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DIVISION OF WATERS

HOWARD T. CRITCHLOW, *Chief*

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

BULLETIN 30

GROUND WATER SUPPLIES *of the* ATLANTIC CITY REGION

BY

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LETTER OF TRANSMITTAL

September 17, 1928.

Dr. Henry B. Kümmel, Director,
Department of Conservation and Development,
Trenton, New Jersey.

Dear Sir:

I am transmitting herewith a report on Ground Water Supplies of the Atlantic City region, prepared by Mr. David G. Thompson, Geologist, United States Geological Survey. The report is based upon field investigations made during the period of about four years beginning July 1, 1924, by the author working in cooperation with the Division of Waters in studying the ground water resources of the State.

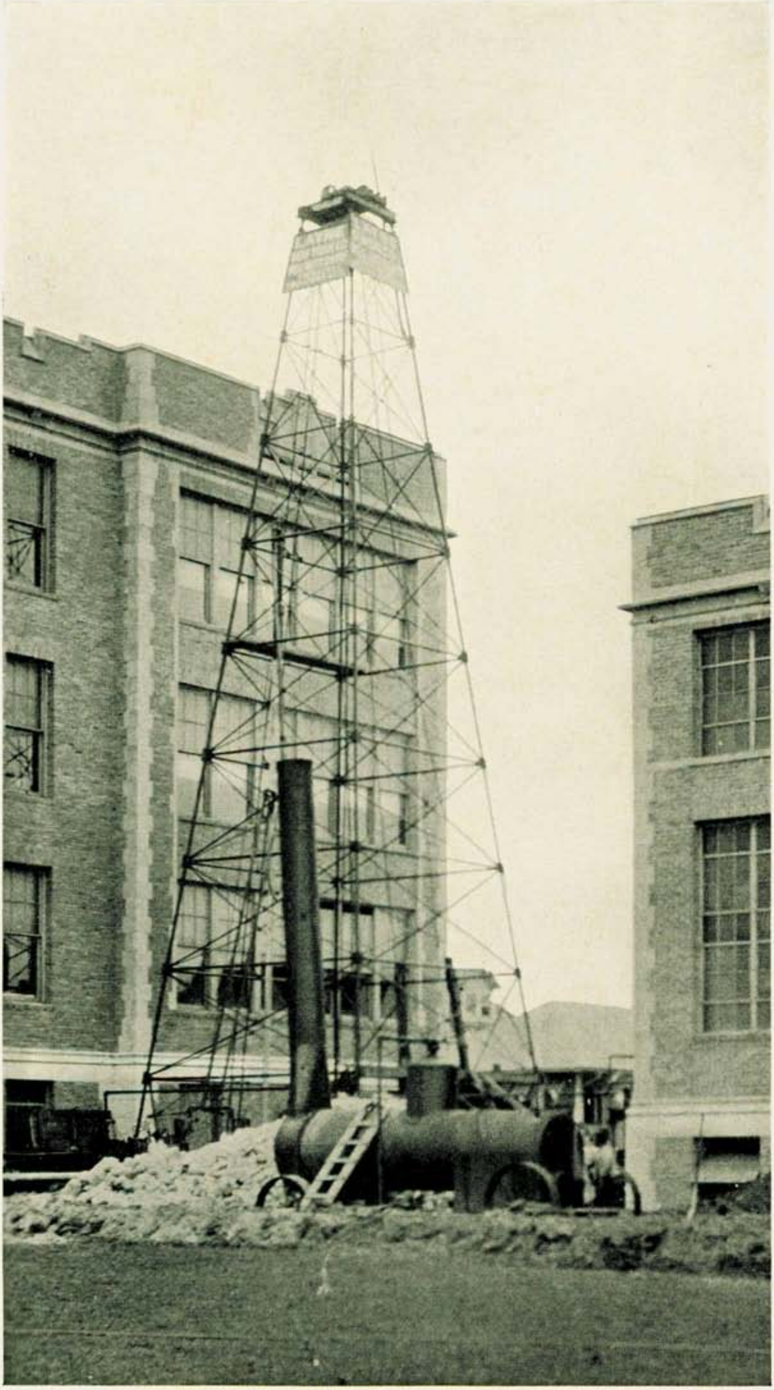
This report is the first of a serious which are being prepared on gound water conditions in several areas throughout the State where large supplies of water are being utilized for potable and public use. The necessity for more accurate knowledge of our water resources, in order to plan intelligently future water supply developments, amply justifies these investigations.

