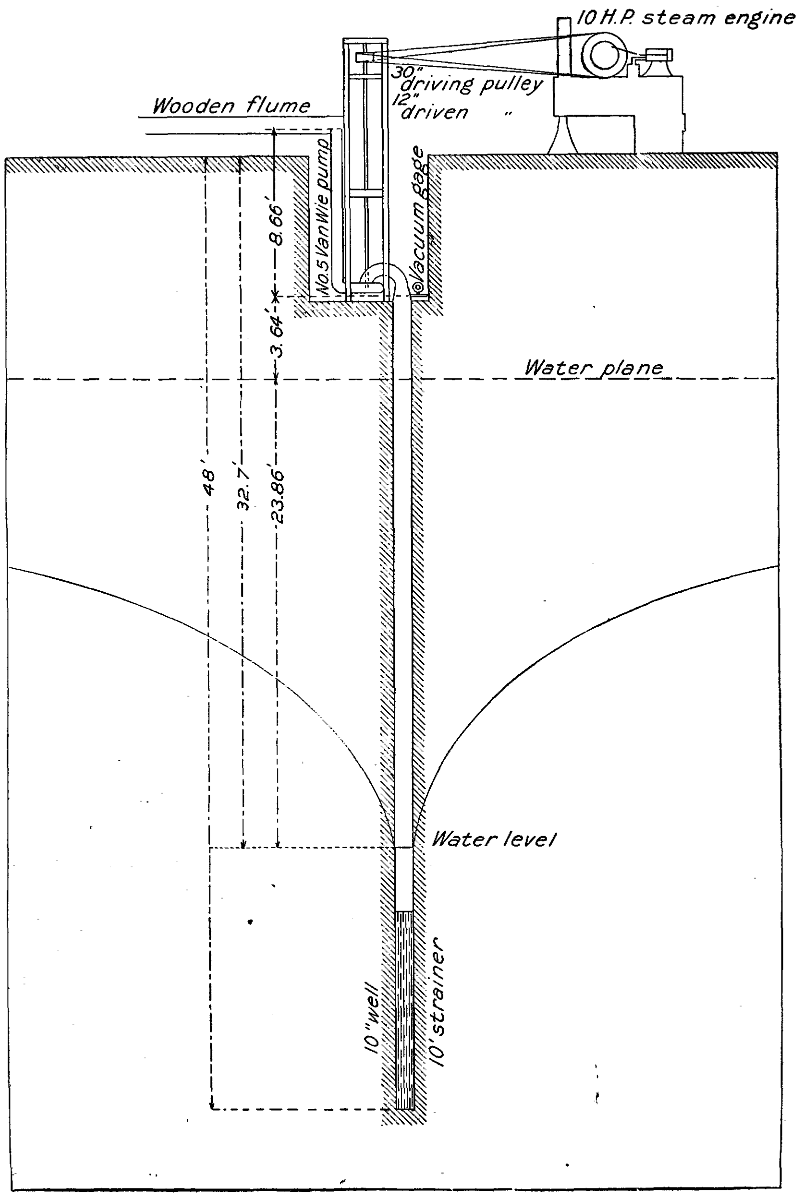


FIG. 66.—Conditions at pumping plant of Theodore Roualt near Las Cruces, N. Mex.

75 cords of cottonwood were consumed by the engine, costing $2 per cord. During the twenty-eight days of twenty-four working hours each, 14,150,000 gallons, or 43.5 acre-feet, of water were pumped.

The total cost of wood being $120, the fuel cost per 1,000 gallons of water recovered was $1.06, or $3.45 per acre-foot. The fuel cost per 1,000 foot-gallons was $0.00031, or about one thirty-second of a cent.

