REPORTS OF THE
DEPARTMENT OF CONSERVATION AND DEVELOPMENT
STATE OF NEW JERSEY

In cooperation with the United States Geological Survey—
Division of Ground Water—O. E. Meinzer, *Geologist in Charge*

BULLETIN 39

GROUND WATER SUPPLIES of the CAMDEN AREA, NEW JERSEY

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DAVID G. THOMPSON

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Board of Conservation and Development

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GROUND WATER SUPPLIES OF THE CAMDEN AREA, NEW JERSEY.

By David G. Thompson

INTRODUCTION.

This report is one of several setting forth the results of investigations as to the safe yield of the principal water-bearing formations in certain parts of New Jersey, carried on cooperatively by the New Jersey Department of Conservation and Development and the United States Geological Survey. Other areas in which similar studies have been made are the Atlantic City area;[1] the Asbury Park area; the Runyon area, including the Perth Amboy well field; the area embracing the well fields of the Commonwealth Water Co., the East Orange Water Department, and other municipalities near the Passaic River in the vicinity of Chatham; and the Garfield Water Department well field and those of several industries in the vicinity of East Paterson.

The results of the study in the Camden area are of value for several reasons. The greater part of the water supply of Camden comes from wells in three fields with an estimated capacity of about 30 million gallons a day, distributed over a triangular area of less than one square mile. This is one of the largest developments of ground water in so small an area in the United States. During the investigation a number of new wells were drilled in this area, and the type of wells and methods of pumping were changed, and observations were possible that otherwise could seldom be obtained under such favorable circumstances. As a result of the building of the new bridge across the Delaware River between Philadelphia and Camden there has been a considerable increase in population and in consumption of water in the Camden area, and this investigation is valuable in showing the extent to which further development of ground water is possible.

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[1] Thompson, David G., Ground water supplies of the Atlantic City region, New Jersey: N. J. Dept. Conservation and Development Bull. 30, 1928.

The observations on which the report is based were made in the period from July 1, 1923, to the date of writing the report, in the early part of 1928.[1] The continuing observations have been confined essentially to the well fields of the Camden Water Department. Certain data in regard to other well fields within a radius of 10 miles of Camden, collected by F. Clark Rule under the direction of the writer in the summer of 1923, and other data obtained from the files of the Department of Conservation and Development are also included in so far as they bear on the problems under consideration. The City of Camden has cooperated heartily through C. P. Sherwood, formerly director of the Department of Streets and Public Improvements, his successor, W. D. Sayrs, Jr., James H. Long, maintenance engineer of the Water Department, and David B. Owen, chief engineer of the Morris pumping station. Much valuable information has been furnished by the Layne-New York Co., which, during the period of the investigation, replaced nearly all the old-type wells of the Camden system with those of the most modern type. The investigation was under the immediate supervision of H. T. Critchlow, then chief of the Division of Waters of the Department of Conservation and Development, and O. E. Meinzer, geologist in charge of the Division of Ground Water of the United States Geological Survey. The late Dr. M. W. Twitchell, assistant State geologist, was consulted on phases relating to the stratigraphy. A number of analyses of water have been made by C. S. Howard, of the United States Geological Survey, and advice in regard to problems arising from the mineral character of the water has been given by W. D. Collins, chemist in charge of the Division of Quality of Water of the same organization. Thanks are also due to those of the other water departments and private well owners in the area who have furnished information.

SUMMARY OF REPORT.

Scope of report.—This report presents statistics of water consumption from public supplies and some private supplies in an area in New Jersey that lies within a radius of 10 miles of the city hall at Camden. Nearly all of the water comes from two formations, and the report is confined to a study of conditions in these formations. Furthermore,

[1] Although this report was completed in June, 1928, publication has been unavoidably delayed. Since its completion changes have been made in some of the sources of public supply, notably through drilling additional wells within the city of Camden, and in the Delair field. It is believed, however, that these changes need cause no change in the general conclusions presented in this report.

attention is confined almost wholly to the results of observations on the three principal well fields of the Camden Water Department insofar as they yield information as to the water-bearing capacity of the formations.

Water supplies of the area.—The public water supplies of the Camden area are furnished by 15 municipally or privately owned systems, of which that of the Camden Water Department is much the largest. In 1926 the average daily consumption of water from all public supplies was nearly 28 million gallons, of which 85 to 90 per cent was supplied by four systems, and about 68 per cent was used in Camden. In addition, several million gallons a day is obtained from private wells. The total quantity of ground water used in the area is between 35 and 40 million gallons a day. This rate of pumpage is not depleting the ground-water storage to any noticeable extent, the water taken out being replaced by recharge from the surface.

Geologic conditions affecting occurence of water.—All but a small part of the ground water is obtained from the Magothy and Raritan formations, which consist of alternating beds of sand, gravel, and clay. These formations crop out in the western part of the area in an elongated belt, with an average width of about two miles, which extends southwest approximately parallel to the Delaware River. The Magothy formation rests on the Raritan formation, which is here the basal formation of the Cretaceous system and is underlain with pronounced unconformity by crystalline rock that contains practically no water. In the eastern part of the area the Magothy formation is overlain by other formations, some of which are water-bearing but which in this area are not used to any great extent.

Source of ground water.—The belt of land in which the Magothy and Raritan formations crop out in the Camden area covers about 36 square miles. If the water pumped from wells were all derived only from this belt the daily recharge would have to be about a million gallons to the square mile in order to replace the pumpage. The data indicate that the recharge per square mile of land area is not as high as this but that water probably seeps into the water-bearing formations from the Delaware River.

Effects of pumping in other parts of the area.—In the summer of 1923 data were collected in regard to public supplies and a few large private supplies obtained from wells in this area. That summer was a notably dry one, and in several communities there was a shortage of water. A study of the data shows that the shortage was due to inadequacy of the pumping equipment or distribution mains, to deterioration of wells, or to increase in consumption from year to year for which adequate provision had not been made. Nowhere in the area was there any indication of marked lowering of the hydrostatic head on the Magothy and Raritan formations as compared to the original static head. When new wells were installed or the old wells cleaned, yields comparable to the original yields were generally obtained.

Conclusions as to quantity of water.—The data obtained show that, in spite of the pumping of large quantities of water from the Magothy and Raritan formations for the Camden waterworks and other systems, there has been no permanent depletion of the supply, and except within about a mile of the three principal well fields of the Camden Water Department there has been very little lowering of the hydrostatic head of the water in these formations. It is evident that an additional large quantity of water can be developed without seriously depleting the supply, although some lowering of the head is to be expected as the rate of pumping is increased. Doubtless the capacity of the Camden well fields can be increased by increasing the capacity of the pumps and drawing the water to a lower level or by constructing new wells in these fields or in additions to them. It will not, however, be economical to take too large a quantity from these small areas, but rather the new developments should be made in other localities.

The public water supplies of the other towns in the Camden area can be considerably enlarged before the effect of pumping in any one locality will become serious. Nevertheless, it is desirable to begin a program of systematic observations on the effect of pumping in different parts of the area, in order to obtain adequate data upon which to base future developments.

Quality of Water.—The water from the Camden wells is generally of good quality except that at times the water from the distribution mains has contained much iron. Analyses made by the United States Geological Survey at a time when the excessive iron content was causing many complaints showed that the iron came almost wholly from certain wells in the Morris field. The water from some of the wells contained 40 parts per million or more of iron. After the wells were cleaned out and rescreened the iron content was reduced below the concentration at which it becomes troublesome. There is some evidence that the iron is not carried by the water as it leaves the formation but is due to corrosion of the well casing and of the mains of the distribution system. The alkalinity of the water from some of the wells is low, and there is therefore danger of more trouble from corrosion.[1]

It has been claimed that none of the water from the Camden wells is derived from the Delaware River, and differences between the composition of the river and well waters has been cited as evidence. As any water percolating from the river into the water-bearing formations would be mixed with water already in the formations, the differences in composition do not appear to warrant the conclusion that none of the ground water is derived from the river. If some of the water enters the formation from the river there is danger of contamination in the future. This danger will be even greater than now if there is any considerable diversion of water from the drainage basin of the Delaware River as has been suggested in recent years. Although there seems to be no immediate danger of contamination it is desirable that the sanitary quality of the water be kept under observation in order to detect the first signs of contamination.

WATER SUPPLIES OF THE AREA.

If a circle is drawn with its center at the city hall in Camden and a radius of 10 miles it will include the sources of water supply of practically all the principal suburbs of the city. With one or two unimportant exceptions the public water supply for this whole area is obtained from wells. The location of the different public supplies is shown on Plate 1.

Most of the city of Camden is supplied by the municipal water department, but the eleventh and twelfth wards, in the northern part of the city, are supplied by the New Jersey Water Co., formerly the Stockton Water Co.

[1] On the other hand, in certain parts of Camden newly drilled wells show high in iron content and in other areas the iron content is low. Moreover, exposures of the Raritan show considerable variation in the amount of iron at different horizons and in different parts of the same horizon, as evidenced by iron crusts, iron cemented sandstone and staining of the sand beds. It is entirely reasonable to assume that there are similar variations in the iron content of beds not so exposed, but traversed by ground waters. Hence variation in iron content may not be wholly due to local corrosion of well casings. H. B. K.

CAMDEN WATER DEPARTMENT.

Historical.—The first public water supply for Camden was furnished by a private company, which was incorporated in 1845.[1] The original pumping plant was near the foot of Cooper Street and presumably pumped water from the Delaware River. About 1854 the pumping plant was moved to Pavonia, near the point where Cooper Creek joins the Delaware River, in the northern part of the city. Water from the river was used until about 1898. The quality of the water gradually became unsatisfactory, and for several years prior to the shutting down of the Pavonia plant other possible sources of supply were investigated. One report, submitted in 1894, recommended the use of water from the Delaware River and the construction of an 80,000,000-gallon settling basin. However, public opinion seems to have favored the development of ground water in preference to river water. Test wells were sunk in several localities, and eventually it was shown that a large quantity of water could be obtained in the vicinity of Morris and Delair, on the Pennsylvania Railroad, about 5 miles northeast of the center of Camden.

In 1898 the supply from the Delaware River was replaced by water from wells in the newly developed Morris field, described below. With this change in water supply there was a remarkable decline in the number of cases of typhoid fever and of deaths from that disease.[2] This was a great achievement at a time when the sterilization of surface water to prevent disease was not as much practiced nor as well understood as at present. The water now furnished through the public distribution system comes from wells in several localities, but most of it comes from three well fields near the stations mentioned.

Morris field.—The largest well field, known as the Morris field, lies between the Delaware River and the Pennsylvania Railroad and extends from the railroad bridge over Pensauken Creek southwestward to Puchack Creek.[3] It is about 7,000 feet long and about 900 feet in maximum width and covers about 95 acres. In this field 101 wells were drilled, chiefly 8 inches in diameter, and most of them were used

[1] Manual of City Council, Camden, N. J., 1922; State Geologist Ann. Rept. for 1898, pp. 105-106, 1899.

[2] Report of the Chief Engineer for year ending June 30, 1907, Camden City Water Department, p. 70 and diagram 2, 1907.

[3] Some maps, including topographic maps of the United States Geological Survey, give the name of this creek as Pochack. The Camden Water Department, however, has adopted the spelling "Puchack" for its well field adjacent to this stream and that spelling is used in this report.

rate of 18 to 19 million gallons a day, which is about the same as the original aggregate yield of the old wells. The old wells were scattered throughout the city's Morris tract. They were generally less than 300 feet apart, and some were only 25 to 50 feet apart. Some of them were situated at the very edge of the Delaware River. In contrast, the nine new wells are all close to the landward or southeast side of the city's property and are 600 to 1,000 feet apart.

Delair field.—In 1915 the city put into service a system of 26 wells in a tract of 15 acres known as the Delair field. This field is a few hundred feet west of Delair station on the Pennsylvania Railroad, immediately north of the tracks leading to a bridge across the Delaware River. The wells are distributed over an area of about 15 acres and have about the same diameters and depths as the wells in the old Morris system. Some of the wells are covered by the river at high tide. They are pumped by suction with two centrifugal pumps, which force the water directly into the distribution mains. The original capacity of this system was about 5 million gallons a day, but in recent years the yield has decreased to about 3½ million gallons a day.[1]

City field.—In 1922 the city drilled four 26-inch wells of the gravel-wall type. These wells, known as City wells numbers 1 to 4, are in the central part of the city, several miles from the Morris and Delair well fields. Wells Nos. 1 and 2 are at the city yards on Federal Street, just south of Cooper Creek; well No. 3 is at the corner of Orchard and Sycamore Streets; and well No. 4 is in a park at Everett and Rose Streets. Well No. 2 was damaged during the construction of a viaduct near by and was abandoned in 1927. At that time another well was drilled at the corner of Kaighn Avenue and Third Street. These wells are equipped with high-duty turbine pumps, which force the water directly into the distribution main and increase the pressure in parts of the city that are far from the Morris station. Each well yields about 1½ million gallons a day.[2]

Puchack field.—In 1924 a new well field, known as the Puchack field, was put into service. This field is in the northeastern part of Delair, southeast of the River Road and directly south of Puchack Creek. It is about 2,000 feet east of the nearest wells in the Delair

[1] Since this report was written, these wells have been replaced (1930) by three wells of the Layne gravel-wall type, and the capacity of this field is now six million gallons a day.

[2] Four additional wells of the same type have recently been drilled in the city. No. 5 is at the Civic Center; No. 6 at Jackson and Ninth; No. 7 on Ninth near Florence; No. 8 at Mechanic near Ferry streets.

field and almost the same distance southeast of the nearest wells in the Morris field. The wells, five in number, range in depth from about 175 to 185 feet, are 26 inches in diameter, and are of the gravel-wall type. Four of them are along a line that extends from northwest to southeast and are about 450 feet apart; the fifth is about 400 feet south of this line (See pl. 2). Each well is equipped with a high-duty turbine pump, which forces water directly into the large main leading to the city. During an 8-hour test on October 16, 1924, the aggregate yield of the five wells was at a rate of 9 to 9½ million gallons a day.

Yields.—The tested yields of the several sources that constitute the Camden water supply are about 18 million gallons a day from the Morris field, 9 million gallons from the Puchack field, 3½ million gallons from the Delair field, and 6 million gallons from the four wells in the city, making a total of about 36½ million gallons a day.[1] The tests of the Morris and Puchack fields were each made when all or a part of the wells in the other field were shut down and when therefore there was not much mutual interference. (See pp. 43, 52.) Allowing for interference, however, the total yield is (1927) doubtless in excess of 30 million gallons.

The daily consumption, even in seasons of greatest use of water, has been less than 50 per cent of the rated yield of the system. However, there is no storage except for the 500,000-gallon reservoir at the Morris pumping station and a standpipe in the city with a capacity of 550,000 gallons, and it is therefore necessary to meet hourly fluctuations in consumption largely by changes in pumpage from the wells, During some daylight hours the consumption greatly exceeds that at night, and therefore the maximum pumping rate for short periods has approached much more closely the total capacity.

OTHER PUBLIC WATER SUPPLIES

New Jersey Water Co.—Next to that of the Camden Water Department the largest supply in the area is that furnished by the New Jersey Water Co., which serves several suburban communities. Prior to August, 1925, the properties now held by this company were operated by two separate companies, the Stockton Water Co., and the New Jersey Water Service Co. The Stockton Water Co. originally supplied water only to the eleventh and twelfth wards in Camden, but

[1] In 1930 the capacity of the Delair field was increased to six million gallons a day (see p. 9) and the new city wells have added an additional amount.

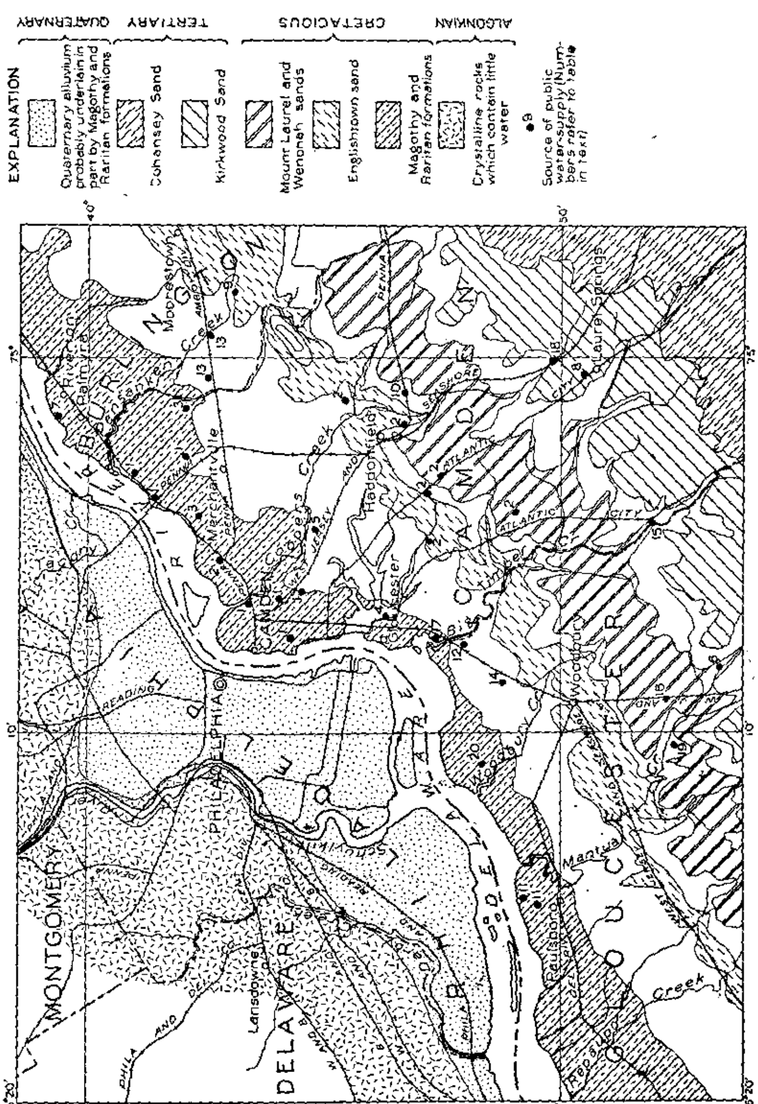

PLATE 1.—Map of Camden area showing principal water-bearing formations and location of sources of public water supplies.

until 1926. The location of these wells is shown on Plate 2. About one-fifth of the wells draw from a shallow water-bearing stratum and are only 50 to 70 feet deep; the others are between 90 and 125 feet deep. The water was pumped from the wells by suction through a system of collection mains, into a small collecting reservoir, and thence by high-duty pumps to the system of distribution mains. About 15 wells in the northern part of the field were pumped by air lift, and their water was discharged into the collecting reservoir by gravity.