I therefore recommend that this report dealing with the Atlantic City region be published as a Bulletin of the Department's reports, in order that the people of the State may have the benefit of the information and conclusions which the author presents therein.

Respectfully submitted,

Howard T. Critchlow,
Chief, Division of Waters.

Approved for publication,
Henry B. Kümmel, *Director.*



Well rig at Atlantic City High School.

GROUND WATER SUPPLIES OF THE ATLANTIC CITY REGION.

By David G. Thompson.

INTRODUCTION.

This report is one of several describing ground-water conditions, especially with respect to the quantity of water available, in certain localities in New Jersey where large quantities of ground water are used. The investigations on which the reports have been based have been carried on by the New Jersey Department of Conservation and Development in co-operation with the United States Geological Survey. The work was done by the writer in consultation with H. T. Critchlow, 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 Geological Survey. He was assisted at different times by Ernest W. Downs, junior engineer of the Geological Survey, and Henry C. Barksdale, formerly of the Geological Survey and now assistant hydraulic engineer of the Department of Conservation and Development. Numerous analyses of water were made in the laboratory of the Geological Survey by C. S. Howard, and W. D. Collins, Chemist in Charge of the Division of Quality of Water of the Survey, has offered valuable suggestions. Other members of the Geological Survey and Department of Conservation and Development have also rendered assistance in many ways. The writer is especially indebted to the late Dr. M. W. Twitchell, Assistant State Geologist of New Jersey, for information in regard to the stratigraphy of the region covered by the present report.

Many persons have assisted by giving freely of information of one sort or another and to them the writer expresses his appreciation. He is especially indebted to Commodore Louis Kuehnle, Commissioner in Charge, Mr. Lincoln Van Gilder, Superintendent, and Mr. Frank Trumbore, Chief Engineer of the Atlantic City Water Department; to Harry Singley, Chief Engineer of the Ventnor Water Works; James Bois, of the Margate Water Department; Mr. Jacob E. Frye, Superintendent of the Longport Water Department; Mr. Howard Banks, Superintendent of the Wildwood Water Co., and officials and drillers of the Layne-New York Co., and the Artesian

Well Drilling Co. for assistance in making tests or collecting special data, and to the owners or operators of wells in the region not specifically mentioned who furnished information in regard to their wells.

The area considered in the report includes the region along the Atlantic coast from Brigantine to Corson's Inlet and on the mainland from Absecon to Somers Point. (See Fig. 1.) Some informa-