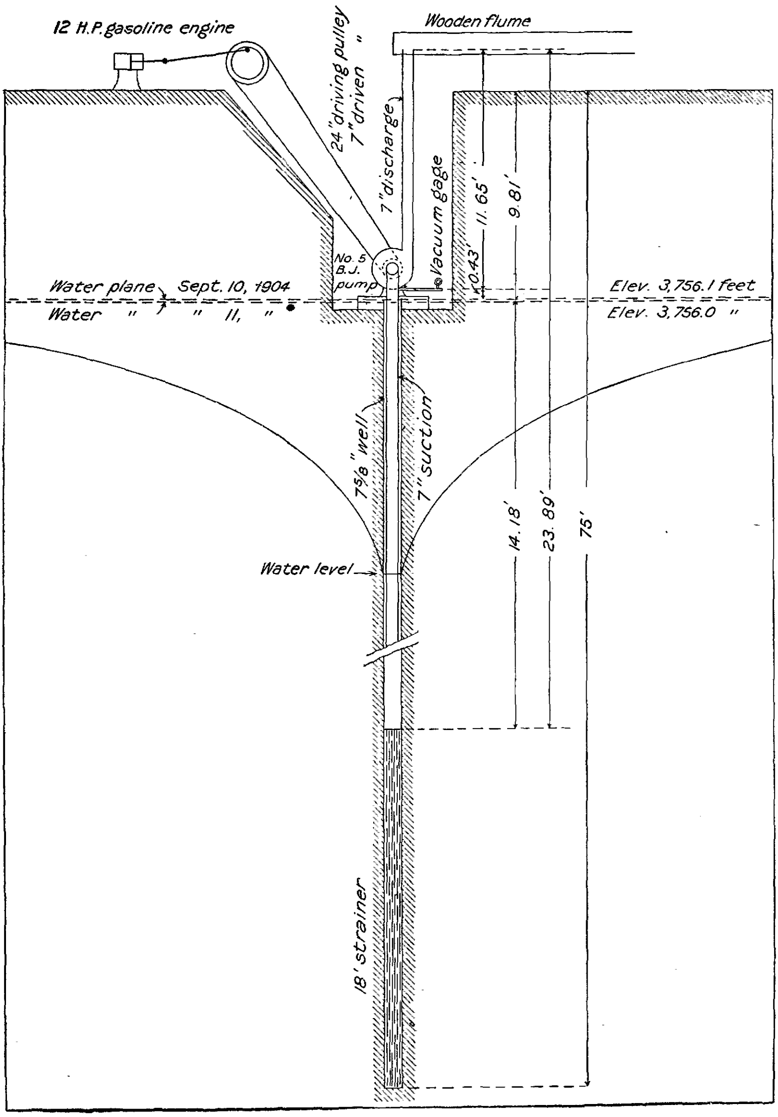


FIG. 67.—Conditions at Horaco Ranch Company's well No. 1, at Berino, N. Mex.

TEST OF HORACO RANCH COMPANY'S WELL NO. 1, BERINO, N. MEX.

Well No. 1 of the Horaco Ranch Company, at Berino, N. Mex., is 75 feet deep, constructed with $9\frac{5}{8}$-inch casing, with 18 feet of Mott strainer. Water is delivered through a $7\frac{5}{8}$-inch vertical discharge-pipe opening into a horizontal wooden flume. Water is recovered by a No. 5 Byron Jackson horizontal-shaft centrifugal pump, driven by a 12-horsepower Weber gasoline engine. The engine was run at a speed of 238 revolutions a minute, the number of explosions being 106 a minute. The speed of the pump was 815 revolutions a minute, it being belted directly to the engine from a 24-inch driving and a 7-inch driven pulley.

The distance from vacuum-gage tap to the water plane on September 11, 1904, was 0.43 foot. The distance of vacuum-gage tap to top of ground was 7.1 feet, and from tap to the end of vertical discharge pipe was 8.95 feet. To this may be added 0.762 foot, the height of water jet above the end of discharge pipe, to obtain the total lift above the vacuum-gage tap. The vacuum gage read 14.5, which, when corrected for altitude, is equivalent to 12.5 inches of mercury, or 14.18 feet of water. The total lift of the pump was, therefore, 23.89 feet.

The discharge was measured by integrating with a Price acoustic current meter in the rectangular flume. At the selected cross section the average depth of the water was 0.278 foot, and the average width was 1.42 feet, giving an area of cross section of 0.395 square foot. The average velocity of the water at the selected cross section was 4.707 feet per second, from which we conclude that the discharge was 1.86 second-feet, or 837 gallons a minute.

The water level in the well was lowered 13.75 feet during pumping, and therefore the specific capacity of the well is 60.8 gallons a minute, or 1.69 gallons a minute for each square foot of well strainer.