In June, 1926, the many old wells in this field were replaced by nine new wells of gravel-wall type drilled by the Layne-New York Co. The old wells, however, have not been abandoned but are available for use in emergencies. These new wells are 26 inches in diameter and range in depth from 107 to 145 feet. They are pumped by individual low-duty turbine pumps, which deliver the water to a concrete reservoir with a capacity of about half a million gallons. From this reservoir the water is pumped into the city by four high-duty centrifugal pumps, each having a capacity of about 6 million gallons a day. In an 8-hour test on June 5, 1926, the yield of the new wells was at a

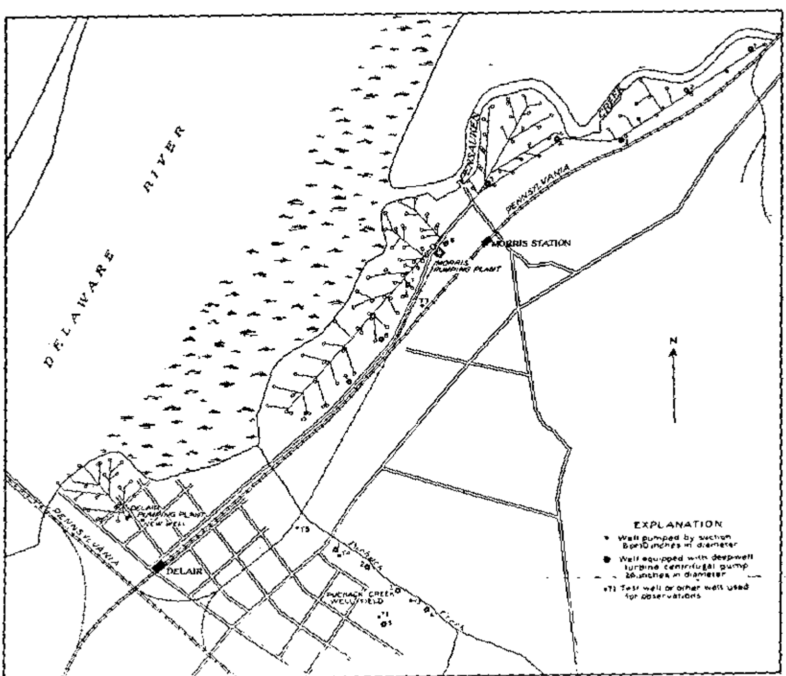

PLATE 2.—Map showing Morris, Puchack, and Delair well fields of the Camden Water Department.

now in addition it also serves territory in certain suburbs outside of the city limits. Its source of supply consists of several wells situated near Baldwins Run and the River Avenue, about 1¾ miles northeast of the Camden city hall. (See Pl. 1.) Most of the wells are 8 inches in diameter and about 120 feet deep. One well, drilled in 1924, is of the gravel-wall type, 26 inches in diameter and 135 feet deep.

Merchantville-Pensauken Water Commission.—The system of the Merchantville-Pensauken Water Commission, which ranks third in the area in quantity of water delivered, was formerly owned by the Merchantville Water Co. It furnishes water to Merchantville and Pensauken Township. The water supply is obtained from a well field on low land along the South Branch of Pensauken Creek, at a small settlement known as Jordantown, and from a single well situated on the River Road about a mile northwest of the center of Merchantville. The field at Jordantown contains 10 wells, which are 8 and 10 inches in diameter and about 115 to 266 feet in depth. The water from some of the wells contains considerable iron, and the entire supply is aerated and filtered before it is delivered to the distribution system. The well near the River Road is of the gravel-wall type, is 135 feet deep, and has a screen 26 inches in diameter. It is equipped with a high-duty turbine pump, which forces water directly into the distribution system. The yield of this well on a preliminary test was more than 1,000 gallons a minute.

Gloucester Water Department.—Gloucester is the only other city in the Camden area in which the average daily consumption is more than a million gallons. This system is supplied from six 8-inch wells about 185 feet deep, each with about 70 feet of screen. Additional wells were authorized under a grant of March 10, 1926, by the Board of Conservation and Development.

Smaller public supplies.—The average daily consumption of several smaller public supplies was about half a million gallons in 1926. Information in regard to some of them is given in other parts of this report.

PRIVATE SUPPLIES.

A large quantity of water is obtained from privately owned wells in the Camden area. At Paulsboro one company uses an average of 2.5 million gallons a day. On the basis of data obtained in regard to some of the largest of the private supplies it is estimated that the average daily consumption from privately owned wells in the Camden area is at least 10 million gallons.

CONSUMPTION.

Amount.—The average daily consumption from public supplies in the Camden area in the 10-year period 1917-1926 is given in the accompanying table. The data are based on reports filed with the Department of Conservation and Development. For many of the supplies reliable data prior to 1917 are not available.

In 1926 the average daily consumption of water from public supplies in the Camden area was 28.75 million gallons, 85 to 90 per cent of which was supplied by the four largest systems. Including the water delivered by the Stockton plant of the New Jersey Water Co., the consumption in the city of Camden in 1926 was about 68 per cent of the total in the entire area. All of this water was obtained from wells. Including about 10 million gallons a day pumped from private wells, the average daily consumption in the area in 1926 was close to 40 million gallons, all of which was obtained from wells.[1]

Increase in consumption.—The table furnishes valuable information in regard to the increase in consumption in the area. In the 10-year yeriod (1917-1926), the consumption from all public supplies increased nearly 10 million gallons, or about 50 per cent, over the consumption in 1917. The greatest increase was in the Camden supply—about 5 million gallons, or 40 per cent over the consumption in 1917. The greatest relative increase occurred in the territory supplied by the Chester Township Water Department, where the consumption in 1926 was more than 40 times that in 1917. Among the larger supplies the greatest relative increase occurred in the territory supplied by the Merchantville-Pensauken Water Commission, where the consumption in 1926 was nearly 7 times that in 1917. There was little or no increase in consumption from several supplies, owing largely to the installation of meters and to other measures to reduce waste of water. The increase in consumption in the Camden area may be attributed largely to more than normal growth in population resulting from the opening of the new bridge between Camden and Philadelphia. This bridge has made a large territory more easily accessible to Philadelphia and has attracted to the New Jersey side of the river a considerable number of people whose business is in that city.

[1] In this connection it is interesting to note that in 1931 the average daily consumption from public supplies for the same area was almost exactly the same as in 1926—29.02 million gallons—85 per cent of which was supplied by the largest systems. For the City of Camden in 1931 it was about 65 per cent of the total. It is evident, therefore, that estimates of future consumption made in 1926 (see p. 14) will probably need some revision downward.

Average daily consumption of water from public supplies in the Camden area, 1917-1926, in thousands of gallons.

No. on Pl. I.		1917	1918	1919	1920	1921	1922	1923	1924	1925	1926	1927
1	Camden Water Department	12,019	12,752	13,036	14,094	12,670	12,657	14,206	16,091	17,215	16,918	17,560
2	New Jersey Water Co., Stockton plant [a]	1,970	2,430	2,450	2,530	2,440 [b]	2,370	2,365	2,151	2,272	2,519	2,276
	Haddon Heights plant [c]	482	489	446	488	507	537	647	877	1,022	1,013	1,151
3	Merchantville-Pensauken Water Com. [d]	404	451	1,000	1,122	1,164	1,365	1,664	2,125	2,157	2,762	1,230
4	Gloucester Water Dept.	1,756	1,730	1,816	1,800 [b]	1,800 [b]	1,739	1,938	1,864	1,723	1,700 [b]	1,511
5	Collingswood Water Dept.	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	571 [m]
6	Woodbury Water Dept.	852	907	925	896	878	900	953	905	841	825	756
7	Riverton and Palmyra Water Co.	609	648	504	534	512	548	645	663	763	664	676
8	Laurel Springs Water Supply Co.	e	202	134	133	157	171	180 [b]	217	488	464	401
9	Moorestown Township Water Dept. [f]	409	412	382 [g]	389	405	405	462	481	471	478	372
10	Haddonfield Water Dept.	227	223	235	277	319	275	347	396	463	552	594
11	Borough of Paulsboro Water Dept.	162	206	199	171	179	218	349	289	364	383	421
12	Borough of Westville Water Dept. [h]	66	159	110	83	84	80	91	104	117	129	137
13	Chester Township Water Dept. [i]	5	5	5	9	10	17	31	62	98	134	183
14	Colonial Manor Water Co.	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	36 [n]
15	Blackwood Water Co.	30	36	42	50	48	67	83	96	96	96	96
16	Wenonah Water Dept.	e	40 [b]	e	e	e	e	81	e	e	97 [b]	90
17	Brooklawn Water Dept.	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	90
18	Lakeside Park Water Co.	4	4	4	4	5	3	3	4	4	7	10
19	Mantua Water Co. [k]	9	9	14	9	9	9	12	10	10	10	23
20	National Park Water Dept.	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	54
	Total of figures given above	19,004	20,703	21,302	22,589	21,187	21,361	24,057	26,335	28,104	28,751	28,238

[a] Stockton Water Co. prior to August, 1925, serving Eleventh and Twelfth Wards in Camden and part of Pensauken Township.

[b] Record incomplete, partly estimated.

[c] New Jersey Water Service Co. prior to August, 1925. The figures given include the following amounts of surface water—390,000 gallons a day in 1917; 352,000 in 1918; 331,000 in 1919; 324,000 in 1920; 312,000 in 1921; 319,000 in 1922; 315,000 in 1923; 359,000 in 1924; 532,000 in 1925. The rest was ground water.

[d] Merchantville Water Co. prior to June 30, 1926.

[e] No report received or record incomplete.

[f] Chester Township Water Department prior to June 26, 1922, but distinct from water department of same name which succeeded the Maple Shade Water Company (note i).

[g] Includes thirty-two (thousand?) gallons per day of surface water, balance from wells.

[h] Westville-Newbold Water Co. prior to July 1, 1926.

[i] Maple Shade Water Co. prior to July 1, 1923.

[k] Job Scott prior to July, 1924. Amounts given are estimates, not actual measurements.

[m] **Last seven months only.**

[n] **Last three months only.**

Future increase.—Without going into detail it is pertinent to consider briefly the probable future increase in consumption of water in the region. The increase in consumption from public supplies in the Camden area in the 10-year period 1917-1926 was about 50 per cent. If this percentage is maintained during successive 10-year periods, the average daily consumption would be approximately 43 million gallons in 1936, 65 million gallons in 1946, and 97 million gallons in 1956. On the other hand, the actual increase in consumption in the 10-year period was about 10 million gallons. If the future increase were to be at this rate the daily consumption would be only about 60 million gallons in 1956. Without a more detailed consideration of statistics it is impossible to say which of these estimates is more nearly correct, but it is reasonable to believe that the true figure may lie between the two estimates.[1]

Average daily consumption.—The following table shows the average daily consumption from the Camden water works in each month in 1925 and 1926. It shows that the consumption is greatest in summer. In 1925 the range in average daily consumption by months was from about 10 per cent below the average for the year to 25 per cent above it, and in 1926 it was from 10 per cent below to about 16 per cent above. However, the range is not as great as in some other localities, notably in the resort towns and cities along the coast. In Camden several million gallons a day is used by two large manufacturing plants,—the Campbell Soup Co., and the Victor Talking Machine Co.,—and the consumption fluctuates with the activities of these plants. The month of greatest consumption is September, which is in the season of peak production by the Campbell Soup Co.

Average daily consumption of water supplied by Camden Water Department, 1925-1926, by months, in thousands of gallons.

Month	1925	1926
January	16,838	16,432
February	16,159	17,096
March	15,735	16,763
April	15,420	17,233
May	15,615	17,160
June	18,095	15,210
July	17,646	16,519
August	19,278	18,513
September	21,438	19,696
October	17,288	16,804
November	16,796	15,426
December	16,257	16,177
The year	17,215	16,918

[1] See footnote on p. 12.

GEOLOGIC CONDITIONS AFFECTING OCCURRENCE OF GROUND WATER.

Geologic formations.—The Camden area is a part of the physiographic province known as the Atlantic Coastal Plain. The formations underlying this province consist principally of sand, gravel, and clay, beneath which, at depths of a few feet to many hundreds of feet in different parts of the province is the so-called "bed rock." In the Camden area the principal formations in general crop out in elongated bands that extend southwestward approximately parallel to the course of the Delaware River between Camden and Bordentown. The beds dip in a southeasterly direction, roughly parallel to a line drawn between Camden and Atlantic City. These geologic conditions are shown in a generalized way on Plate 1 and Figure 1.[1] Plate 1 shows only the principal water-bearing formations.

The geologic formations present in the Camden area and their essential characteristics are shown in the following table. The formations are arranged in the order of their age, the youngest at the top of the table.

Chief water-bearing formations.—Throughout the Camden area are scattered deposits of sand and gravel, with some clay, constituting the Cape May and Pensauken formations, of Pleistocene age, which overlie the older formations. The thickness of these deposits ranges from a few inches to 20 feet. As a whole, the materials are so permeable that water can pass easily through them and enter the underlying formations. The deposits doubtless contain much water, but because of their variable thickness and distribution they are not of value as water-bearing formations except for small supplies for domestic use. Only incidental consideration is given to them in the subsequent discussion of water-bearing formations of the area.

Exclusive of these Pleistocene deposits the water-bearing formations in this area are the Kirkwood sand, the Mount Laurel and Wenonah sands, the Englishtown sand, and the Magothy and Raritan formations. All these formations consist largely of sand and gravel. However, only the Magothy and Raritan are of much importance in this area. The others are found only in the eastern part, where they crop

[1] The map and cross section are based on Lewis, J. V., and Kümmel, H. B., Geologic map of New Jersey, New Jersey Dept. Conservation and Development, 1910-1912, and maps in U. S. Geol. Survey Geol. Atlas, Philadelphia folio (No. 162), 1909.

out or lie near the surface and doubtless supply shallow private wells. Nearly all the wells for public supplies are, however, drilled to the Magothy and Raritan formations, largely because they are known to be the best water-yielding formations and are within a reasonable distance of the surface. Farther east the depth to the Magothy and Raritan formations becomes increasingly greater, and it has been more economical to utilize the shallower formations. Data in regard to these formations are given in reports by the late M. W. Twitchell;[1] and the effects of pumping from some of them, in the Atlantic City and Asbury Park regions, are described in reports by the writer.[2]

Depth to bed rock.—The lowest sedimentary formation in the area is the Raritan formation. It rests on hard bed rock or basement rock. Where the bed rock crops out west of the Delaware River it consists of gneiss and other metamorphic rocks, and presumably it is much the same in the Camden area. The surface of the bed rock slopes in an easterly or southeasterly direction, so that its depth increases with distance eastward from Delaware River. It crops out at the West Philadelphia yards of the Pennsylvania Railroad, in Fairmount Park, and, farther northeast, just west of the New York line of that railroad where it crosses Tacony Creek at Frankford. In the north end of the Morris well field of the Camden Water Department the bed rock was struck at depths of 100 to 131 feet below sea level.[3] In wells recently completed in the southern part of this field bed rock was not struck at depths of 102 to 145 feet below sea level. In test well No. 1, about 450 feet southwest of well No. 3, in the Puchack well field and further from the Delaware River, the bed rock was about 205 feet below sea level. At Moorestown bed rock was struck at a depth of about 500 feet below sea level. Farther east the depth to bed rock becomes so great that it has not been struck in wells east of Moorestown; nor was it struck in a well 2,300 feet deep that was drilled at Atlantic City. The

[1] Twitchell, M. W., Important ground-water horizons in New Jersey: Report of the Water Policy Commission to Senate and General Assembly of New Jersey, pt. 2, pp. A46 A53, February, 1927; also unpublished report on ground waters of New Jersey.

[2] Thompson, D. G., Ground-water problems on the barrier beaches of New Jersey: Geol. Soc. America Bull., vol. 37, pp. 463-474, 1926; Ground-water supplies in the Atlantic City region: New Jersey Dept. Conservation and Development Bull., 30, 1928; Ground-water supplies in the vicinity of Asbury Park, Idem. Bull. 35, 1930; Memorandum on investigation of quantities of ground water available for public and industrial supplies in New Jersey: Report of the Water Policy Commission to the Senate and General Assembly of New Jersey, pp. A29-A40, February, 1927.

[3] State Geologist Ann. Rept. for 1898, p. 108, 1899.

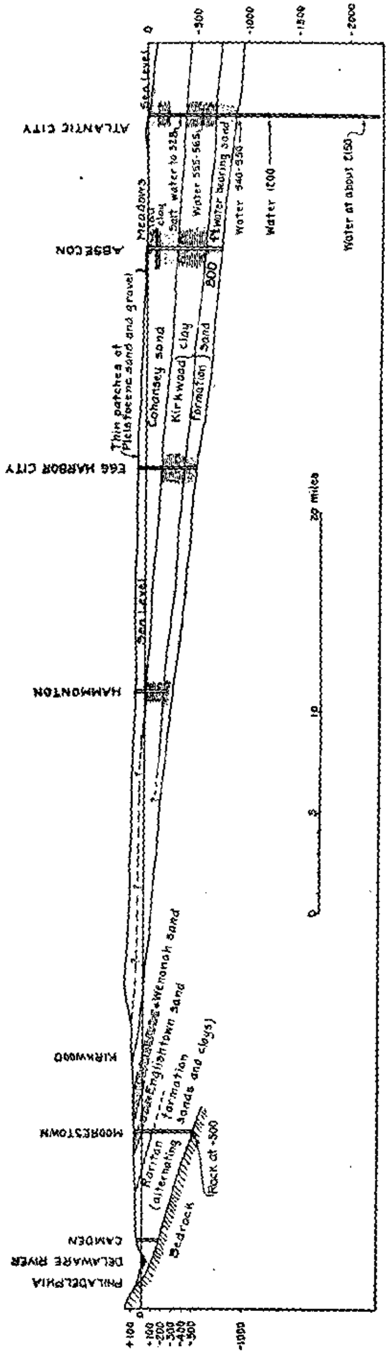

FIG. 1—Generalized cross section from Philadelphia to Atlantic City, showing principal water-bearing horizons.

GEOLOGIC FORMATIONS IN THE CAMDEN AREA [a]

Formation name	Thickness [b] (Feet)	Character, Distribution, Etc.
QUARTERNARY		
Cape May formation	0—20	Sand and gravel, with some clay, irregularly distributed; not important as a water-bearing formation.
Pensauken formation	0—20	Sand and gravel, with some clay, irregularly distributed; not important as a water-bearing formation.
TERTIARY		
Cohansey sand	100—250	Chiefly sand, with some gravel and clay. Does not occur in Camden area.
Kirkwood sand	100	Sand with beds of clay. Crops out only in a small part of Camden area and is not important as a water-bearing formation.
Vincentown sand	25—70	Principally calcareous sand or glauconitic quartz sand.
Hornerstown marl	30	Principally greensand glauconite marl and clay.
CRETACEOUS		
Navesink marl	25—40	Principally greensand marl.
Mount Laurel and Wenonah sands	40—80	A good water-bearing sand but not much used in Camden area.
Marshalltown formation	30—35	Principally black sandy clay or greensand marl.
Englishtown sand	20—100	A good water-bearing sand in northeastern part of Coastal Plain, but in Camden region the area underlain by this sand is not large and it is not much used for water supply.
Woodbury clay	50	Black nonglauconitic clay.
Merchantville clay	60	Black glauconitic micaceous clay.
Magothy formation Raritan formation	175—425	Alternating beds of sand, gravel, and clay. Principal water-bearing formations in Camden area.
ALGONKIAN		
Pre-Cambrian formations	....	Hard gneiss rock, which in the Camden area underlies sediments of the Coastal Plain and crops out on Pennsylvania side of Delaware River. Does not contain much water.

[a] Based chiefly on Lewis, J. V., and Kümmel, H. B., The geology of New Jersey: New Jersey Geol. Survey Bull. 14, 1915, and Geologic map of New Jersey, 1910-1912.

[b] Range in thickness indicated is for entire Coastal Plain and not merely for the Camden area.

bed rock is practically impervious and yields only small supplies of water from crevices in it. When it is struck in the Camden area it is considered useless to drill deeper.

The Magothy and Raritan formations.—The beds described as the Magothy and Raritan formations were formerly considered as one, the Raritan, but more recently they have been separated.[1] However, they are shown on the geologic map of New Jersey as a single unit, and for the purpose of this report they may be considered together. As shown on Plate 1, these formations outcrop on the east side of the Delaware River in a belt adjacent to the river. Presumably they also lie beneath the river and they are present in some locations west of the river, but are covered by sand and gravel beds of Quaternary age (principally Cape May and Pensauken formations).[2] On the geologic map in the Philadelphia folio no outcrop of these formations is shown west of the river in the area opposite Camden. In much of the area in New Jersey where they are shown on that map they are actually covered by beds of sand and gravel and clay belonging to the Cape May and Pensauken formations. The belt in which they are shown to outcrop has an average width of somewhat less than 2 miles but ranges in width from less than a quarter of a mile near Westville to 3 or 4 miles along Cooper Creek in Camden. This belt, from a point 10 miles southwest of Camden to a point 10 miles northeast of the city, covers about 36 square miles.

The Magothy and Raritan formations consist of alternating beds of sand, gravel, and clay. The Raritan formation is dominantly light colored, but the Magothy beds include some darker lignitic and glauconitic (greensand) material.[3] The beds are variable, and it is generally impossible to trace any well-defined bed for more than a few hundred feet. This is shown by the logs of the new wells in the Morris and Puchack fields. (See fig. 2.)

The sand and gravel penetrated in the new wells drilled in the Morris and Puchack fields appear to be very permeable and to yield water very freely. Some of the material consists of large gravel. In well No. 3 in the Puchack field cobbles 5 inches in diameter were found, and in test well No. 2 drilled by the city in the southeast corner of the same field cobbles 3 inches in diameter were common.

The maximum thickness of the Magothy and Raritan formations in the Camden area is about 240 feet, but owing to erosion in the Morris,

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[1] Lewis, J. V., and Kümmel, H. B., The geology of New Jersey: New Jersey Geol. Survey, Bull. 14, p. 64, 1915.

[2] Annual Report of the State Geologist of New Jersey for 1896, p. 111 *et seq.*

[3] Lewis, J. V., and Kümmel, H. B., op. cit., p. 64.

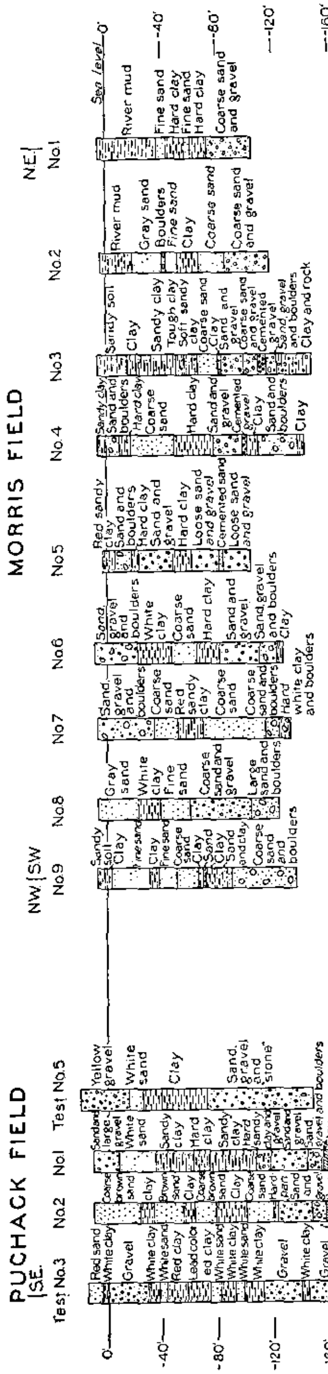

FIG. 2—*Logs of wells in the Morris and Puchack well fields.*

Puchack, and Delair well fields it is considerably less. In the wells in the Puchack field bed rock was struck at depths of 163 to over 205 feet below sea level. In a test well drilled a few hundred feet north of Pensauken Creek it was struck at only 70 feet. As some of the surficial materials in these places are of Quaternary age the thickness of the Magothy and Raritan beds is less than the depth to bed rock.

At the east edge of the area in which the Magothy and Raritan formations crop out the beds disappear beneath the Merchantville clay, which is a black clay about 60 feet thick. Farther east this clay is overlain by the Woodbury clay, which is about 50 feet thick. These clays are relatively impervious and prevent water from percolating through them into the Magothy and Raritan formations. Accordingly, all the water that enters the Magothy and Raritan must do so west of the outcrop of the Merchantville clay.

OBSERVATIONS ON WELLS OF THE CAMDEN WATER DEPARTMENT.

DETERMINATION OF THE SAFE YIELD.

Methods.—A large quantity of water is stored in the water-bearing formations in the Camden area. However, if the safe yield of these formations is not to be exceeded, the annual draft on them must not be more than the average quantity that is annually added to them. It therefore becomes an important problem to determine if possible the quantity added annually, or, as it is commonly called, the average annual recharge.

Meinzer[1] has described four groups of methods used to determine the annual recharge or safe yield of ground-water reservoirs. These he calls the intake, discharge, water table (or storage), and underflow (or flux) methods. In the study of the Camden area a different method was used that may be considered a modification of the water-table method. It consists largely of observations of fluctuations of the water levels in wells and of a study of their relation to fluctuations in the rate of pumping from the water-bearing formations. This method has also been used in the Atlantic City and Asbury Park areas.[2]

[1] Meinzer, O. E., Quantitative methods of estimating ground water supplies: Geol. Soc. America Bull., vol. 31, pp. 329-338, 1920.

[2] Thompson, D. G., Ground-water supplies in the Atlantic City region: New Jersey Dept. Conservation and Development Bull. 30, 1928; Ground-water supplies in the vicinity of Asbury Park; New Jersey Dept. Conservation and Development Bull. 35, 1930; and Methods of estimating ground-water supplies in artesian basins (in preparation).

Valuable data were obtained by means of water-stage recorders in regard to the movements of the water levels in two test wells—since March, 1924, in test well No. 4, in the Puchack field, and since August, 1924, in test well No. 3, in the Morris field. (See pl. 2.) The water level in several other wells in the three fields was measured at frequent intervals during pumping tests of the recently installed wells in the Morris and Puchack fields and at other times. The altitude of all observation wells with respect to mean sea level was determined by instrumental leveling.

In order to draw conclusions from a study of the relation between fluctuations of the water levels in the wells and of pumpage from them it is necessary to understand the nature of the fluctuations and the causes of changes of different kinds. For example, there are gradual changes that cover long periods, and superimposed on these are rather sharp fluctuations of considerable magnitude that occur frequently. Therefore, in the following pages attention is given to the interpretation of the different types of fluctuations observed. It seems that this interpretation can be made best if the data are presented in chronologic order.

Test of March 27, 1924.

Puchack field.—The first observations were made during preliminary tests of the recently completed wells in the Puchack field. These tests were made before the permanent pumps were installed and afforded opportunity for observations that would otherwise have been difficult to obtain.

On March 27, 1924, observations were made during a pumping test of well No. 1 of this field.[1] The depth of water was measured in all available wells in the field—namely wells Nos. 1 and 2 and test wells Nos. 1, 3, and 4. Wells Nos. 3, 4, and 5, were not yet completed, and no measurements of the water level in them were made. (See figs. 3 and 4.)

[1] In the Morris and Puchack fields there are two types of wells—test wells and wells equipped with pumps—and in each field according to the system of the Camden Water Department these wells are numbered from one up. Thus in the Morris field there is a test well No. 1 and a pump well No. 1 and in the Puchack field there is likewise a test well No. 1 and a pump well No. 1. To avoid confusion in the following descriptions it has been necessary to prefix the name of the field wherever well numbers are given and the word "test" wherever it was applicable. Wherever "test" is not used the number refers to a 26-inch well equipped with a turbine pump with the following exception: A well of small diameter on the old suction system of the Morris field, according to the system of the City Water Department, is known as 15-173, but for convenience in this report it is called well No. 15.

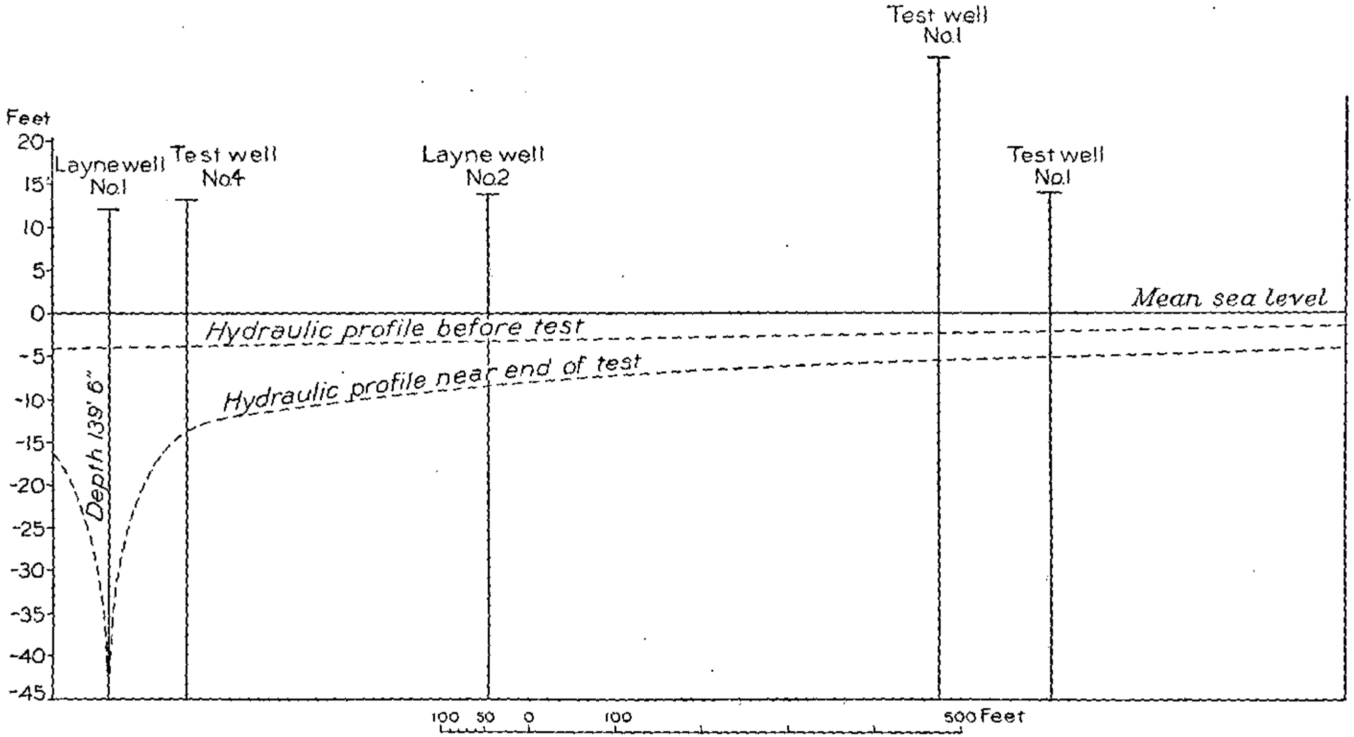

FIG. 3—Hydraulic profiles in the Puchack well field at the beginning and near the end of the pumping test of well No. 1, March 27, 1924.

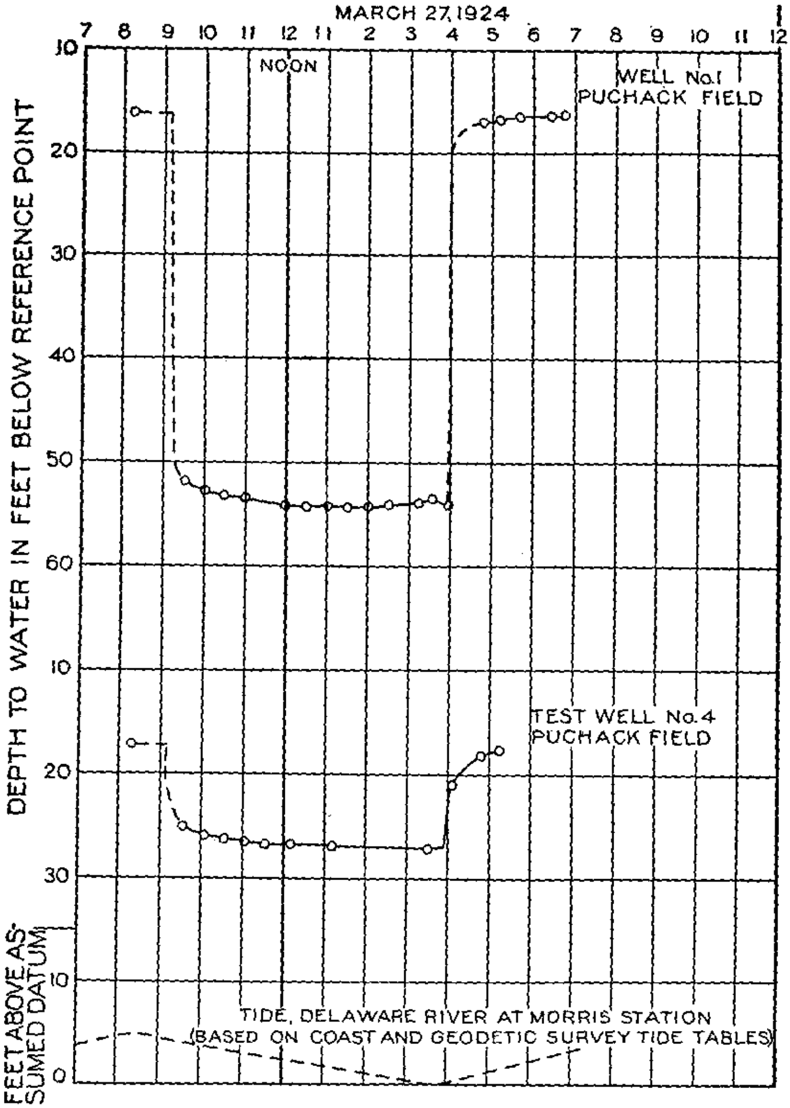

FIG. 4—Graph showing movement of water levels in well No. 1 and test well No. 4 in the Puchack field, and tide level in the Delaware River March 27, 1924.

Pumping Test of Puchack Well No. 1, March 27, 1924.

Pumping began at 9.10 a. m.; stopped at 3.55 p. m.; length of test, 6¾ hours. Yield of well at end of test, 1,320 gallons a minute, 1.9 million gallons a day. This rate was maintained or exceeded during the entire test. Maximum drawdown, 38.09 feet. Specific capacity, or yield, per foot of drawn down, 33.8 gallons a minute.

Figure 3 shows that before pumping began the water level in all the observation wells was below sea level and the hydraulic gradient was toward well No. 1—that is, in the general direction of the Morris and Delair fields, where pumping was in progress. This condition suggests that the Puchack wells lie within the zone of influence of one or both of the other fields, and the suggestion was verified by later observations. In well No. 1, which was pumped at a rate of 1.9 million gallons a day, the water level dropped 38 feet, but the drop in the other wells was not great, a fact which indicates a high permeability of the water-bearing formations. The cone of influence, however, extended some distance beyond the Puchack field. (See p. 46.)

The graphs in Figure 4 show that in the pumped well the water level dropped about 35 feet in the first 20 minutes, but thereafter the decline was much slower and at a decreasing rate. During the first hour after 9.30 a. m. the drop was 1.2 feet, and in the next hour it was only 0.6 foot. From about 2 p. m. to 3.35 p. m., the water level rose about 0.7 foot. When the pumping was stopped the water level rose rapidly, and in less than three hours it was practically as high as it had been before pumping began. This is in contrast to conditions in other localities, where many hours or even several days may be required for the water level to rise to its position prior to pumping.[1] This condition indicates that the water-bearing formation in the Puchack field has a high permeability.

The water level in test well No. 4, which is about 90 feet from the pumped well, moved in much the same way as the water level in the pumped well, except that the amount of movement was much less. One notable difference, however, was that while the water level rose slightly in the pumped well during the later part of the test, it fell continually in test well No. 4. The drop during the last two hours was only about 0.1 foot, and in the hour preceding that period it was about the same. Nevertheless numerous careful measurements showed a distinct downward movement. Furthermore, in the other observa-

[1] See reports by the writer on ground-water supplies in the Atlantic City and Asbury Park areas.

Well [a]	Distance from well No. 1	Water level before test		Water level at lowest point		Maximum lowering of water level
		Depth below reference point (feet)	Depth below sea level (feet)	Depth below reference point (feet)	Depth below sea level (feet)	(feet)
	Feet					
Well No. 1	0	16.13	4.16	54.22	42.25	38.09
Test well No. 4...........	90	17.13	3.91	27.01	13.79	9.88
Well No. 2	440	17.10	3.35	22.67	8.92	5.57
Test well No. 1...........	955	31.67	....	34.68	....	3.01
Test well No. 3...........	1,080	16.13	2.18	19.08	5.13	2.95

[a] Wells are arranged in order of their distance from well 1. (See pl. 2.)

tion wells a similar drop was observed. The cause of the water level rising in the pumped well while it fell in the other wells is not known. The rise in the pumped well may have been due to a decrease in the rate of pumping from the Morris wells but was more probably due to a slight decrease in the rate of pumping from well No. 1 itself. Unfortunately detailed records of the rate of pumping in the two fields were not kept. The water level probably continued to drop in the other wells, because, for reasons not yet fully understood, stable conditions are not immediately reached when pumping begins or the rate of pumping is changed. This fact was especially brought out by observations made in July, 1927. (See pp. 58-59.)

Test of April 3, 1924.

Puchack field.—On April 3, 1924, observations were made during a preliminary test of well No. 2, in the Puchack field. The essential results were as follows:

Pumping Test of Puchack Well No. 2, April 3, 1924.

Pumping began at 10.54 a. m.; stopped at 4.57 p. m. Length of test 6 hours, 3 minutes. Yield of well during test, 1,440 gallons a minute. Maximum drawdown. 32.6 feet. Specific capacity, 44.2 gallons a minute.