Although the amount of water recovered at well No. 1 is very materially greater than at well No. 3, the cost for fuel is substantially the same. The amount of gasoline consumed is slightly less than 1.2 gallons an hour, which at 17 cents a gallon makes the hourly cost 20 cents. The amount of water recovered being 837 gallons a minute, or 50,220 gallons an hour, the fuel cost for each 1,000 gallons of water was $0.004, or $1.30 per acre-foot of water recovered. The lift at well No. 1 being 23.89 feet, the cost of fuel for each 1,000 foot-gallons was $0.000167, or one-sixtieth of a cent.

SUMMARY OF RESULTS OF TESTS OF PUMPING PLANTS IN THE VALLEY OF THE RIO GRANDE IN LOWER PART OF NEW MEXICO AND WESTERN END OF TEXAS.

The accompanying table shows the results of tests of a number of pumping plants used for irrigation, and situated in the valley of the Rio Grande in the lower part of New Mexico and the western end of Texas. Most of the entries on the table explain themselves. Under the heading "Location" is given the nearest post-office to the ranch on which the pumping plants are located. The first three pumping plants, those of Felix Martinez, W. N. French, and E. J. Hadlock, are located about 3 miles east of El Paso, Tex. The plants of J. A. Smith and J. S. Porcher are located in the valley of the Rio Grande about 8 miles east of El Paso, Tex. The pumping plants of Parker, Boyer, Burke, Carrera, Hager, Hines, Roualt, Totten, and the Agricultural College are located in the valley of the Rio Grande in the neighborhood of Las Cruces, N. Mex. The pumping plants of the Horaco Ranch Company are located near the post-office of Berino, N. Mex., which is situated 24 miles north of El Paso and 17 miles south of Las Cruces.

The fuel used in most of these pumping plants is gasoline, which term as here used includes the "distillate" manufactured from Texas crude oil, which is extensively used for fuel purposes. Its caloric value is somewhat less than that of the gasoline used in the Eastern States.

DETERMINATION OF VACUUM.

In all of the pumping plants except the one of E. J. Hadlock water was recovered by means of centrifugal pumps, which in nearly all cases were directly coupled to the top of the well casings. In order to determine the suction of the pumps, it was necessary to drill a hole in the goose neck of the centrifugal pumps and insert the vacuum gage. The measurements to determine the distance the pumps were required to lift the water were made from this vacuum-gage tap as datum in all cases. In column 6 is given the distance the pump is required to lift the water above the vacuum-gage tap. In column 7 the vacuum reading is given in feet of water. Therefore the total lift of the pump can be found in each case by adding the corresponding numbers in columns 6 and 7. In column 8 is given the distance that the natural level of the water in the well is lowered during pumping. If the vacuum gage had been placed at the exact level of the undisturbed ground water, the readings in column 8 would be identical with those in column 7. The numbers in column 8 are less than those in column 7, because in all cases the vacuum gage stood some distance above the natural level of the water in the well.

SPECIFIC CAPACITY.

The numbers in column 11 express the readiness with which the well furnishes water to the pump. The numbers in each case were found by dividing the numbers in column 10 by the corresponding numbers in column 8. These numbers therefore express the amount of water the well would furnish if the water level in the well was lowered but 1 foot. They constitute what is known as the "specific capacity" of the well, and are large in case of a good well and small in case of a poor well. (See Chapter VII.)

In column 12 there are given the same magnitudes as are expressed in column 11, reduced in each case to 1 square foot of well strainer.

Results of tests of pumping plants in the valley of the Rio Grande in New Mexico and Texas.