The hydraulic profile before and near the end of the test (fig. 5) gives some information as to the shape of the cone of influence. The profile before pumping began was below sea level in the entire field and sloped toward the northwest end of the field, as at the beginning of the test on March 27. Furthermore, when the water was lowest the cone of influence was not quite symmetrical, as it should be if the water were moving in at an equal rate from all directions; but at corresponding distances from the pumped well the head was slightly lower in the side toward the Morris and Delair fields than on the opposite side. This is further evidence supporting the theory that the Puchack well field lies within the area of influence of one or both of the other fields.

Well [a]	Distance from well No. 2	Water level before test		Water level at lowest point		Maximum lowering of water level
	(feet)	Depth below reference point (feet)	Depth below sea level (feet)	Depth below reference point (feet)	Depth below sea level (feet)	(feet)
Well No. 1	440	16.83	4.86	22.15	10.18	5.32
Test well No. 4	355	17.80	4.58	23.79	10.57	5.99
Well No. 2	0	17.88	4.13	50.42	36.67	32.54
Test well No. 3	650	16.60	2.65	20.68	6.73	4.08
Test well No. 1	620	32.07	2.46	36.11	6.50	4.04

[a] Arranged in order across the well field.

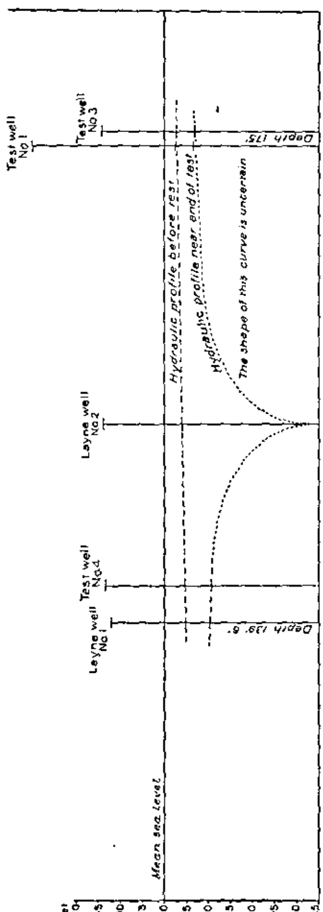

FIG. 5.—Hydraulic profile in the Puchack well field at the beginning and near the end of pumping test of well No. 2, April 3, 1924.

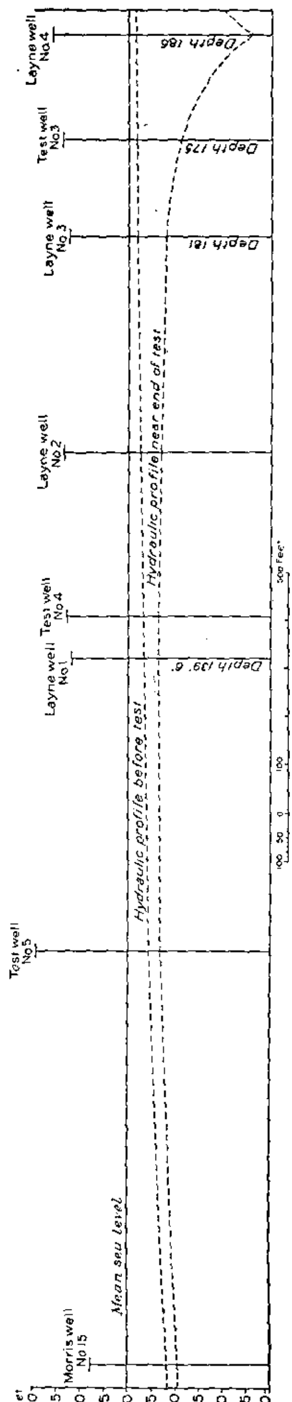

FIG. 6.—Hydraulic profiles in the Puchack field at the beginning and near the end of pumping test of well No. 4, May 10, 1924.

TEST OF MAY 9 AND 10, 1924.

Puchack field.—During a preliminary pumping test of well No. 4, in the Puchack field, on May 9 and 10, 1924, observations were made on three wells that had not been measured during the previous test—namely, well No. 15-173 (hereafter designated as No. 15) and test well No. 3 in the Morris field and test well No. 5 in the Puchack field. Test well No. 5 is just east of the track connecting the Trenton branch of the Pennsylvania Railroad with the Atlantic City branch and is 600 feet northwest of Puchack well No. 1. The essential results of the test on May 10 are as follows:

Pumping Test of Well No. 4, Puchack Field, May 10, 1924.

Summary of observations.—Pumping began at 8.30 a. m.; stopped at 1.35 p. m. Length of test 5 hours, 5 minutes. Yield of well during test 1,675 gallons a minute, 2.4 million gallons a day. Maximum drawdown, 24.75 feet. Specific capacity, 67.7 gallons a minute.

A noteworthy feature of this pumping test was the large yield of the well—1,675 gallons a minute (2.4 million gallons a day), and the comparatively small drawdown. This is the largest yield obtained from one well in the Puchack field.

Hydraulic profile.—The hydraulic profile before pumping was similar to those on March 27 and April 3 in that throughout the field it sloped northwestward and in all observation wells the water level was below sea level. As previously stated, this suggests that the wells in the Puchack Creek well field lie within the area of influence of either the Delair or Morris Station well fields. As shown in Figure 6, the hydraulic profile sloped from Puchack test well No. 5 to Morris well No. 15.[1] From this fact it is concluded that the hydraulic gradient is caused by pumping in the Morris field rather than in the Delair field. This is a natural assumption, because at the time of the test the draft from the Morris wells was at least double that in the Delair wells, and the distance from the Puchack field to the nearest wells in the Morris field is at least 1,000 feet less than to the nearest wells in the Delair field.

[1] In Figure 6 the location of each well is determined by its distance in a direct line from Puchack well No. 4 and not its distance from the adjacent wells. Because of this fact and because the line of the profile between Puchack well No. 1, Puchack test well No. 5, and Morris well No. 15 makes a large angle, the distance between wells Nos. 5 and 15 is shown as much less than the actual distance. The profile is constructed in this manner to show the influence of the Puchack well No. 4 at different distances from it.

Well[a]	Distance from well No. 4	Water level before test		Water level at lowest point		Maximum lowering of water level
	(feet)	Depth below reference point (feet)	Depth below sea level (feet)	Depth below reference point (feet)	Depth below sea level (feet)	(feet)
Puchack field:						
Well No. 4	0	17.13	1.16	41.88	25.91	24.75
Test well No. 3	215	15.39	1.44	24.37	10.42	8.98
Well No. 3	415	13.99	1.60	19.80	7.41	5.81
Well No. 2	865	16.05	2.30	20.42	6.67	4.37
Test well No. 4	1,215	16.14	2.92	19.56	6.34	3.42
Well No. 1	1,300	15.26	3.29	18.32	6.35	3.06
Test well No. 5	1,900	23.64	4.22	26.10	6.68	2.46
Morris field:						
Well No. 15	2,750	15.58	6.39	18.18	8.99	2.60
Test well No. 3	3,600	17.45	10.64	19.49	12.68	2.04

[a] Arranged in order of distance from Puchack well No. 4.

Some of the data of this test are shown in Figures 6 and 7.

It has been suggested that the hydraulic gradient from Puchack well No. 4 toward the northwest represents the normal ground-water slope toward the Delaware River. This does not seem possible, for the water table was everywhere below sea level. A slope or gradient of the water table implies flow of water, and it would not be possible to have a flow of water to a point below sea level—that is, below the level of

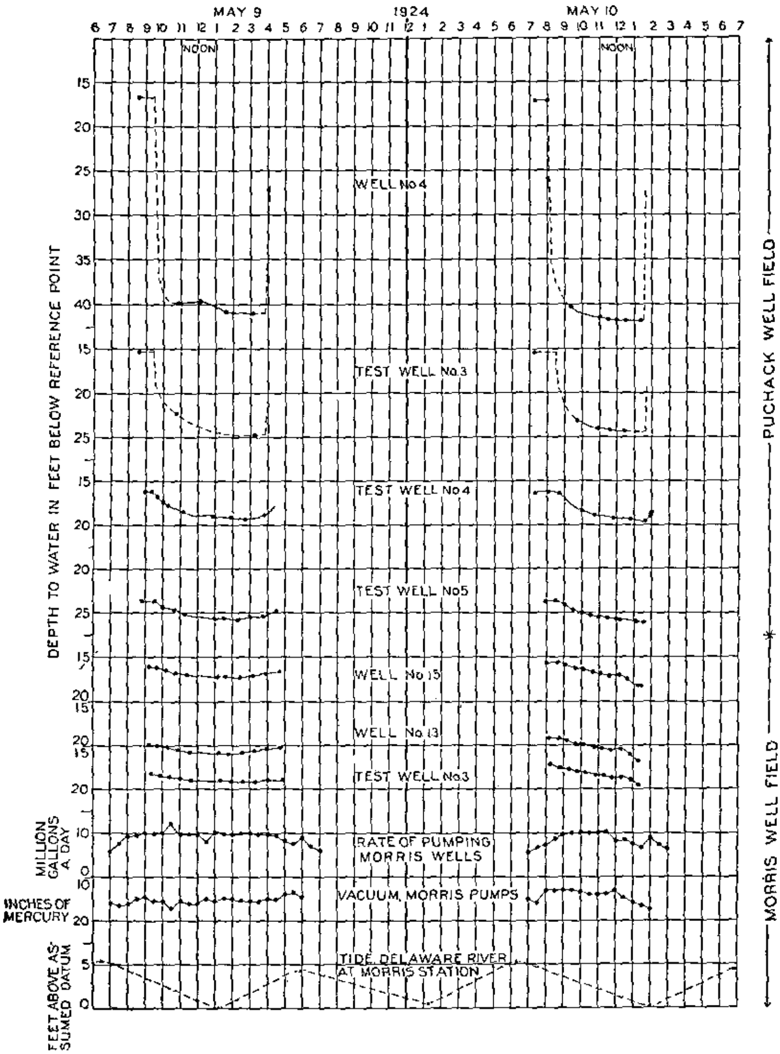

Fig. 7.—Graph showing movement of water levels in observation wells in the Puchack and Morris fields, rate of pumping and vacuum at Morris plant, and tide level in Delaware River, May 9 and 10, 1924.

the Delaware River. Moreover, additional observations made on July 30, and 31, 1924, (See pp. 34-42) showed conclusively that the hydraulic gradient in a northwesterly direction, observed before pumping was begun in the Puchack field described in this report, was due to pumping in the Morris field.

Cone of influence.—On both May 9 and 10 the water levels in the Puchack and Morris wells dropped during almost the entire time that Puhack well No. 4 was pumped, and the drop was nearly the same in Morris well No. 15, Puchack test well No. 5, and Puchack well No. 1. This raises a question as to whether the pumping of Puchack well No. 4 caused any lowering of the water level in the Morris wells. Figure 6 shows that the cone of influence of Puchack well No. 4 apparently dies out between Puchack well No. 1 and Puchack test well No. 5, and that farther west the hydraulic gradient is toward the Morris field. It must be remembered, however, that if there was no pumping in the Morris field and the hydraulic profie before pumping was as shown in Figure 6, the full limit of the cone of influence would be determined by the point of intersection of the profile during pumping with that prior to pumping. Obviously this point would be much nearer the Morris field; actually it would be at least 200 or 300 feet northwest of Puchack test well No. 5. The problem is complicated by the pumping in the Morris field, especially as it is known that the area of influence of the Morris wells extends beyond the Puchack field. (pp. 40-41.) From the profiles alone it is impossible to say whether during the pumping tests on May 9 and 10, the lowering of the water betwen Puchack well No. 1 and Morris well No. 15 was due primarily to pumping from Puchack well No. 4 or to pumping from the Morris wells.

Tidal effect.—On May 9 the water level in test wells Nos. 4 and 5, in the Puchack field, and well No. 15 and test well No. 3, in the Morris field, moved in general in the same way. (Figure 7.) It is noteworthy that during the later part of the pumping period on that day the water level in all these wells rose slightly. The vacuum in the Morris field, which is an approximate index of the water level in the wells of that field, was generally the same for most of this time and it seems probable that the rise in the water level can not be fully explained by changes in pumpage in the Morris field. During this period of rise the tide was also rising. Inasmuch as it is known that tidal movements cause changes in water level in other localities, it is believed that the rise in tide may explain part of the rise of the water level in these wells. On May 10 the tide was falling during the entire period that

Puchack well No. 4 was being pumped, and there was no rise in the water level in the other wells such as was observed on the preceding day.

Result of cutting out air-lift wells.—A significant feature is shown on the graph for May 10. Shortly after 12.30 p. m. a marked drop in the water level occurred in wells Nos. 15, 13, and test well No. 3 in the Morris field and at the same time the vacuum on the Morris suction system increased. This was in spite of the fact that there was a considerable decrease in the rate of pumpage from the Morris field. This apparently anomalous condition is believed to have been due to the fact that, as the consumption decreased, about fifteen wells pumped by air lift in the northeastern part of the Morris field were shut off at 12.10 p. m., and the rate of pumpage from the wells in the southwestern part of the field was suddenly increased by the amount previously obtained from the air-lift wells. This resulted in a greater lowering of water level in the wells in the southwestern part of the field. This combination of conditions is described more fully on pages 38-39. Following this change in distribution of draft, there was a slight drop in water level in test well No. 5, but no evidence of any drop in test well No. 4 in the Puchack field. It appears, therefore, that even if the Puchack field lies within the area of influence of the Morris field, the effect of the increase in draft created in the manner just described was small.

The tests of May 9 and 10 gave no definite evidence that Puchack well No. 4 affected the water level or yield of the wells in the Morris field. Unfortunately during the tests of Puchack wells Nos. 1 and 2 no observations had been made on any wells in the Morris field, and therefore no information is available as to the effect of either of those wells on the Morris wells. On the basis of the results of the test on Puchack well No. 4, it appears that pumping Puchack well No. 1 might produce some noticeable effect on the wells in the southern part of the Morris field.

Test of July 30 and 31, 1924.

Conditions of the test.—The observations during the tests of March 27, April 3, and May 9 and 10 had given evidence that the area of influence of the Morris wells extended beyond the Puchack field, and that the tide might have some effect on the water level and yield of the wells in the two fields. The observations had been made only during pumping tests of wells in the Puchack field, and it was desirable to obtain data on conditions when there was no pumping in that field. Accordingly observations were made on July 30 and 31, 1924. On these days, in addition to wells previously measured, the tide level in the Delaware River was measured at frequent intervals from a pier near Morris station. Unfortunately since the previous tests vandals had thrown debris into Puchack test well No. 5, situated between the

Tide levels and water levels in wells in the Puchack and Morris fields. July 31, 1924. Taken when Puchack field was not pumped.

Well	Highest water level (feet)		Lowest water level (feet)		Maximum fluctuations in water level
	Depth below reference point	Above or below sea level	Depth below reference point	Above or below sea level	(feet)
Puchack field:					
Well No. 4	13.97	− 0.80	14.18	− 1.01	0.21
Test well No. 3	15.20	− 1.25	15.47	− 1.52	0.32
Well No. 2	13.51	− 2.56	13.91	− 2.96	0.40
Test well No. 4	16.16	− 2.94	16.55	− 3.33	0.39
Morris field:					
Well No. 15	16.77	− 7.58	17.95	− 8.76	1.18
Test well No. 3	18.68	−11.87	19.97	−13.16	1.29
Tide at Morris station	3.54	+ 2.66	8.88	− 2.68	5.34

two well fields, and it was not possible to make any further measurements in that well. The principal results for July 31 are given in the following table, and those for both days are shown in Figure 8.

Fluctuation due to change in pumping.—A noteworthy feature shown by the graph (fig. 8) is that the water level in the wells in the Puchack field was moving up or down almost continuously and that in general the movement was coincident with like movements in the wells in the Morris field. Movement similar to that in Puchack well No. 4 and Puchack test well No. 4 and of an amount between that in those two wells, was observed in the Puchack well No. 2 and Puchack test well No. 3. These fluctuations are produced chiefly by fluctuations in the rate of pumping in the Morris field. For example, on July 30, beginning at about 7 p. m., there was a rise of the water level in the wells. In test well No. 4 in the Puchack field, which was equipped with an automatic recorder, the rise was shown to continue until 9 or 10 p. m. The graph shows that at the beginning of the upward movement of the water level there was a marked decrease in the rate of pumping, and there seems little doubt that it was this decrease that initiated the rise of the water level. During all this time the tide was dropping. A somewhat similar relation existed at about the same time in the evening of July 31, when the water level rose as the rate of pumping decreased, although the tide was falling. It is noteworthy that the changes in pumping affect not only the observation wells in the Morris field, but also those in the Puchack field. In this way the evidence corroborates that given by the hydraulic profile in Figures 3, 5, and 6, in demonstrating that the Puchack field lies within the area of influence of the Morris wells.

Tidal effects.—A careful study of the curves in Figure 8 shows, however, that the changes in rate of pumping are not the sole cause of fluctuations in the water levels in either the Puchack or Morris field. For example, from noon until 3 or 4 p. m. July 31 the water levels in the several wells rose more or less steadily, although the rate of pumping did not likewise decrease. From about 4.30 p. m. to 6.30 p. m. the rate of pumping decreased slightly, but the water level in all the wells dropped considerably. In seeking for a cause for these differences it is found that at the times mentioned the movement of the water level in the wells is in the same direction as the movement of the tide. A careful study of the curves in Figure 8, of those in Figure 4, and of other curves that are not reproduced here gives convincing evidence that the movement of the water level in the wells is affected by the

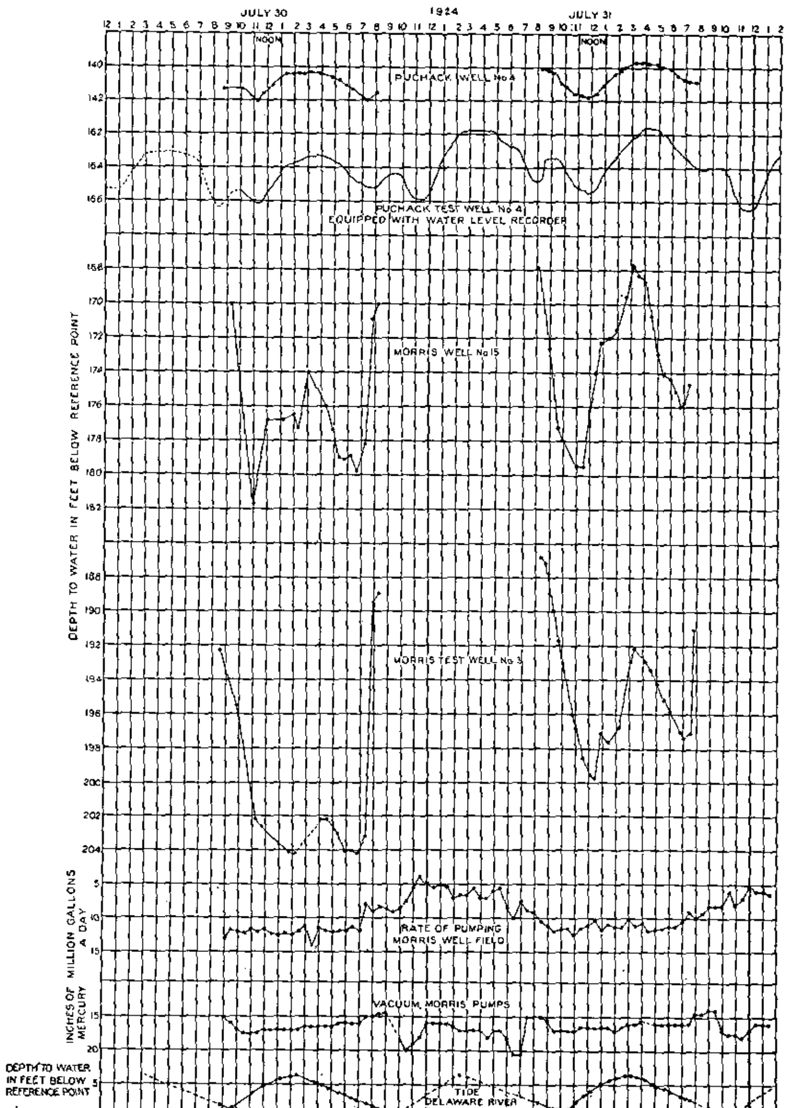

Fig. 8.—Graph showing movement of water levels in observation wells in the Puchack and Morris fields, rate of pumping and vacuum at the Morris plant, and tide level in Delaware River, July 30 and 31, 1924.

tide movement. Such relation has been observed in many other localities.[1] The tide affects the Morris wells much more than the Puchack wells, evidently because they are so much nearer to the river. It appears that the effect in the Morris field amounts to at least several inches, and with extreme ranges of tide it may be a foot or more. Such an effect on the head may be sufficient to produce some change in the yield of the wells, reducing it at times of extremely low tide and increasing it at extremely high tide. The engineers at the Morris pumping plant state that this is an observed fact.

Other fluctuations.—The curves in Figure 8 show certain fluctuations of water level in the recorder well, No. 4, in the Puchack field that can not be explained either by change in the rate of pumping or by the tide. For example, between 9.30 and 11 p. m. on July 30 the water level in the well dropped, although the tide was rising and the rate of pumping from the Morris field was decreasing. This and similar conditions at other times indicate a third factor, which must be sought. While conceivably this may result from pumping in a distant field, this cause seems inadequate and it is more probable that the explanation is to be sought within the Puchack, Morris or Delair field.

The graph shows that at the times when the water level in the recorder well, No. 4, in the Puchack field moved in the direction opposite to that of the tide and the rate of pumping, there was a change in the vacuum of the pumps at the Morris pumping plant that was in the same direction as the movement of water level in the well. Thus shortly before the drop in the water level in well No. 4 there was a sharp increase in the vacuum, indicating that the suction lift was increasing and presumably the water level in the pumping wells was lower. This was in spite of a noticeable drop in the rate of pumping.

This condition appears to be the result of the methods of pumping used at the time the observations were made. The wells in the northeastern part of the Morris field were pumped by compresed air and were used only when the yield of the other wells was not sufficient to meet the consumption. They were generally shut off during the night and operated continuously during the day. The water from the air-

[1] Veatch, A. C., Fluctuations of the water level in wells, with special reference to Long Island, New York: U. S. Geol. Survey Water-Supply Paper 155, pp. 63-69, 1906. Meinzer, O. E., Compressibility and elasticity of artesian acquifers: Economic Geology, vol. 23, No. 3, pp. 263-291, 1928; Thompson, D. G., Ground-water supplies in the Atlantic City region: New Jersey Dept. Conservation and Development Bull. 30, p. 97, 1928.

lift wells was carried by gravity to the large collection well which also drew from the suction system and from which the steam pumps drew. Fluctuations in the draft when they were operating were taken care of by speeding up or slowing down the steam pumps operating on the suction system. When the "air wells" were started there was sudden shifting of the center of draft of the field and hence of its area of influence toward the air-well field from a point farther south. At the same time there was also probably a considerable increase in quantity of water fed to the collecting well, for the consumption from the entire system seldom increased immediately as much as the yield of the air-lift wells. As a result the head of water in the collection well increased, or, what is the same thing, the suction lift, indicated by the vacuum, decreased. The draft on the wells on the suction system suddenly became much less, and the net result was that the water level in parts of the field most remote from the air-lift wells rose. When the air-lift wells were stopped the reverse action took place.

On July 30 the air compressor was stopped at about 8.45 p. m., and for some time thereafter the suction wells had to contribute a larger quantity of water than they had yielded prior to that time. The center of the area of influence was shifted toward the southwest, with the result that the water level in the observation wells in that end of the field was lowered, even though there was no essential increase and at times even a decrease in the rate of pumping. This lowering of head was sufficient to show in well No. 4 in the Puchack field.

From the foregoing discussion it becomes apparent that in considering the cause of fluctuations of water levels in the Puchack and Morris fields it is not sufficient merely to consider the quantity of water pumped but the distribution of the draft between different parts of the well fields. More specifically in the case under consideration it is necessary to consider the vacuum even more than the rate of pumping.

Effect of counteracting factors.—In connection with the study of the movements of the water level shown in Figure 8 and other graphs it may be mentioned that a flat section on the curves, indicating no movement, may be produced not only by completely stable conditions—that is, no change of tide or change in draft—but also by the counteracting effect of two or more causes. Thus the rate of pumping may decline at such a rate as to produce the same affect but in the opposite direction as a falling tide. The result will be no movement of the water level.

Extent of area of influence of the Morris wells.—Questions now to be determined are: How far does the area of influence of the Morris wells extend; and how great is its effect on the Puchack wells?

All wells of the Puchack field lie within the sphere of influence of the Morris wells, as shown by the following facts. The original static head or nonpumping level in the Morris wells is said to have been 2 feet above sea level.[1] Presumably in the Puchack field it was as high or a little higher. On the other hand, during the tests of March 24, April 3, May 10, and July 31, when the Puchack wells were not being pumped, the water level ranged from 4.92 to 6.58 feet below the original static level in test well No. 4 and from 3.25 to 5.65 feet below in test well No. 3. In well No. 4, which is about 2,800 feet from the nearest well in the Morris field, the observed water level was from 2.80 to 3.16 feet below the original level, but no measurements were made on this well on April 3, when the lowest levels were observed in the other wells. During these tests the water levels in the Morris field ranged from about 8 to 15 feet below the original static level in wells that were not being pumped. It is noteworthy, however, that at any given time the difference between the water level in the northwestern part of the Puchack field and the nearest observation well in the Morris field was not great. For example, before pumping was begun on May 10, 1924, the water level was only 3.1 feet lower in well No. 15 than in well No. 1. The water levels in all wells in the Puchack field were below mean sea level during the entire period of the test, and the hydraulic profile sloped toward the Morris field. At its highest point the water level in Puchack well No. 4 was 0.8 foot below mean sea level and 3.46 feet below the highest point reached by the tide. It was therefore obviously below the level of the Delaware River. These facts prove that all the wells in the Puchack field lie within the area of influence of the Morris wells.

But the effects of pumping the Morris wells extend beyond Puchack field. In Figures 3, 5, and 6, the hydraulic profile in the Puchack field when the pump wells were not operating is shown as a nearly straight line. Actually it is probably not a straight line but approaches the horizontal with increasing distance from the pumped well. If the original, or non-pumping hydraulic profile in Figure 3 is continued as a straight line it is found to intersect the original static level at a distance of 2,100 to 2,200 feet from test well No. 3 in the Puchack field and 4,500 to 4,600 feet from the nearest pumped

[1] Report of the Chief Engineer, Camden City Water Department, for year ending June 30, 1907, p. 91 and diagram 10, 1907.

wells in the Morris field. It is evident that in less than a mile from the limits of the Morris field, at the rate of pumping on March 27, 1924, the lowering of the head below its original static level was very slight.

Added effects of Puchack pumping.—The question arises as to the effect of pumping the Puchack wells in extending the area of influence of the two fields. If the profile near the end of the pumping test in Figure 3 is extended as a straight line it intersects the original static level within 2,200 or 2,300 feet of Puchack test well No. 3—that is, only 100 or 200 feet beyond the point of intersection of the profile when Puchack well No. 1 was not pumped. The portion of the profile shown on the graph for the period when Puchack well No. 1 was pumped is so short that its departure from a straight line is probably relatively greater than the other profile, and the error may be greater. The point at which its departure from the original level is equivalent in amount to that for the other profile at a distance of 2,200 feet from Puchack test well No. 3 is doubtless more, but not much more, than 200 feet farther out. When Puchack well No. 4 was pumped alone it was not possible to get any observations to show its effect in extending the area of influence of the two fields. It is a reasonable assumption that the area of influence was extended by a distance approximately equal to the distance between Puchack wells Nos. 1 and 4, (about 1,300 feet), with some allowance for differences in the yield of the two wells. Thus with well No. 4 pumping and with the Morris wells pumping at the same rate as on March 27, 1924, the limit of the area of influence in the direction of the profiles shown in Figures 3, 5, and 6 would be about 3,500 feet southeast of the Puchack test well No. 3, or 6,000 feet from the nearest wells in the Morris field.

Extension due to pumping Morris wells to capacity.—The hydraulic profiles at the beginning of the test shown in Figures 3, 5, and 6 represent conditions when the Puchack wells were not pumped and the Morris wells were pumped at a rate considerably below their present capacity. The question arises as to the extent of the area of influence of the Morris wells if they are pumped to capacity, say about 18 million gallons a day. This problem can be approached by a consideration of the hydraulic profile at the beginning of the test of Puchack well No. 4 on May 10, 1925 (fig. 6). At that time the Morris wells were pumped at about 7 million gallons a day, and the Delair wells probably were pumped at 3 or 4 million gallons a day. According to graphic methods, the point at which the influence of the

Morris wells became negligible on that day was about 2,000 feet southeast of test well No. 3 in the Puchack field—about 4,500 feet from the nearest pumped well. According to Darcy's law of the flow of water through sand the loss of head should be directly proportional to the rate of pumping. Therefore, if the pumpage from the Morris wells is increased from 7 million to 18 million gallons a day the resulting profile can be determined from the profile for the smaller amount, assuming that the increase in pumpage is distributed among all wells in proportion to the original distribution.

By this method it was determined that under conditions similar to those existing on May 10, 1924, for a rate of pumping of 18 million gallons from the Morris field the water level in Puchack well No. 1 would be about 14 feet below the original static level, or 12 feet below mean sea level when none of the wells in the Puchack field were pumping. In Puchack test well No. 4 it would be about 13 feet below the original level, and in Puchack well No. 4 it would be about 8 feet below that level. At a distance of 1,000 feet southeast of Puchack test well No. 3, which is used as a landmark, the head would be about 4 feet below the original level, and 1,500 feet from test well No. 3 it would be about 3 feet below that level. However, the lowering of head would apparently be practically negligible within 2,500 feet of test well No. 3. The profiles beyond the limits of the Puchack field may be somewhat in error owing to inaccuracies of the graphic method, but the results are significant in showing that at a distance of about a mile southeast of the Morris field the lowering of head when the pumping rate is 18 million gallons a day is very small, probably not enough to affect seriously wells situated that far from the field. If the Puchack wells are pumped at the same time the point at which the lowering of the head become negligible will be pushed somewhat farther out.

The statements just made refer to conditions along the line of the profile shown in Figure 6, which extends approximately in a line at right angles to the axis of the Morris field. The Delair wells which were probably being pumped at the same time, are situated approximately along the extension of this axis. It is believed that under such conditions the lowering of head would be greatest in directions at right angles to the axis of the fields. Therefore, northeast and southwest from the Morris and Delair fields respectively the lowering of head for a given rate of pumping may be somewhat less than along the line of the profile in Figure 6.

TEST OF OCTOBER 16, 1924.

Conditions of the test.—Observations were made on the Puchack, Morris, and Delair wells on October 16, 1924, when an acceptance test by the city was run on the five pump wells in the Puchack field. The wells were run continuously for somewhat more than 8½ hours.

The Delair wells were not pumped during this test. Most of the Morris wells were being pumped, but the air-lift wells were not used. During this test conditions were different from those in earlier tests in that the water from the Puchack wells was pumped directly into the distribution mains, whereas previously the wells were not connected to the mains. The pressure in the mains against which the Puchack pumps operated fluctuated with consumption in the city and with changes in the rate of pumping in the Morris field. Fluctuations in the pressure in the mains affected the yield of the Puchack wells, for the yield varies with the head against which the pumps operate. The relation is not a simple one, however. The pumps are designed for most efficient operation between certain limits of head and at certain speeds, but it is not always possible to keep within these limits. Because of the interaction of several factors there is more or less change in the pumping level in the wells, and their yield.

The essential results of the test are as follows:

Test of Five Wells in the Puchack Field, October 16, 1924.

All wells were in operation prior to 8 a. m., but observations began at that time. Wells 4 and 5 shut off about 4.40 p. m. Length of test, more than 8½ hours. Total yield ranged from 6,520 to 6,650 gallons a minute (9.38 to 9.57 million gallons a day). Average yield, about 6,600 gallons a minute (9.5 million gallons a day). Pressure on distribution mains, 57 to 58 pounds to the square inch. During the test, Morris field was pumped at a rate ranging from 9 to about 5.4 million gallons a day.

Results of the test.—Fluctuations in the water levels in several of the wells, in the rate of pumping in the Puchack and Morris fields, and in the tide level in Delaware River are shown graphically in Figure 9.

In the pumped wells in the Puchack field the water level dropped slightly but continuously through the early part of the test, as shown by the curves for wells Nos. 1 and 4 in Figure 9. In most pumped wells a drop in the water level for some time after pumping begins is not unusual and is believed to be due to a lag in the adjustment of hydrostatic conditions to a state of equilibrium. In those wells there was a slight rise in the water level, amounting to 0.3 or 0.4 foot, after about 2 p. m., and similar rises were noted in the other pumped wells but this is not clearly shown because of the small scale of the graph. This slight rise during the later part of the test might have been due to the rising tide or to an increase in the pressure in the mains.

Well	Water level at highest point (feet)		Water level at lowest point (feet)		Maximum fluctuation
	Depth below reference point	Above or below sea level	Depth below reference point	Depth below sea level	(feet)
Puchack field:					
Well No. 1	67.10	—54.33	70.05	—57.28	2.95
Well No. 2	67.45	—53.10	69.10	—54.75	1.65
Well No. 3	81.10	—67.71	82.10	—68.71	1.00
Well No. 4	57.50	—40.83	59.35	—42.68	1.85
Well No. 5	87.00	(a)	91.70	(a)	4.70
Test well No. 3	44.60	—30.65	45.82	—31.87	1.22
Test well No. 4 (equipped with recorder)	29.73	—16.51	36.10	—22.88	6.37
Delair field test well	19.67	— 5.17	21.18	— 6.68	1.51
Morris field:					
Well No. 15-173	20.42	—11.23	22.82	—13.63	2.40
Test well No. 3 (equipped with recorder)	19.76	—14.51	22.21	—16.96	2.45
Tide at Morris station	2.60	+ 3.60	8.10	— 1.90	5.50

a Altitude of reference point not obtained.

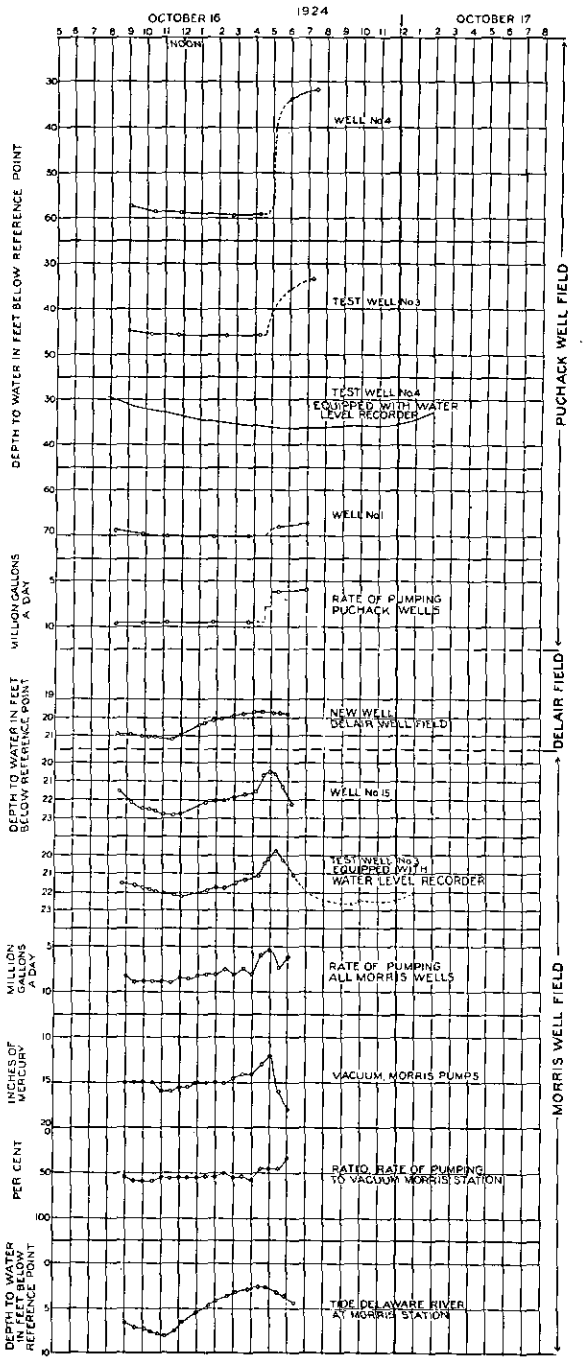

FIG. 9.—Graphs showing movement of water levels in wells and rate of pumping and vacuum in the Puchack, Morris, and Delair well fields and changes of tide level in Delaware River on October 16, 1924.

The water level in an observation well in the Delair field, which for convenience may be designated test well No. 1, followed closely the tide level and obviously was affected by the tide more than by the pumping. On the other hand, the curves of Puchack wells Nos. 1 and 4, did not follow the tide so closely, and the low points were not reached for two hours or more after the time of low tide. The record shows a slight decrease in yield at the time of observation, at 3.45 p. m. The main pressure at this time was 1 pound higher than at the two previous observations. An increase in main pressure, other conditions being equal, would cause a slight decrease in the yield of the wells, which in turn would result in a slight rise in the water level. The rise in pressure was doubtless due to decreased consumption during the afternoon, as is shown by the rate of pumping at the Morris field. (See fig. 9.)

Although the water level in the pumped wells rose slightly during the later part of the test, in test well No. 4, which was equipped with a water-stage recorder, the water level dropped continually, and did not reach its lowest stage until more than half an hour after wells Nos. 4 and 5 had been shut off. This is believed to be due to the lag in adjustment of the hydrostatic conditions. Evidently the tide did not produce a controlling influence over the water level in test well No. 4.