1. Name of plant.	2. Location.	3. Horse-power.	4. Fuel used.	5. Price of fuel.	6. Lift above vacuum.	7. Vacuum in feet of water.	8. Amount water is lowered.	9. Total lift.	10. Yield gallons minute.	11. Specific capacity.
					Feet.		*Feet.*	*Feet.*		*Gal. min.*
Felix Martinez	El Paso, Tex	10	Electricity	0.05	16.77	25.50	22.16	38.93	378	17.50
W. N. French	do	8	Gasoline	.14	12.65	18.05	13.35	30.70	269	20.20
E. J. Hadlock	do	5½	do	.14	5.20	22.60	13.03	27.80	258	19.80
J. A. Smith No. 1	do	28	Crude oil	.03	14.00	22.70	16.24	36.70	938	57.40
J. A. Smith No. 2	do	22	Gasoline	.14	15.45	26.10	21.00	41.45	1,325	63.20
J. S. Porcher	do	15	do	.14	12.80	23.07	20.59	35.87	658	32.00
F. C. Barker	Las Cruces, N. Mex	5	do	.17	20.18	25.40	22.48	45.58	131	5.83
E. M. Boyer	do	12	do	.17	17.60	22.70	19.76	40.30	658	33.30
F. Burke	Mesilla, N. Mex	21	do	.17	14.85	25.60	22.85	40.45	725	31.75
J. C. Carrera	Mesilla Park, N. Mex	8	do	.17	12.65	14.20	8.48	26.85	648	74.60
W. N. Hager	do	12	do	.17	17.17	17.60	15.20	34.77	325	22.30
A. L. Hines	Mesilla, N. Mex	8	do	.17	19.05	17.00	14.08	36.05	271	19.20
T. Roualt	Las Cruces, N. Mex	10	Wood	2.00	8.66	25.50	23.86	34.16	351	16.00
G. H. Totten	Mesilla, N. Mex	28	Gasoline	.17	16.95	26.40	22.50	43.35	464	20.60
Agricultural College	Mesilla Park, N. Mex	20	Wood	2.25	17.10	12.45	11.37	29.55	1,000	88.00
Horaco Ranch Company No. 1.	Berino, N. Mex	12	Gasoline	.17	9.71	14.18	13.75	23.89	837	60.80
Horaco Ranch Company No. 2.	do	12	do	.17	10.36	24.90	23.64	35.26	191	8.10
Horaco Ranch Company No. 3.	do	12	do	.17	11.56	20.80	18.55	32.36	750	40.40

1. Name of plant.	2. Location.	12. Specific capacity per square foot strainer.	13. Cost of plant.	14. Interest and depreciation.	15. Labor and other cost.	16. Fuel cost per hour.	17. Fuel cost 1,000 foot-gallons.	18. Fuel cost per acre-foot.	19. Total cost per acre-foot.
		Gal. min.		*Per hour.*	*Per hour.*		*Cents.*		
Felix Martinez	El Paso, Tex	1.21	$1,200	$0.108	$0.050	$0.243	$\frac{1}{27}$	$3.43	$5.75
W. N. French	do	1.37	800	.072	.120	.112	$\frac{1}{44}$	2.26	6.13
E. J. Hadlock	do	.792	800	.072	.140	.074	$\frac{1}{58}$	1.58	6.02
J. A. Smith No. 1	do	1.01	3,000	.270	.150	.0975	$\frac{1}{171}$	.70	2.96
J. A. Smith No. 2	do	1.37	2,200	.198	.150	.35	$\frac{1}{94}$	1.43	2.79
J. S. Porcher	do	1.28	1,500	.135	.150	.21	$\frac{1}{67}$	1.73	4.10
F. C. Barker	Las Cruces, N. Mex	.337	1,200	.108	.120	.09	$\frac{1}{40}$	3.73	13.20
E. M. Boyer	do	1.969	1,200	.108	.150	.163	$\frac{1}{98}$	1.34	3.47
F. Burke	Mesilla, N. Mex	.734	2,100	.189	.150	.34	$\frac{1}{52}$	2.52	5.17
J. C. Carrera	Mesilla Park, N. Mex	3.530	900	.081	.120	.177	$\frac{1}{59}$	1.48	3.16
W. N. Hager	do	.760	1,200	.108	.150	.31	$\frac{1}{22}$	5.14	9.57
A. L. Hines	Mesilla, N. Mex	1.790	800	.072	.120	.255	$\frac{1}{23}$	5.10	8.95
T. Roualt	Las Cruces, N. Mex	.627	1,200	.108	.180	.223	$\frac{1}{32}$	3.47	7.91
G. H. Totten	Mesilla, N. Mex	.760	2,500	.225	.150	.37	$\frac{1}{33}$	4.34	7.91
Agricultural College	Mesilla Park, N. Mex	2.780	2,000	.180	.200	.52	$\frac{1}{34}$	2.83	4.88
Horaco Ranch Company No. 1.	Berino, N. Mex	1.690	992	.090	.090	.16	$\frac{1}{75}$	1.04	2.21
Horaco Ranch Company No. 2.	do	.178	992	.090	.090	.204	$\frac{1}{20}$	5.80	10.90
Horaco Ranch Company No. 3.	do	.892	992	.090	.090	.16	$\frac{1}{89}$	1.16	2.46

The numbers in this column, therefore, express the amount of water in gallons per minute furnished by 1 square foot of well strainer under a head of 1 foot of water. They are a numerical expression of the degree of coarseness of the material in which the well is placed.

COST AND OPERATING EXPENSES.

In column 13 are given the costs of the various plants expressed in round numbers. These are in most cases an estimate at the rate of $100 per horsepower for the total cost of engine, pump, and wells. In a few special cases the cost is at a higher rate than the above. In estimating the expense of operating the various plants, the depreciation in the total value of the plant has been taken at 10 per cent, and the rate of interest at 8 per cent. It is difficult to make an accurate estimate of the amount of cost that should be charged up to the water recovered by an irrigation plant, on account of the presence of several unknown factors. If the plants were in operation every day in the year it would be relatively easy to make an accurate estimate of these factors in the operating expense. As it is, the plants are in operation for a longer or shorter period, depending upon circumstances, which vary from year to year. Most of the plants are used merely as an auxiliary to the supply of ditch water. In making the estimate of the charge for interest and depreciation it has been assumed that the plants are in operation for two thousand hours each season. This corresponds to a continuous twenty-four hours' daily use for three months, or two hundred days of ten hours each, and probably represents a fair average of the actual conditions.

In column 15 there is given a charge for labor and other expenses, including oil, batteries, and such other incidental expenses as are not properly included under the head of depreciation. The operation of the gasoline plants can easily be put in charge of unskilled labor, and for the smaller plants full time is not required of such labor.

FUEL COST.

That part of the operating expenses which is properly chargeable to fuel cost can be accurately determined. Column 16 expresses the cost for fuel per hour at the various plants. Column 18 expresses the cost per acre-foot of water recovered. In column 17 there is given the cost of fuel for lifting 1,000 gallons of water through a distance of 1 foot. For the purpose of comparison the results are expressed in fractional parts of a cent.

In column 5 is given the price of fuel. The price of gasoline is given in cents per gallon in barrel lots. The price of electricity is given in cents per kilowatt hour. Cost of wood at the ranch of T. Roualt is the cost of cottonwood per cord. The price of wood at the Agricultural College of $2.25 per cord is the rate for small Tornillo wood, which has a higher caloric value than the cottonwood used by Roualt.

COMMENTS ON THE RIO GRANDE PUMPING PLANTS.

The pumping plants of Martinez, French, Hadlock, Smith, and Porcher are all located in the bottom lands of the Rio Grande from 3 to 8 miles east of El Paso, Tex. From column 12 of the table it will be seen that the specific capacities of these wells per square foot of well strainer are nearly the same at the plants of Martinez, French, Smith No. 2, and Porcher, varying only between 1.21 gallons a minute at Martinez's well to 1.37 at French's well. These numbers, it should be remembered, give the amount of water furnished by each square foot of well strainer for 1 foot head of water. The numbers express, therefore, the degree of coarseness of the material in which the strainer is placed, provided, of course, that the well strainers themselves offer little or no resistance to the admission of water to the well. The specific capacity per square foot of strainer at the Smith plant No. 1 and the Hadlock plant is much smaller than the others. In the case of the Hadlock well there is no doubt but that this result is due to the fact that three of the Hadlock wells draw from surface water above a clay which overlies the sand and gravel from which the fourth well and the neighboring wells of Martinez and French draw their supply. In addition to this the strainers on these three wells of Hadlock consist of nothing but common pipe with drilled round holes. This poor form of strainer is sufficient in itself to cut down very materially the specific capacity of the wells.

The low specific capacity at Smith's plant No. 1 is probably due chiefly to a local deposit of fine-sized water-bearing sand. There is no covering layer of clay over the water-bearing sands and gravels at the location of these wells. The sands contain so little coarse material that fine sand is constantly being drawn into the wells by the pumps. This draft on the sand deposit at the east of the three wells at Smith's plant No. 1 is such that several wagon loads of gravel have been hauled from time to time and placed in the pit of the east well to replace the sand removed by the pumps.

The tests of the nine wells in the Rio Grande Valley near Las Cruces, N. Mex., form an interesting study. If we arrange them in order of their specific capacities per square foot of well strainer the list is as follows:

Specific capacity, per square foot of strainer, of nine wells in Rio Grande Valley near Las Cruces, N. Mex.