The water level did not drop in test well No. 3 in the Puchack field, as it did in test well No. 4, although the conditions were similar. It is possible that wells Nos. 3 and 4, which affected test well No. 3 most, had been pumped longer than the wells that affected test well No. 4, and that test well No. 3 had reached a nearly stable condition before observations were begun.

An unusual condition appears in that after Layne wells Nos. 4 and 5 were shut off the water level in Layne well No. 1 rose more than 2 feet but no rise was recorded in test well No. 4. This rise in No. 1 (see fig. 9) may have been due to readjustment in the pressure on the main and in contributions of water from the other pumped wells, consequent upon stopping No. 4 and 5. The failure of test well No. 4 to rise in harmony with No. 1, may have been due to lag.

It has been estimated that on May 10, 1924, when the Morris wells were yielding about 7 million gallons a day, their cone of influence extended about 4,500 feet from the nearest pumping well. (See p. 40.) If the influence of the Puchack wells under the same rate of pumping extends approximately as far, the southwestern part of the Morris field should be within the area of influence of the Puchack wells. On May 10, 1924, when the pumping rate at the Morris field was 7 million gallons a day, the head below the supposed original level in the nearest part of the Puchack field was about 5 feet. Therefore, it ought to be supposed that when the Puchack wells were pumped at a rate of 9 million gallons a day the head in the nearest part of the Morris field should be reduced at least as much. If there is any difference, the greater concentration of draft in the Puchack field should cause a greater lowering of head at a given distance. A study of the water-level movements alone does not, however, reveal any definite effect of the Puchack wells on the Morris wells. The water levels in well No. 15 and test well No. 3, in the Morris field, follow in general the movement of the tide, and the times of highest and lowest stages in the wells agree closely with the corresponding points in the tide. However, between 4 and 5 p. m. the water level in the two wells rose much more rapidly than would be expected if influenced only by the tide, and after about 5 p. m. it fell much more rapidly. It happened that two of the wells in the Puchack field were shut off during the later part of the period. The rapid rise in the Morris wells might be attributed to this fact were it not that most of the rise occurred before the Puchack pumps were stopped. A more probable cause is found in the fact that the rate of pumping from the Morris wells declined greatly and the vacuum decreased. (See fig. 9.) When the two Puchack wells were shut off some of the pumping load was shifted to the Morris field, and the pumping rate increased considerably. This resulted in a marked lowering of the water level in the Morris wells. Thus it appears that at critical times, when marked changes of conditions in the Puchack field might have caused noticeable effects, compensating changes occurred in the Morris field itself. These completely obscured any movements which may have been due to pumping the Puchack wells. The weight of evidence from this test indicates that on this occasion, at least, pumping the Puchack wells at the rate of 9.5 million gallons a day did not materially affect the level in the Morris field.

Figure 10 shows comparative curves of the water levels in several of the observation wells, the rate of pumping in the two fields, the tide level in Delaware River, and the ratio of the rate of pumping in the Morris field to the water level in well No. 15 on July 31, October 7, and October 16, 1924. On July 31 none of the Puchack wells were pumped; on October 7 wells Nos. 1, 2, and 4 were pumped at about 6 million gallons a day; and on October 16 all the wells were pumped at about 9.5 million gallons a day. No measurements were available on July 31 on well No. 1, in the Puchack field, or the observation well in the Delair field.

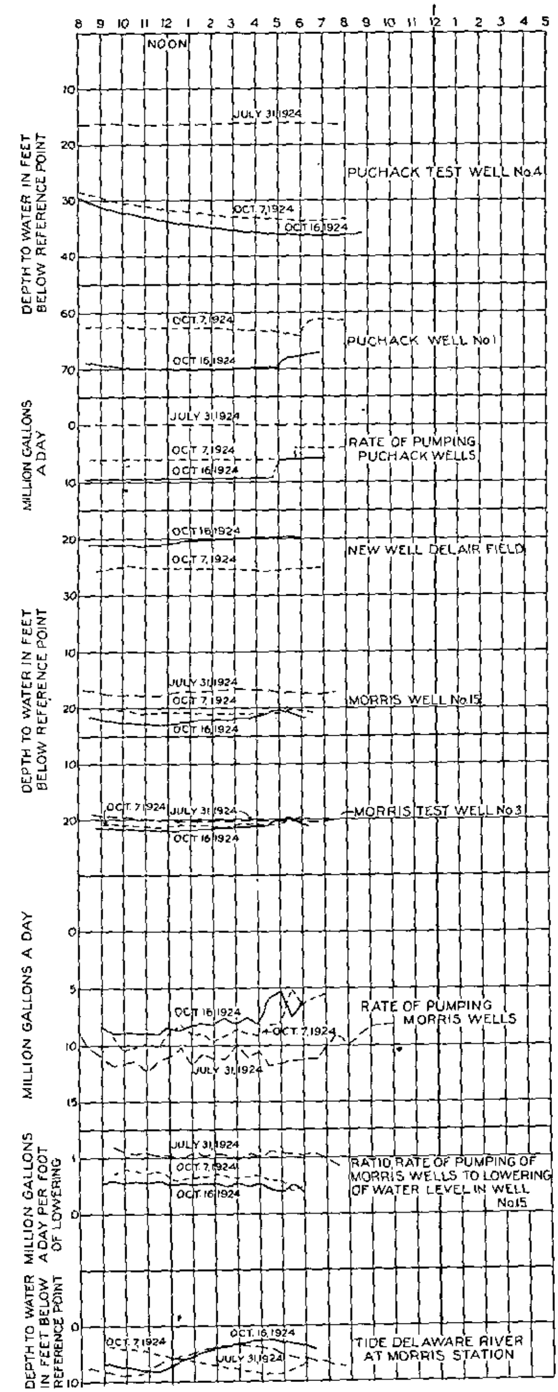

FIG. 10.—Graph showing movement of water levels in wells, rate of pumping, and other comparative data for the Puchack and Morris well fields, July 31, October 7, and October 16, 1924.

As shown by Figure 10, the rate of pumping from the Morris wells was in general greatest on July 31 and least on October 16, but the water levels were highest on July 31 and lowest on October 16. The yield per foot of lowering was only a little more than half as great on October 16 as it was on July 31. It was also somewhat less on October 16 than on October 7. The most obvious reason for these relations is found in the differences in pumpage in the Puchack field. However, the distribution of the draft in different parts of the Morris field must also be considered. (See pp. 38-39.)

The station records show that on July 31 the air-lift wells were in use, but on October 7 and 16 they were not. Thus on the first date the center of the area of influence of the Morris wells was farther northeast than on the other two dates. Unfortunately no measurements were made at times when the draft was being shifted from one part of the Morris field to another. A study of the relation between the rate of pumping and the vacuum at the Morris pumping plant on July 31 (see fig. 10) shows that when the center of the area of influence was shifted the rise or fall of the water level in the collecting well was from 2 to 5 feet. The change in water level would be greatest near the center of the area of influence and least in the wells on the outskirts of the field. Therefore the change in water level in well No. 15 due to the shifting of the center of the area of influence would be less than the limits just stated. As the difference between the water levels in well No. 15 on July 31 and October 16 at most times was 5 feet, it seems that although part of it was due to the use of the air-lift wells on the first day and not on the second, some of it may have been due to the fact that the Puchack wells were not pumped.

As the air-lift plant was not operated on October 7 to October 16, differences in the water level on those days can not be attributed to differences in the distribution of draft on the well field. The only other known factors that might explain them are differences in the tide and in the rate of pumping in the Puchack field. Figure 10 shows that on the two days the tide was in almost opposite phases. Moreover, the curves of ratio of pumping rate to lowering of water level in well No. 15 for the two days do not show any irregularities that might be attributed to the tide, but rather show a fairly uniform difference at all times. It is therefore concluded that the difference in the yield of the Morris field on October 7 and 16 was due primarily to differences in the rate of pumping in the Puchack field.

If the operation of the Puchack wells is effective in reducing the yield of the Morris wells what is the quantitative measure of this effect? On October 7, between 9.30 a. m. and 4 p. m. the average rate of yield of the Morris field was 9,300,000 gallons a day, and the average depth to the water level below the original static level[1] in well No. 15 was 13.83 feet. Between the same hours, on October 16, the average rate of yield was only 8,300,000 gallons a day and the average depth to water was 15.24 feet, giving a yield of only 550,000 gallons a day per foot of lowering. A lowering of 15.24 feet on October 7 would have produced 10,200,000 gallons a day. In other words, the yield of the wells on October 16 was nearly a million gallons less for a greater depth to water than it was on October 7. Obviously if the average depth to water on October 16 had been maintained as it was on October 7, namely 13.83 feet, the yield of the system would have been less than 8,300,000 and the difference in yield on the two days would have been even greater than stated. For larger yields the difference would have been somewhat proportionate.

Test of June 5, 1926.

Conditions of the test.—After the completion of the five new wells that form the Puchack system the Camden Water Department constructed nine wells of the same type in the Morris field to replace nearly a hundred wells of smaller diameter that had been in service for many years. As shown in Plate 2, the new wells are situated along the east side of the Morris field and are spaced along a northeast-southwest line at distances of 600 to 1,000 feet. Each well is operated by a turbine centrifugal pump that delivers the water to a collecting reservoir.

An acceptance test of these wells was made on June 5, 1926. Some observations were made from 8.45 a. m. to 5.45 p. m. on that day, but it was not possible to continue observations to the end of the test at 8 p. m. Nevertheless the data obtained afford valuable information in regard to conditions in the Morris, Puchack, and Delair fields. (See fig. 11.) Although pumping was started at 8.45 a. m., the system was not working to capacity until after 10.30 a. m. Shortly after noon the electric current was cut off by trouble in a transformer station, and pumping was not resumed until 2.05 p. m. In the meantime the Puchack and Delair wells were put into service to supply the city. Because of these irregularities in the operating conditions no consideration is given in the following discussion to the yield of the system prior to 3 p. m.

[1] Assuming that the original static level was 2 feet above tide, which may not be correct, since the level fluctuated with the tide, where first observed. H.B.K.

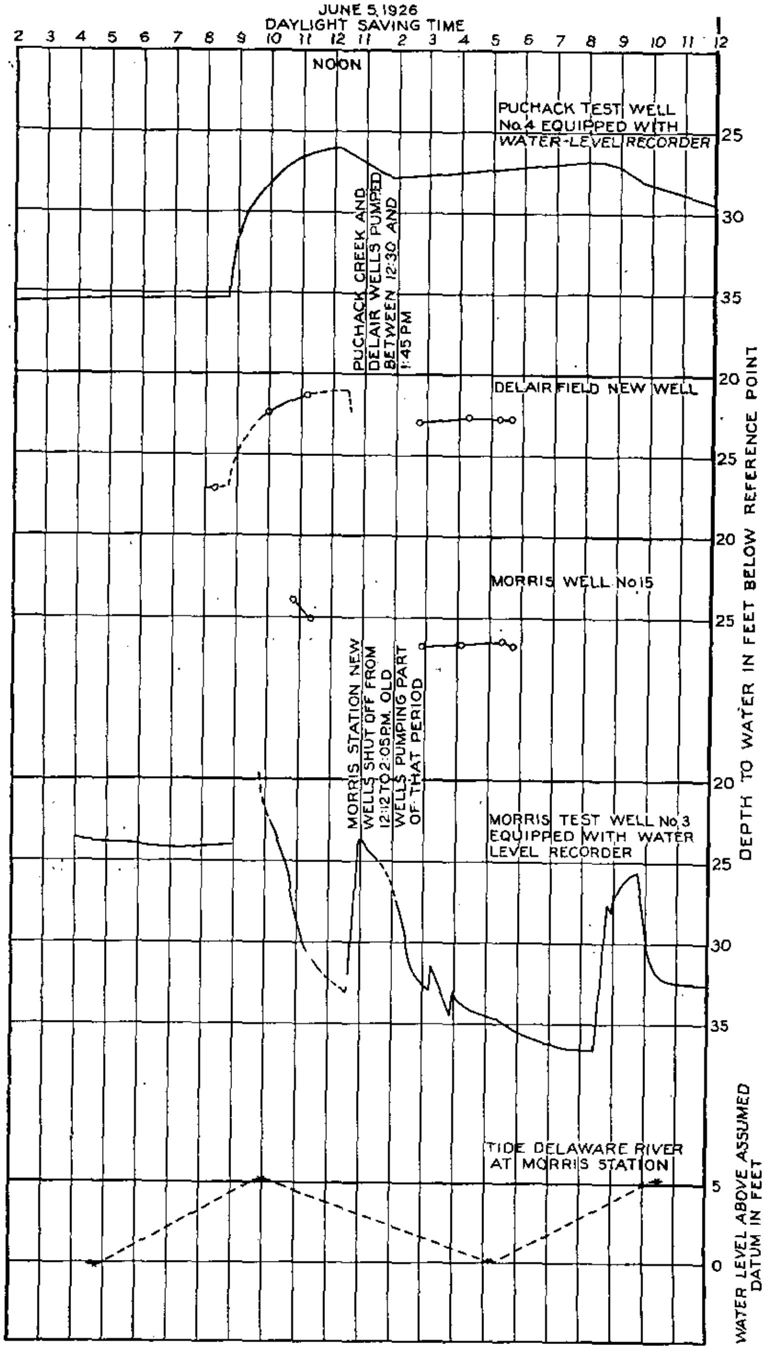

FIG. 11.—Graph showing movement of water level in wells in the Puchack, Morris, and Delair well fields on June 5, 1926.

The method of operation of the new pumping station is such that it is not possible to measure directly the yield of the wells. The water is first pumped by the turbine centrifugal pumps into a collecting reservoir and is thence pumped into the distribution mains by four high-duty pumps. The flow of water to the mains is measured by a Venturi meter. The high-duty pumps operate at about 6 million gallons a day each, with only slight variations, according to the pressure in the mains and the depth to the water level in the collecting reservoir. Their rate of delivery can not be changed much except by starting or stopping one or more of them. The only way in which the rate of pumping from wells can be measured is by observing the water level in the reservoir and correcting the rate of pumpage shown by the Venturi meter for increases or decreases in storage in the reservoir.

Results.—The average of the observed rates of discharge of the high-duty pumps, as shown by the indicator dial of the Venturi meter, between 3 and 5.48 p. m., was 18.6 million gallons a day. During the same period the counter dials on the meter showed a discharge of 2,130,000 gallons, which is at a rate of only 18.24 million gallons a day. During the same period the water level in the collecting reservoir fell 1.21 feet. As the reservoir holds about 45,600 gallons for each foot of depth the pumpage into the mains was greater than the pumpage from the wells by about 55,000 gallons in the period, or an average of about 450,000 gallons a day. The average yield of the wells, according to the record of the counter dial with deduction for loss in storage, was therefore at the rate of 17.8 million gallons a day.

Figure 11 shows that the water level in test well No. 3, in the Morris field, fell continuously during the entire period that all the wells in that field were in operation. Interruptions in the downward trend were due to the shutting off of one or more of the wells in the field. The notable rise shortly after noon occurred when all the pumps in the field stopped. The minor rises shortly after 3 p. m. and again at 4 p. m. occurred when well No. 7 and well No. 6, respectively, were shut off for a few minutes.

Figure 11 also shows that during practically the whole time that the Morris wells were pumped the water level in test well No. 4, in the Puchack field, rose except when the Puchack wells were in operation. Some of the wells in that field were pumped for several hours prior to the time when the Morris wells were started but were then shut down. The water level at first rose quickly and later at a slower and

Discharge of high-duty pumps and water level in collecting reservoir at Morris pumping plant, June 5, 1926.

Time	Reading of indicator dial of Venturi meter	Reading of counter dial of Venturi meter	Pressure on distribution main	Water level in reservoir	Remarks
	Million gallons a day	*Ten thousand gallons*	*Pounds per square inch*	Feet [a]	
8.45 a. m.	....	....	..	10.71	Started high-duty pumps at 8.45 a. m.
9.05	....	....	60	11.04	All wells pumping except No. 6. Two high-duty pumps on.
10.15	....	....	60.5	8.75	All wells pumping except No. 6. Two high-duty pumps on.
10.30	13.0	....	63	9.15	All wells pumping except No. 6. Two high-duty pumps on.
10.52	16.75	....	72	10.17	All wells on and 3 high-duty pumps on.
11.27	19.0	....	66 (?)	10.23	All wells on and 3 high-duty pumps on.
11.45	....	....	66	10.12	All wells on and 3 high-duty pumps on.
12.12 p. m.	....	....	..	.....	All wells and high-duty pumps shut off at 12.12 p. m. because of trouble with electric current. All wells started at 2.05 p. m.
2.20	18.8	....	67	11.58	All wells pumping and 3 high-duty pumps on.
3.00	18.6	4,859	68	11.50	All wells pumping and 3 high-duty pumps on.
3.30	18.9	....	67	11.17	Well No. 7 shut off from about 3.16 to 3.20 p. m.
3.45	18.6	....	68	11.06	Well No. 7 shut off from about 3.16 to 3.20 p. m.
4.00	18.4	4,934	68	10.79	Well No. 6 shut off at 3.57 and started at 3.59 p. m.
5.06	18.8	5,020	66	10.54	Well No. 5 shut off at 4 and started at 4.02 p. m.
5.48	18.4	5,072	68	10.29	All wells pumping.
Average or total 3 to 5.48 p.m.	18.6	213	67.5	1.21 [b]	

[a] Readings in feet and inches reduced to nearest hundredth of foot.
[b] Difference in water level between 3 p. m. and 5.48 p. m.

slower rate. By noon it was rising very slowly, and it probably would not have risen much farther.

During the period from 12.15 to 1.45 p. m., when the Puchack wells were being pumped, the water level in test well No. 4 did not drop nearly as low as it was prior to the beginning of the test at 8.45 a. m. This may have been due in part to the fact that none of the Morris wells were being pumped. When pumping was resumed in the Morris field and the Puchack wells were again shut off, the water in test well No. 4 did not rise very rapidly, nor did it rise as high as just before noon. This is in agreement with the suggestion that if the Puchack wells had not been pumped the water level would not have risen much farther—in other words, that when the Morris wells were pumped at a rate of 18 million gallons a day the head in the Puchack field was lowered to about the level in test well No. 4—namely, about 26 to 27 feet below the top of the casing, or 13 to 14 feet below sea level. This is 15 to 16 feet below the supposed original static level. On the basis of data obtained May 10, 1924, it was estimated that if the old wells in the Morris field were pumped at a rate of 18 million gallons a day the water level in test well No. 4, in the Puchack field, would be lowered to a depth of about 12.6 feet below the original static level. In the test of June 5, 1926, for that rate of pumping the water level in test well No. 4 was actually lowered 3 or 4 feet lower. It is believed that this difference may be explained in part by the difference in distribution of the pumped wells in the Morris field. The nine wells in use on June 5, 1926, are all near the southeast side of the well field, whereas most of those in use on May 10, 1924, are farther northwest. Accordingly on June 5 the center of the area of influence was farther southeast, near the Puchack field.