Name of well.	Gals. per min.	Name of well.	Gals. per min.
Carrera	3.530	Hager	0.760
Agricultural college	2.320	Totten	.760
Boyer	1.969	Roualt	.627
Hines	1.790	Barker	.337
Burke	.934		

The first three wells are located near the eastern edge of the river channel, and the high specific capacity of the wells is undoubtedly due to coarse mountain débris which has been deposited along the eroded edge of the mesa. The high specific capacity at Hines's plant seems to be exceptional to the general lower average prevailing in the intermediate district lying between the border of the mesa and the river channel, as is represented by the plants of Hager, Totten, Burke, and Barker. The low specific capacity of the Barker well is due in part to its small diameter, and it is to be classed, therefore, with the Burke, Totten, and Hager wells rather than with the Roualt well. This last well is close to the river channel. Its low specific capacity is an indication of the progressive fineness of the deposits as we approach the river from the mesa.

It should be considered that the specific capacities of the wells first named in above list are exceptionally high rather than that the others in the list are exceptionally low. Even the specific capacity of the Roualt well, of over one-third of a gallon a minute per square foot of well strainer, would be considered high in many parts of the country.

The specific capacity of the three wells on the Horaco ranch, near Berino, N. Mex., presents an interesting study. These plants are located but a few hundred feet apart and are identical in all respects except in the depth of the wells. The wells are 9⅝ inches in diameter, and each has 18 linear feet of well strainer at the bottom, formed by drilling 1½-inch holes in the 9⅝-inch casing and wrapping the casing with No. 8 galvanized-iron wire, leaving one-eighth inch space between. The enormous difference in the specific capacities of these wells is entirely due to the fact that No. 1 is 75 feet deep, No. 2 is 53 feet deep, and No. 3 is 62 feet deep. The small expense necessary to sink well No. 2 from a depth of 53 feet to a depth of 75 feet will change the cost of the water recovered from $10.90 per acre-foot to $2.21 per acre-foot.

The group of pumping plants near Las Cruces are for the most part very recently constructed, and changes will undoubtedly be made in many of the plants, based upon the experience of the present irrigation season. The wells at the Agricultural College were the first ones constructed in this part of the valley, and an excellent report of tests on these wells by Professors Vernon and Lester was issued in April, 1903. The very high specific capacity of the college wells has had its influence upon the construction of the other plants. With a few exceptions, we may say that the pumping plants in the Mesilla Valley have engines and pumps entirely too large for the wells, or, as may be preferably stated, the wells are too small for the pumps and engines. By comparing the high lifts recorded in column 9 of the table with the amount of lowering of the water in the wells, which is recorded in column 8, it will be seen that the lift of many of the plants can be considerably decreased by increasing the amount of strainer surface in the wells.

In most cases this will mean the construction of additional wells, as the strainer surface can not be otherwise sufficiently increased. The necessity of keeping the lift of the pump down to a minimum is greatly emphasized in irrigation plants, and large strainer surface is the first requisite.

The efficiency of the smaller plants can also be increased by the construction of storage reservoirs or ponds for the accumulation of water before it is used for irrigation. In this way the duty of the water can be considerably increased. Barker's plant is the only one having such reservoirs. For plants that yield over a second-foot of water the reservoir is undoubtedly of little additional value.

The determination of the speeds of the centrifugal pumps at the various plants showed that in many cases the speed had not been properly adjusted. In all cases the speeds were too high. This was undoubtedly due to the fact that the vacuum had never been determined, so that the total lift of the pump was unknown.

INDEX.

O

PUBLICATIONS OF UNITED STATES GEOLOGICAL SURVEY.

[Water-Supply Paper No. 140.]

The serial publications of the United States Geological Survey consist of (1) Annual Reports, (2) Monographs, (3) Professional Papers, (4) Bulletins, (5) Mineral Resources, (6) Water-Supply and Irrigation Papers, (7) Topographic Atlas of United States—folios and separate sheets thereof, (8) Geologic Atlas of the United States—folios thereof. The classes numbered 2, 7, and 8 are sold at cost of publication; the others are distributed free. A circular giving complete lists may be had on application.

Most of the above publications may be obtained or consulted in the following ways:

1. A limited number are delivered to the Director of the Survey, from whom they may be obtained, free of charge (except classes 2, 7, and 8), on application.