The lowering of water level of 15 to 16 feet in Puchack test well No. 4, when the Morris wells, the nearest of which was only 2,000 feet distant, were being pumped at a rate of 18 million gallons a day is surprisingly small as compared to the lowering of the water level in most other localities. For example, in the vicinity of Atlantic City the water level in wells penetrating the so-called 800-foot sand is more than 16 feet below the original static level in an area at least 5 miles wide and more than 20 miles long, although the total average daily pumpage from the sand in the entire area is less than 10 million gallons.[1] In Atlantic City, where the pumpage is heaviest, the water level in a well at a distance of nearly a mile from the nearest pumped

[1] Thompson, D. G., Ground-water supplies in the Atlantic City region: New Jersey Dept. Conservation and Development Bull. 30, pp. 68-76, 1928.

wells was more than 50 feet below the original static head when the total pumpage in the city was only about 5 million gallons. In the Asbury Park area the water level in 1924 and 1925 in wells in the Mount Laurel and Wenonah sands that were not pumped was as much as 65 feet below the original static level, although the draft from the formations was less than 1,500,000 gallons a day.[1] From these comparisons with other productive water-bearing formations it is seen that the lowering of the water level in the Camden wells was very small.

Test of July 25 to August 31, 1927

Reasons for test.—During each of the pumping tests that have been described the automatic water-stage recorders indicated that the water level continued to drop as long as near-by wells were in operation. (See figs. 4, 7, and 10.) Numerous charts from the recorders show that during normal pumping operations the water level in each field is almost continually either rising or falling, which also indicates a lag in the adjustment of the water level to changes in the rate of pumpage. There is evidence that in other localities the lag may extend over a period of weeks or months. As the yield of the wells declines when the head drops it is desirable to know how long the water level will continue to go down in the wells at Camden and whether it will go down so far as to cause serious decline in yield. For this reason arrangements were made with the Camden Water Department to make a prolonged test.

Conditions of the test.—Since the new wells in the Morris field have been put into service the possible variations in the distribution of the draft have become very great. With nine wells in the Morris field, five in the Puchack field, and the suction system in the Delair field many combinations of pumping wells are possible, and each will produce different effects on the water levels in the observation wells. With these problems in mind and with the necessity of meeting the continual demand for water, the following plan was prepared: Four wells in the Puchack field were to be pumped continuously for several days. During the test all the Delair wells and if possible the Morris wells nearest to the Puchack field were to be shut off. Fluctuations in consumption were to be taken care of by starting or stopping wells in the northeastern part of the Morris field.

[1] Thompson, D. G., Ground water supplies in the vicinity of Asbury Park; New Jersey Dept. Conservation and Development Bull. 35, p. 39, 1930.

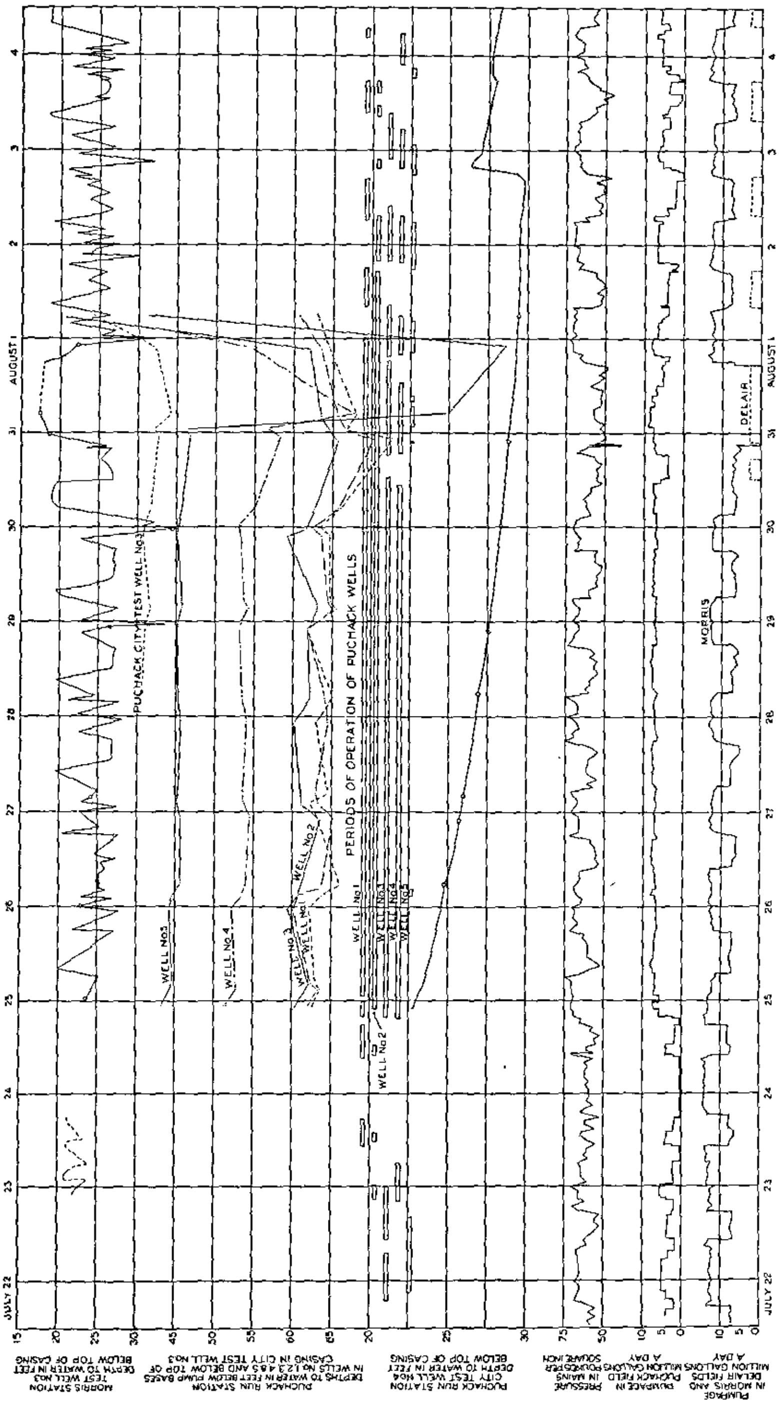

FIG. 12.—Graph showing movements of water levels in observation wells, rate of pumping, pressure in distribution main, and hours of operation of wells in the Puchack, Morris and Delair fields, July 22 to August 4, 1927.

Wells Nos. 1, 2, 3, and 4, in the Puchack field, were put into service about noon on July 25, 1927, and were pumped continuously until 11 p. m. July 30. At that time well No. 4 was shut down. Well No. 3 was shut down about an hour and a half later. Owing to a misunderstanding of the arrangements Morris wells Nos. 8 and 9, nearest to the Puchack field, were operated each night, and thus the conditions were not as uniform as it had been hoped they would be. Morris wells Nos. 5 and 7 were shut down for repairs and were not operated during the test. Continuous records of the water levels in test well No. 3, in the Morris field, and in test well No. 4 in the Puchack field, were obtained by means of automatic water-stage recorders, and occasional measurements were made of the depth to the water level in the pumped wells and in test well No. 3, in the Puchack field. Data in regard to rates of pumping and pressure on the distribution main were obtained from the routine records of each pumping plant. The field observations were made by H. C. Barksdale, then assistant hydraulic engineer of the Department of Conservation and Development, and he also performed the arduous task of compiling and plotting the numerous data obtained during the test. The essential data are shown in Figure 12.

For comparison with conditions before and after the test the record in Figure 12 extends from July 22 to August 4. Data were obtained in regard to 28 factors, including time of operation of each well and hourly records of rate of pumping. Even so the story has proved incomplete, and it can not be fully told because certain data whose value was not anticipated are lacking.

The daily pumpage from each of the three well fields during the period of the test is as follows:

Total pumpage from Puchack, Morris, and Delair fields, and average pressure on distribution main in Puchack field, July 22 to August 4, 1927.

Date	Pumpage (million gallons)				Average pressure on main at Puchack field [a] (Pounds per square inch)
	Puchack field	Morris field	Delair field	Total	
July 22	3.675	11.140	0.860	15.675	(b)
23	2.430	11.390	.000	13.820	(b)
24	0.959	11.850	.960	13.769	(b)
25	5.148	11.500	.000	16.648	63
26	7.079	10.890	.000	17.969	64
27	7.322	9.810	.000	17.132	63
28	7.281	9.640	.000	16.921	64
29	7.363	9.790	.000	17.153	63
30	7.167	7.890	.000	14.957	61
31	6.874	3.490	2.360	12.724	(b)
Aug. 1	5.544	8.750	1.110	15.404	(b)
2	4.865	10.410	1.180	16.455	(b)
3	3.941	10.470	1.180	15.591	(b)
4	4.482	10.620	1.170	16.272	(b)

[a] Average of hourly readings.
[b] Not computed.

Results of the test.—The problem of primary interest in the test was to determine how long the water level in the Puchack field continued to drop after pumping began. The graph (fig. 12) shows that in test well No. 4 the water level dropped continuously throughout the test; in fact, the lowest point was not reached until about 4 a. m. August 3, fully three days after pumping on some of the wells in the Puchack field was stopped. When the downward movement stopped the water level did not remain constant but rose rapidly, obviously because the pumpage from the well field was greatly reduced. It is apparent from the curve that if the same pumping conditions had been maintained for a longer period the water level would have dropped even farther. Extrapolation of the curve indicates that the water level probably would have continued to drop for a total of about 18 days from the beginning of the test.

The fact that the water level in test well No. 4 dropped for three days after the first reduction in pumpage indicates a lag in the establishment of stable conditions. The extended curve shows that the water level would have dropped for a much longer time and seems to indicate a lag of still greater duration. The fact that there was no marked rise in the water level in test well No. 4 until both well No. 1 and well No. 2 were cut off on August 3 suggests that both of these wells exert considerable influence on the test well, and that if they had not been shut off the water level would have dropped even farther than it did. There is, however, evidence that it is not alone these two wells that affect test well No. 4, for the water level dropped during the afternoon of August 3 and the morning of August 4 when neither of these wells were pumped.

The water levels in the pumped wells rose and fell as much as 2 or 3 feet on a single day, doubtless on account of variations in the rate of pumping. The record of test well No. 4 does not show definitely any influence from the great changes in the rate and distribution of pumping in the Morris field. For example, when wells Nos. 8 and 9 were started at night an estimated draft at a rate of about 4 million gallons a day was suddenly imposed on the southwestern part of the field, but the record of test well No. 4 does not show any distinct changes. However, this does not prove that wells Nos. 8 and 9 have no effect on the Puchack wells, for Nos. 8 and 9 were operating at night, when the total draft from the Morris field was only 50 to 75 per cent of the daytime consumption. Moreover, because test well No. 4 is so near wells Nos. 1 and 2, in the Puchack field, any slight effect from the Morris wells would largely be obscured.

An attempt was made to study the effect of long-continued pumping on the yield of the wells by determining a relation between changes in pressure in the mains and rate of pumping. Figure 12 shows that variations in operating conditions were generally at a minimum between midnight and 5 a. m. The records for these hours are given in the following table:

Rate of pumping, in million gallons a day, and pressure on distribution main, in pounds to the square inch, in the Puchack field at certain hours on July 26 to 30, 1927.

Hour	July 26		July 27		July 28		July 29		July 30	
	Pumping rate	Pressure	Pumping rate	Pressure	Pumping rate	Pressure	Pumping rate	Pressure	Pumping rate	Pressure
Midnight	7.2	60	7.8	55	7.2	60	7.5	56	7.2	55
1 a. m.	7.0	60	7.7	54	7.5	60	7.7	56	7.4	54
2 a. m.	7.0	60	7.7	55	7.5	57	8.0	54	7.4	54
3 a. m.	7.0	60	7.7	56	7.8	53	7.5	58	7.3	55
4 a. m.	6.8	63	7.7	58	7.5	57	7.5	56	7.1	52
5 a. m.	6.8	62	7.6	58	7.2	66	7.6	58	6.8	56
Average for period	7.0	61	7.7	56	7.4	59	7.6	56	7.2	54

Even in these hours there was considerable variation in the relation between the rate of pumping and the pressure. However, the yield for a given pressure was much less on July 30 than on any previous days, not only in the early morning hours but also for the day as a whole. On July 30 the average pressure was lower than on any other of the five days under consideration, but the total pumpage was less than on three of the other days and only a little more than on the day when the pressure was highest.

The following method gives some information on this problem. If a group of wells in the two fields were pumped for certain periods each day, other factors remaining constant, the total pumpage should be constant. If the period of pumping of different wells is changed in a definite ratio the yield would be in proportion to such change in time. If the rate of yield of some of the wells is much less or greater than that of others this relation will not hold if the period of operation of some of the wells is changed disproportionately with respect to the period of others, for it alters the average rate of yield for the group. The pumping periods of the Morris Station wells were fairly uniform during the test and it is believed this method may be applied within certain limits. In applying this method the results in the bottom line of the following table are expressed in terms of consumption if all the wells had been operated for 24 hours.

The results show three things. The yield of the wells was relatively high on July 25 before prolonged pumping in the Puchack field began; it was rather low on the last day of the test; and on the other days, although the yield was about half way between that on the other two days, there was not much change from day to day. The difference in yield from July 26 to July 29, inclusive, is so small that, considering the variable factors involved, it cannot be said that there was any appreciable difference in capacity of the wells on those days. On the other hand the differences in yield on July 25 and 26, and 29 and 30 are so great that there is little doubt that the capacity of the wells was decidedly different on those days. The explanation that immediately suggests itself to account for the differences in yield on different days is the prolonged pumping of the Puchack wells. However, if prolonged pumping caused such a difference there should be a progressive decrease in capacity from the first day of the test to the last day. Furthermore, this decrease should also be most marked in the early part of the test. The fact that this was not so suggests that some other influence may have been active, but what it was has not been determined.

Hours of pumping in quantity of water pumped from and estimated capacity of Morris and Puchack well fields, July 25 to 30, 1926

	July 25	July 26	July 27	July 28	July 29	July 30
Total hours pumped:						
Morris wells [a]	115.50	120.5	111.5	111.5	112.0	107.5
Puchack wells	68.25	97.5	96.0	96.0	96.0	96.0
Total	183.75	218.0	207.5	207.5	208.5	203.5
Per cent of possible hours of operation (288)	63.8	75.7	72.0	72.2	72.2	70.7
Total pumpage, in million gallons Morris wells [a] ...	11.500	10.890	9.810	9.640	9.790	7.890
Puchack wells	5.148	7.079	7.322	7.281	7.363	7.167
Total	16.648	17.969	17.132	16.921	17.153	14.957
Estimated pumpage if all wells were operated 24 hours	26.10	23.74	23.79	23.50	23.76	21.16

[a] Does not include wells Nos. 5 and 7 which were shut down for repairs.

The decrease in the apparent capacity of the two well fields computed from the wells actually used was 5 million gallons a day. Assuming that wells 5 and 7 in the Morris Station field had yielded in the same proportion as the others the estimated total capacity of all the wells would have been about 30.5 million gallons a day on July 25 and only 24.7 million gallons on July 30, a decrease of nearly 20 per cent. Such a great decrease in capacity in a few days is worthy of further study.

SEASONAL AND ANNUAL FLUCTUATIONS IN WATER LEVEL

Atlantic City and Asbury Park regions.—In some localities of New Jersey where investigations of ground-water supplies have been made there is considerable fluctuation of the water level in wells from season to season and from year to year. For example, in the so-called 800-foot sand in the Atlantic City area both the pumping and nonpumping level fluctuate as much as 20 feet in a year; and each succeeding year the water has dropped to a lower level than in the preceding year.[1] The drop in level from one year to another has ranged from 4 to 10 feet. In the 34 years since the first well was drilled into the formation the head has dropped from a few feet to as much as 100 feet below the original static level in different parts of an area covering some 300 or 400 square miles. At Avon-by-the-Sea the annual range in movement of the water level in the wells drawing from the Mount Laurel and Wenonah formations is as much as 50 feet,[2] but definite data are not available as to changes in water level from year to year. In that area the maximum drop in head from the original static level in about 43 years is estimated to be as much as 65 feet. These seasonal and annual fluctuations bear a relation to the water-bearing capacity of the formations. Thus the seasonal fluctuation in water level in the Atlantic City area is caused by a difference in pumpage of 4 or 5 million gallons a day but the much greater fluctuation at Avon-by-the-Sea is caused by a difference in pumpage of only about 1.5 million gallons a day.

In the Camden fields.—The lowest water level reached each day in test well No. 3, in the Morris field, and in test well No. 4, in the Puchack field, as shown by automatic water-stage

[1] Thompson, D. G., Ground-water supplies of the Atlantic City region: New Jersey Dept. Conservation and Development Bull. 30, pp. 54-59, 1928.

[2] Thompson, D. G., Ground water supplies in the vicinity of Asbury Park; New Jersey Dept. Conservation and Development Bull. 35, p. 30, 1930.

recorders, is presented in Figure 13. The graphs must be interpreted with a knowledge of operating conditions at different times. The water level in test well No. 4, in the Puchack field, showed no large fluctuations prior to about August 15, 1924. The wells in the Puchack field were put into service on October 1, 1924, and any movements of more than a foot that occurred before that date were generally due to pumping of the wells for test purposes. During this period the water level, between 16 and 17.5 feet below the top of the casing, was the nonpumping level. Unfortunately the record is available for only a few days until June 1, 1925. The characteristic feature of the curve after the Puchack system was put into service is its great range in movement from day to day, due to changes in the total draft on the field and the distribution of draft from the several wells. The water level in test well No. 4 of course, drops most when well No. 1 is pumped and least when well No. 4 or well No. 5 is pumped. Also the longer well No. 1 is pumped the lower the water level goes. Therefore, when well No. 1 is pumped for a long period the water level in the observation well may be lowered much more than if Nos. 4 and 5 are pumped for the same period with greater total discharge.