2. A certain number are allotted to every member of Congress, from whom they may be obtained, free of charge, on application.

3. Other copies are deposited with the Superintendent of Documents, Washington, D. C., from whom they may be had at prices slightly above cost.

4. Copies of all Government publications are furnished to the principal public libraries in the large cities throughout the United States, where they may be consulted by those interested.

The Professional Papers, Bulletins, and Water-Supply Papers treat of a variety of subjects, and the total number issued is large. They have therefore been classified into the following series: A, Economic geology; B, Descriptive geology; C, Systematic geology and paleontology; D, Petrography and mineralogy; E, Chemistry and physics; F, Geography; G, Miscellaneous; H, Forestry; I, Irrigation; J, Water storage; K, Pumping water; L, Quality of water; M, General hydrographic investigations; N, Water power; O, Underground waters; P, Hydrographic progress reports. This paper is the forty-third in Series O, the complete list of which follows (PP=Professional Paper; B=Bulletin; WS=Water-Supply Paper):

SERIES O, UNDERGROUND WATERS.

WS 4. A reconnaissance in southeastern Washington, by I. C. Russell. 1897. 96 pp., 7 pls.
WS 6. Underground waters of southwestern Kansas, by Erasmus Haworth. 1897. 65 pp., 12 pls.
WS 7. Seepage waters of northern Utah, by Samuel Fortier. 1897. 50 pp., 3 pls.
WS 12. Underground waters of southeastern Nebraska, by N. H. Darton. 1898. 56 pp., 21 pls.
WS 21. Wells of northern Indiana, by Frank Leverett. 1899. 82 pp., 2 pls.
WS 26. Wells of southern Indiana (continuation of No. 21), by Frank Leverett. 1899. 64 pp.
WS 30. Water resources of the Lower Peninsula of Michigan, by A. C. Lane. 1899. 97 pp., 7 pls.
WS 31. Lower Michigan mineral waters, by A. C. Lane. 1899. 97 pp., 4 pls.
WS 34. Geology and water resources of a portion of southeastern South Dakota, by J. E. Todd. 1900. 34 pp., 19 pls.
WS 53. Geology and water resources of Nez Perces County, Idaho, Pt. I, by I. C. Russell. 1901. 86 pp., 10 pls.
WS 54. Geology and water resources of Nez Perces County, Idaho, Pt. II, by I. C. Russell. 1901. 87–141 pp.
WS 55. Geology and water resources of a portion of Yakima County, Wash., by G. O. Smith. 1901. 68 pp., 7 pls.
WS 57. Preliminary list of deep borings in the United States, Pt. I, by N. H. Darton. 1902. 60 pp.
WS 59. Development and application of water in southern California, Pt. I, by J. B. Lippincott. 1902. 95 pp., 11 pls.
WS 60. Development and application of water in southern California, Pt. II, by J. B. Lippincott. 1902. 96–140 pp.
WS 61. Preliminary list of deep borings in the United States, Pt. II, by N. H. Darton. 1902. 67 pp.
WS 67. The motions of underground waters, by C. S. Slichter. 1902. 106 pp., 8 pls.

B 199. Geology and water resources of the Snake River Plains of Idaho, by I. C. Russell. 1902. 192 pp., 25 pls.
WS 77. Water resources of Molokai, Hawaiian Islands, by W. Lindgren. 1903. 62 pp., 4 pls.
WS 78. Preliminary report on artesian basins in southwestern Idaho and southeastern Oregon, by I. C. Russell. 1903. 53 pp., 2 pls.
PP 17. Preliminary report on the geology and water resources of Nebraska west of the one hundred and third meridian, by N. H. Darton. 1903. 69 pp., 43 pls.
WS 90. Geology and water resources of a part of the lower James River Valley, South Dakota, by J. E. Todd and C. M. Hall. 1904. 47 pp., 23 pls.
WS 101. Underground waters of southern Louisiana, by G. D. Harris, with discussions of their uses for water supplies and for rice irrigation, by M. L. Fuller. 1904. 98 pp., 11 pls.
WS 102. Contributions to the hydrology of eastern United States, 1903, by M. L. Fuller. 1904. 522 pp.
WS 104. Underground waters of Gila Valley, Arizona, by W. T. Lee. 1904. 71 pp., 5 pls.
WS 110. Contributions to the hydrology of eastern United States, 1904; M. L. Fuller, geologist in charge. 1904. 211 pp., 5 pls.
PP 32. Geology and underground water resources of the central Great Plains, by N. H. Darton. 1904. 433 pp., 72 pls.
WS 111. Preliminary report on underground waters of Washington, by Henry Landes. 1904. 85 pp., 1 pl.
WS 112. Underflow tests in the drainage basin of Los Angeles River, by Homer Hamlin. 1904. 55 pp., 7 pls.
WS 114. Underground waters of eastern United States; M. L. Fuller, geologist in charge. 1904. 285 pp., 18 pls.
WS 118. Geology and water resources of east-central Washington, by F. C. Calkins. 1905. 96 pp., 4 pls.
B 252. Preliminary report on the geology and water resources of central Oregon, by I. C. Russell. 1905. 138 pp., 24 pls.
WS 120. Bibliographic review and index of papers relating to underground waters published by the United States Geological Survey, 1879–1904, by M. L. Fuller. 1905. 128 pp.
WS 122. Relation of the law to underground waters, by D. W. Johnson. 1905. 55 pp.
WS 123. Geology and underground water conditions of the Jornada del Muerto New Mexico, by C. R. Keyes. 1905. 42 pp., 9 pls.
WS 136. Underground waters of the Salt River Valley, by W. T. Lee. 1905. 196 pp., 24 pls.
B 264. Record of deep-well drilling for 1904, by M. L. Fuller, E. F. Lines, and A. C. Veatch. 1905. 106 pp.
PP 44. Underground water resources of Long Island, New York, by A. C. Veatch and others. 1905.
WS 137. Development of underground waters in the eastern coastal plain region of southern California, by W. C. Mendenhall. 1905. 140 pp., 7 pls.
WS 138. Development of underground waters in the central coastal plain region of southern California, by W. C. Mendenhall. 1905. 162 pp., 5 pls.
WS 139. Development of underground waters in the western coastal plain region of southern California, by W. C. Mendenhall. 1905. 105 pp., 7 pls.
WS 140. Field measurements of the rate of movement of underground water, by C. S. Slichter. 1905. 122 pp., 15 pls.

The following papers also relate to this subject: Underground waters of Arkansas Valley in eastern Colorado, by G. K. Gilbert, in Seventeenth Annual, Pt. II; Preliminary report on artesian waters of a portion of the Dakotas, by N. H. Darton, in Seventeenth Annual, Pt. II; Water resources of Illinois, by Frank Leverett, in Seventeenth Annual, Pt. II; Water resources of Indiana and Ohio, by Frank Leverett, in Eighteenth Annual, Pt. IV; New developments in well boring and irrigation in eastern South Dakota, by N. H. Darton, in Eighteenth Annual, Pt. IV; Rock waters of Ohio, by Edward Orton, in Nineteenth Annual, Pt. IV; Artesian well prospects in the Atlantic coastal plain region, by N. H. Darton, Bulletin No. 138.

Correspondence should be addressed to

THE DIRECTOR,
UNITED STATES GEOLOGICAL SURVEY,
WASHINGTON, D. C.

OCTOBER, 1905.

LIBRARY CATALOGUE SLIPS.

[Mount each slip upon a separate card, placing the subject at the top of the second slip. The name of the series should not be repeated on the series card, but the additional numbers should be added, as received, to the first entry.]

Author.

Slichter, Charles S[umner] 1864–

. . . Field measurements of the rate of movement of underground waters, by Charles S. Slichter. Washington, Gov't print. off., 1905.

122, iii p. illus., XV pl., diagrs. 23^{cm}. (U. S. Geological survey. Water-supply and irrigation paper no. 140)

Subject series: O, Underground waters, 43.

1. Water, Underground.

Subject.

Slichter, Charles S[umner] 1864–

. . . Field measurements of the rate of movement of underground waters, by Charles S. Slichter. Washington, Gov't print. off., 1905.

122, iii p. illus., XV pl., diagrs. 23^{cm}. (U. S. Geological survey. Water-supply and irrigation paper no. 140)

Subject series: O, Underground waters, 43.

1. Water, Underground.

Series.

U. S. Geological survey.

Water-supply and irrigation papers.

no. 140. Slichter, C. S. Field measurements of the rate of movement of underground waters. 1905.

Reference.

U. S. Dept. of the Interior.

see also

U. S. Geological survey.