The curve for Morris test well No. 3 shows features different from that of Puchack test well No. 4 for a large part of the period covered, owing largely to different methods of operation. Before the Puchack wells were put into service fluctuations in consumption from day to day were taken care of largely by changing the draft on the Morris field, but afterward they were taken care of largely by the Puchack wells, and the daily pumpage from the Morris field varied less. However, even before the Puchack wells were put into use the fluctuation in Morris test well No. 3 was relatively small, evidently because of the location of the observation well in relation to the pumped wells and the method of pumping with steam pumps working on suction. Fluctuations in consumption, great or small, were cared for by changing the speed of the pumps, but pumping never stopped. The draft on the field was distributed among many wells. Furthermore, the depth to which the water could be lowered was limited by the limit of suction lift. After the new wells in the Morris field were put into service, on June 5, 1926, the fluctuation of the water level in Morris test well No. 3 became much greater and more like that of Puchack test well No. 4. This was obviously due to the new method of pumping, by which the water level was drawn down to a much greater depth in a few wells. Furthermore, as the speed of the pumps can not be

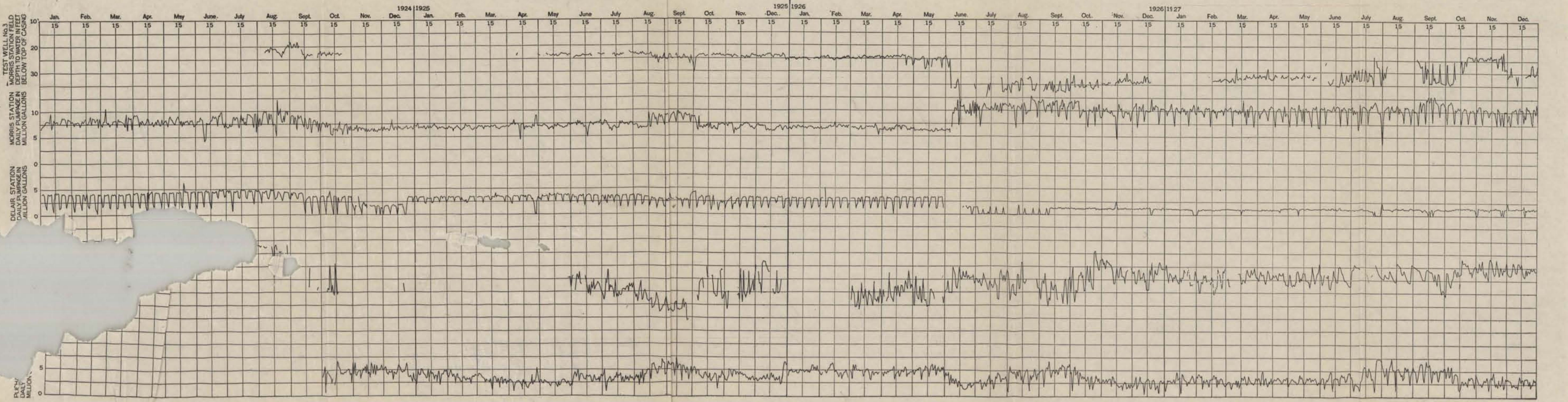

FIG. 13.—Graph showing lowest water level each day in Morris testwell No. 3, and Puchack test well No. 4, and daily pumpage in the Morris, Puchack, and Delair fields, 1924-1927.

varied to meet changes in consumption, such changes must be taken care of by starting or stopping the pumps on one or more of the wells. Morris test well No. 3 is, of course, affected most by No. 7, which is nearest to it.

The lowest level reached in Morris test well No. 3 was about 42.5 feet below the top of the casing (about 38 feet below the supposed original static level). On the day this occurred, June 14, 1926, the total pumpage from the Morris field was 10.7 million gallons. The lowest level reached in Puchack test well No. 4 was about 46 feet below the top of the casing, or 35 feet below the original static level. This was on September 25, 1925, when the total pumpage was 5.67 million gallons. In each well the lowest level was not reached on days when the total pumpage was greatest but was doubtless produced by prolonged pumping of the wells that affected the observation wells the most.

The most significant fact shown by the water-stage recorders on the two test wells is that, in spite of considerable fluctuations in pumpage, the movements of the water level are not great as compared to those in the Atlantic City and Asbury Park areas. The small fluctuations are especially impressive when the much greater range in pumpage in the Camden fields is considered and when it is remembered that the observation wells in the Camden fields are within 100 to 300 feet of the nearest pumped wells, whereas in the other two areas some of the observation wells in which there have been great fluctuation are a mile or more from the nearest pumped wells. On the basis of data obtained in the tests described above, it is believed that during the period covered by Figure 13 the maximum lowering of head below the original static level at points a mile from the Morris or Puchack fields has not been as much as 10 feet and seldom if ever as much as 5 feet.

As previously stated (pp. 40, 50), the original static level in the Morris field is said to have been 2 feet above mean sea level. The only available data as to the water level in observation wells and the extent of the area of influence of the Morris field during pumping in the early history of its existence are certain measurements made on May 11, 1907.[1] These show that on that date the water level in the so-called Fischers Point well was 1.43 feet below sea level or 3.43 feet below the original static level.[2] This well was close to the Delaware River and

[1] Report of the Chief Engineer, Camden City Water Department, for year ending June 30, 1907, p. 93 and diagram 10, 1907.

[2] The record does not show whether this measurement was made at high or low tide, or whether it is an average of several measurements through one tidal period. Recent observations show considerable oscillation of level due to tide particularly in wells near the river. H. B. K.

probably not far from the southwesternmost well in the present Delair well field. It was about 2,500 feet from the nearest pumped well in the Morris field. The rate of pumping on May 11, 1907, is not known but the average rate of pumping during the month of May in that year was a little more than 13 million gallons a day. No recent data are available for the Fishers point well or for any well very close to it. However, Puchack test well No. 4 is about the same distance as the Fishers Point well from the nearest well in the Morris field. On July 31, 1924, when the pumping rate from the Morris wells ranged from 10.0 to 12.4 million gallons a day, the lowest level reached by the water in that Puchack well was 1.01 feet below sea level, or about 3 feet below the supposed original static level. Thus it seems that there was little or no lowering of the head in the vicinity of the Morris field from 1907 to 1924.

CAPACITY OF MORRIS, PUCHACK, AND DELAIR WELL FIELDS

The Morris wells have been pumped at a rate of 18 million gallons a day and the Puchack wells at a rate of 9.5 million gallons a day (see pp. 43, 52). The capacity of the Delair wells is said originally to have been 5 million gallons a day, but in recent years these wells have yielded only 3.5 to 4 million gallons a day.[1] The total theoretical capacity of the three fields is therefore between 31 and 32 million gallons a day. However, the maximum rate in any of the fields has been maintained for only a few hours at a time. Moreover, the Puchack and Delair wells were shut down while the Morris wells were tested, and during the test of the Puchack wells the Delair wells were shut down and the Morris wells were operated at a low rate. There has therefore been no test to determine the total capacity of the three fields if operated simultaneously for a prolonged period.

The observations discussed above indicate that heavy pumping in one field affects to some extent the yield of wells in the other two fields. It is surprising, however, that, considering the large quantities of water pumped, the interference between the well fields is no greater. Data presented on page 63 indicate a decline of nearly 6 million gallons, or 20 per cent, in the estimated capacity of the Morris and Puchack wells from the beginning to the end of a six-day period. If the other two fields were pumped to capacity the yield of the Delair wells would also be reduced. If the conditions during the test of July

[1] The new Layne gravel-wall wells, completed in 1930, have restored the capacity to about 6 million gallons daily.

25 to 30, 1927, were truly representative they indicate that the capacity of the three well fields is several million gallons a day less than the total of 31 or 32 millions based on tests of the individual fields. As stated on page 57, it is not certain that the conditions were entirely representative, but the difference is so great that the subject deserves further investigation.

EFFECTS OF PUMPING IN OTHER PARTS OF THE AREA

In the summer of 1923 data in regard to public supplies and a few large private supplies obtained from wells in this area were collected by F. Clark Rule under the direction of the writer. That summer was a notably dry one, and in several communities there was danger that the water supply would prove inadequate. A study of the data shows that the lack of sufficient supply was due in part to inadequacy of the pumping equipment or distribution mains, in part to deterioration of wells which had been in use a long time and whose screens had become clogged or worn out, and in part to increase in consumption from year to year without adequate increase in the capacity of the systems. Nowhere in the area was there any indication of marked lowering of the hydrostatic head on the Magothy and Raritan formations as compared to the original static head. When new wells were installed or the old wells cleaned, yields comparable to the original yields were generally obtained.

POSSIBILITY OF FURTHER DEVELOPMENTS OF GROUND-WATER SUPPLIES

The consumption of water from the Magothy and Raritan formations in the Camden area in 1926 is estimated to have been between 35 and 40 million gallons a day. Yet except in the immediate vicinity of pumped wells there has been no appreciable lowering of the water levels in wells. Hence it is evident that the water-bearing capacity of the Magothy and Raritan formations in the Camden area is very great. In fact, it is believed that they have a greater water-bearing capacity than any other formation in the State. Furthermore, in few localities in the United States has so large a quantity of water been pumped in so small an area with so little effect on the head and yield.

There is no doubt that a much larger draft may be imposed on the Magothy and Raritan formations in this area without depleting the supply. It is to be expected that there will be some lowering of the head as the rate of pumping is increased, but a large additional supply can be developed before the limit of economic pumping lift is reached. Doubtless the capacity of the Camden well fields can be increased by increasing the capacity of the pumps and drawing the water to a lower level or by constructing additional wells in these fields or in additions to them. It will not, however, be economical to take a large additional quantity from these small areas.

The public water supplies of the other towns in the Camden area can be considerably enlarged before the effect of pumping in any one locality will become serious. Nevertheless it is desirable to begin a program of systematic observations on the effect of pumping in different parts of the area, in order to obtain adequate data upon which to base future developments.

QUALITY OF WATER

The problem of supplying water of satisfactory quality to the city of Camden has required considerable attention from the officials of the City Water Department in recent years. The water as delivered in the city is in general of good quality except that at times it has contained so much iron as to make it almost unfit for some domestic purposes, especially for laundry work. The condition was aggravated when the consumption was high because the water moving through the mains at a high rate picked up much deposited iron that was not disturbed at lower rates of pumping.

The problem of lowering the iron content in the water was taken up by W. D. Collins, chemist in charge of the Division of Quality of Water of the United States Geological Survey, who spent several days at the well fields collecting samples from different wells and determining their iron content. Subsequently, during the course of the investigation, many partial and several complete analyses of water from different wells were made. Complete analyses, however, are available only for wells in the Puchack field and of one sample of water from a tap in the city which probably represents a mixture from two or more well fields. A number of analyses are given in the following table:

Analyses of water from wells of Camden Water Department, Cooper Creek, and Delaware River. (Parts per million)

	1	2	3	4	5	6	7	8	9	10	11
Total dissolved solids......	66	77	56	58	47	..	..	..	78	118	47
Silica (SiO_2)	6.2	6.5	6.5	..	7.0	..	..	..	13	..	..
Iron (Fe)	.06	a .47	.03	.09	.03	b	.6	b	c .87	.18	00
Calcium (Ca)	8.3	9.6	5.1	5.2	3.3	..	..	..	10	..	..
Magnesium (Mg)	5.2	1.8	1.4	.4	1.0	..	..	..	2.4	..	..
Sodium (Na)	4.6	9.7	5.3	..	3.0	..	..	..	5.4	..	..
Potassium (K)	.7	2.5		..			..	..		..	..
Bicarbonate radicle (HCO_3).	25	24	3.7	3.7	3.7	22	34	8	26	48	6
Sulphate radicle (SO_4).....	13	16	1.6	..	1.1	..	..	..	17	29	11
Chloride radicle (Cl)	5.4	7.0	3.0	7.0	2.5	7	4	23	4.8	5.5	2.3
Nitrate radicle (NO_3)......	9.1	12	26	15	16	..	..	..	.51	3.8	.4
Total hardness as $CaCO_3$ (Calculated)	42	31	16	15	12	..	..	d 60	35	d 48	d 23

a Includes 0.33 part per million which was precipitated when the sample was received.
b Less than 0.1.
c Includes 0.37 part per million which was precipitated when the sample was received.
d Determined.

1. Tap at city hall in Camden, probably a mixture of water from Morris and Delair fields and possibly from some of the wells in the city. Collected March 24, 1922. Analyzed by Margaret D. Foster.

2. Morris station, faucet on steam pump. Collected March 26, 1924. Analyzed by C. S. Howard.

3. Well No. 1, Puchack field. Collected March 27, 1924, during preliminary pumping test. Analyzed by C. S. Howard.

4. Well No. 2, Puchack field. Collected April 3, 1924, after pumping 2¾ hours during preliminary test. Analyzed by C. S. Howard.

5. Well No. 4, Puchack field. Collected May 10, 1924, after pumping 4¾ hours during preliminary test. Analyzed by C. S. Howard.

6. Delair pumping station, mixed water from all wells in the Delair field. Collected May 8, 1923. Analyzed by W. D. Collins.

7. City well No. 1, on Federal Street, near Cooper Creek. Collected May 8, 1923. Analyzed by W. D. Collins.

8. City well No. 4, in Park at Ross and Whitman Streets. Collected May 9, 1923. Analyzed by W. D. Collins.

9. Cooper Creek, near Haddonfield. Collected July 22, 1925. Analyzed by C. S. Howard.

10 and 11. Delaware River at Torresdale, Pa., final filter effluent supplied to city of Philadelphia. Sample 10 gives the maximum quantity and sample 11 the minimum quantity of constituents in samples analyzed by Philadelphia Waterworks in 1920.

All the waters for which analyses are given in the above table have a small mineral content and are suitable for domestic and boiler use except that they may be somewhat corrosive.

The iron content shown by the analyses is not high enough to cause any trouble. If the iron present does not exceed 0.4 to 0.5 part per million there will generally be little or no trouble from staining of clothing or utensils. In all the samples except No. 9, which is not used for public supply, the iron content is much less than this danger point. However, tests for iron in samples from many of the wells in the Morris field in 1923 showed much higher amounts. In samples from 15 wells in that field, collected on May 7 to 9, 1923, the iron ranged from less than 0.1 part to 40 parts per million, and in one well it was 450 parts per million. Samples taken at the pumps at the Morris station contained 4.5 to 8 parts per million. Before this water reached the city it was diluted to a slight extent with water from the Delair station, and in some parts of the city there was further dilution with water from the isolated city wells.

A series of samples taken from the distribution main at the Morris station at intervals of an hour showed rather definitely that the iron content increased as the rate of pumping increased, because the iron had precipitated in the wells or pipe lines and at the higher rates of pumping the velocity was so great that the precipitate was picked up and carried along. When some of the wells were started great quantities of iron precipitate were discharged.

In an effort to reduce the iron content in the system the wells that furnished the water having the greatest quantities of iron were shut off. As rapidly as possible all the wells were cleaned out, and new screens were put in many of them. This was very effective in reducing the iron. Within about a month the iron in samples collected at the pump had been reduced to between 1.5 and 1.8 parts per million. This result was accomplished largely by shutting off the wells with the highest iron content. In August, 1923, about two-thirds of the wells had been cleaned and overhauled, the iron in water taken from the pumps at the Morris station had dropped to 0.4 or 0.5 part per million. In a series of hourly samples collected from the Morris pumps on October 16 and 17, 1923, the iron ranged from 0.11 to 0.42 part per million except two that were 0.5 and 0.8 part per million. The average of 24 hourly samples was 0.28 part per million, which is below the limit at which trouble results from excessive iron. In a series of 14 samples from taps at different points in the city analyzed by the water department in March, 1924, the iron ranged from a trace to 0.15 part per million.

On December 8, 1926, the writer collected a sample from each of the new wells in the Morris and Puchack fields, from the three isolated city wells then in use, and from taps at several points in the city. The Delair pumping plant was not in operation, and no samples were obtained from it. The results are given in the following table:

Partial analyses of samples from Camden waterworks.

[*Collected Dec. 8, 1926, by D. G. Thompson, U. S. Geol. Survey. Analyzed by W. D. Collins. Parts per million.*]

	Iron (Fe)	Bicarbonate radicle (HCO_3)	Sulphate radicle (SO_4)a	Chloride radicle (Cl)	Nitrate radicle (NO_3)	Total hardness as $CaCO_3$
Morris field:						
Well No. 1	0.01	10	14	12	22	42
Well No. 2	.02	10	8	8	24	44
Well No. 3	.01	5	10	6	17	38
Well No. 4	.01	33	10	6	7	48
Well No. 5	.7	54	12	6	6	66
Well No. 6	.09	78	4	7	12	38
Well No. 7	.8	83	3	6	9	82
Well No. 8	.01	34	8	9	9	46
Well No. 9	.01	13	18	7	4	37
High-duty pump No. 4	.2	38	8	9	14	57
Puchack field:						
Well No. 1	.01	2	3	11	17	25
Well No. 2	.01	5	2	6	18	21
Well No. 3	.01	2	1	8	18	20
Well No. 4	.01	5	1	1	7	14
Well No. 5	.03	2	1	10	21	25

Isolated city wells:						
Well No. 1	.25	23	20	10	3	36
Well No. 3	.01	17	80	51	35	166
Well No. 4	.01	37	28	25	28	74
Taps in city:						
Barber shop, 318 S. 5th St.	.09	28	8	8	15	46
Cafe, northwest corner 3d St. and Kaighn Ave.	.12	23	20	14	18	57
No. 3 fire station, S. Broadway near Emerald St.	.02	22	24	14	19	64
Store, northwest corner Rose and Everett Sts.	.01	5	22	26	28	58
Store, northwest corner 9th and State Sts.	.6	35	6	9	15	50
Barber shop, 13 S. 3d St.	.1	28	6	9	16	46

[a] By turbidity.

The iron was less than 0.1 part per million in all the wells except Nos. 5 and 7, in the Morris field, and the isolated city well No. 1. It appears that the iron content in the water as a whole is not high, and the question arises as to the source of the iron that has caused so much trouble in the past. The alkalinity as bicarbonate is so low as to suggest the possibility that the water may be corrosive under certain conditions. If it is, the large quantities of iron delivered in the city can be explained by corrosion of either the distribution mains or the well casings and screens. The great quantities of iron discharged from some of the wells fits in with this explanation, but no data have yet been obtained to show whether there has also been extensive corrosion in the pipe lines. As shown by the analyses on pages 69, 72, the alkalinity in the water from the Puchack wells is very low, and there is danger that at some time in the future corrosion may again cause an increase in the iron content. The alkalinity of the water from the new wells in the Morris field is somewhat higher, and there appears to be less danger from corrosion from the water delivered by those wells.

In the opinion of the writer some water enters the Magothy and Raritan formations from the Delaware River or its tributaries. (See page 3.) It has been held that this could not be true, because the river water is different in chemical composition from that obtained from the wells. For comparison analyses of water from the Delaware River and Cooper Creek, one of its tributaries, are given on page 69. The surface waters are not altogether like the ground waters, but the differences may be explained as the result of mixing of river water with the ground water. In this connection it is noteworthy that the water from the new wells in the Morris field is in general more like the river water than the water from the Puchack wells, which are farther from the river.

If any of the ground water does enter the formation from the river there is a possibility that it may become contaminated, especially if the rate of pumping is increased. The danger of pollution may be increased if there is any large diversion of water from the upper drainage basin of the Delaware River such as that contemplated by the State of New York. Such diversion would prabably have the two-fold result of providing less water to dilute the waste materials now carried by the river and it would permit the salt water of Delaware Bay to back farther up the river.

It is by no means certain that the salt water zone would migrate far enough up the Delaware River to effect the Camden wells. However, that such a migration is possible is shown by the experience on the Sacramento River in California, where as a result of diversion for irrigation and deficient precipitation, the boundary lines between water of given saltiness advanced upstream several miles.[1] Even if there is no diversion from the watershed it is nevertheless possible that the sanitary quality of the water from the wells may be impaired by percolation from the river. These considerations emphasize the desirability of frequent bacteriological tests of the water to detect the first indications of pollution, so that the water may be chlorinated in time to prevent disease.

[1] Biennial report of the division of water rights, California Dept. Public Works, for 1920-1922, pp. 84-89, 1923; for 1923-1924, pp. 128-130, 1925; for 1925-1926, pp. 100-103, 1927.

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