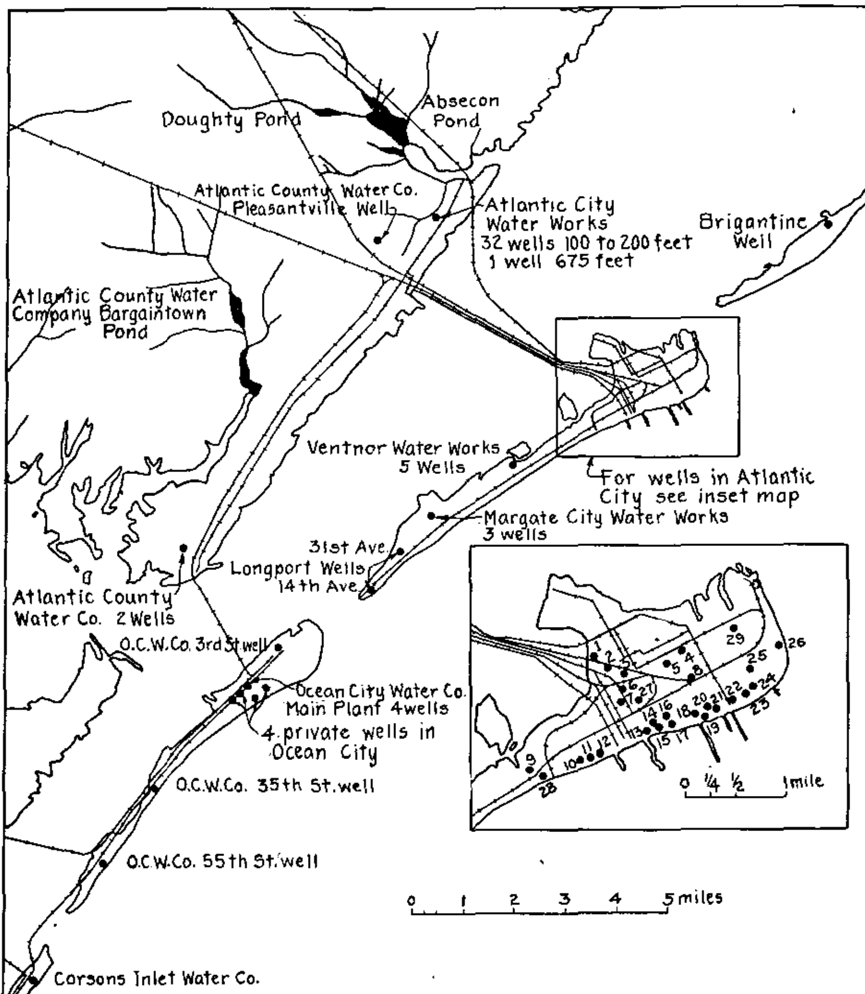


FIG. 1.—Map of the Atlantic City region showing location of surface water and principal well supplies.

tion is also given in regard to conditions along the coast as far south as Wildwood.

The report contains the principal results of the investigation through April 30, 1928. It is believed that the general conditions affecting the occurrence of ground water in the region are now well understood, but some important details remain to be studied further. The observations are being continued, and it is hoped that later a report may be prepared containing further data which may lead to more definite conclusions as to the effect of future increases in pumpage from wells in the region.

KEY TABLE FOR FIG. 1.

Numbers on inset map of Atlantic City refer to privately owned wells as follows:

1. Atlantic City Electric Co. (2 wells)
2. Pennsylvania Railroad
3. Atlantic City Gas Co.
4. Supplee-Wills-Jones Dairy Co.
5. Abbott Dairy Co.
6. Reading Railroad (abandoned)
7. Atlantic City Brewing and Ice Co.
8. Guarantee Trust Bldg.
9. Atlantic City High School
10. Chelsea Hotel
11. Ambassador Hotel
12. Ritz-Carlton Hotel
13. Shelbourne Hotel
14. Dennis Hotel
15. Marlborough-Blenheim Hotel (2 wells)
16. Brighton Hotel
17. Traymore Hotel (2 wells)
18. Knickerbocker Hotel
19. Chalfonte Hotel (2 wells)
20. Haddon Hall (2 wells—1 not used)
21. Strand Hotel
22. Blackstone Hotel (not used)
23. St. Charles Hotel
24. The Breakers Hotel (2 wells)
25. Galen Hall
26. Royal Palace Hotel
27. American Ice Co.
28. President Hotel (not yet in use)
29. Citizens Ice Co. (abandoned)

SUMMARY OF REPORT.

The present water supply for the Atlantic City region is obtained from three sources; namely, water from streams on the mainland, shallow wells on the mainland, and deep wells on the beaches. The water from the first two sources is used principally for part of the public supply of Atlantic City and for mainland towns between Absecon and Somers Point. The deep wells are used for public supplies at Brigantine and from Ventnor southward to Wildwood, and for private supplies for many hotels and industrial plants in Atlantic City and Ocean City.

The estimated average daily consumption from all sources in the entire region in 1927 was about 22 million gallons a day. Of this about 30 per cent was from streams, 27 per cent from shallow wells on the mainland, and 43 per cent from deep wells. In the 10 years between 1917 and 1927 the consumption from public supplies increased about 7.4 million gallons or 82 per cent above the consumption in 1917. Data in regard to pumpage from private wells are not available for the 10-year period, but in three years, from 1924 to 1927, the average daily consumption increased about one million gallons. It is estimated that within the next 20 years the average daily consumption from all sources may increase more than 20 million gallons.

The supply of surface water at present available is insufficient to meet the expected increase in consumption. To provide for future needs it will be necessary to go many miles to streams not now used, or to develop additional supplies from wells. For several reasons wells offer the simplest methods of increasing the supply. In many regions where large quantities of ground water have been developed the head on the water, as shown by the water level in wells, has dropped considerably and in some places the supply has been greatly overdrawn. In the Atlantic City region the problem is complicated by the fact that many of the wells are situated very close to the ocean, and as shown by experience in other regions along seacoasts there may be danger that the water-bearing formations will become contaminated by salt water. In view of these facts it is advisable to consider the extent to which additional ground-water supplies can be developed. It is the purpose of this report to determine the probable effect of considerable increases in pumpage from the water-bearing formations and the availability of these formations for future increases in supply. It is not within the scope of the report, however, to consider the relative merits of different sources of supply from the standpoint of cost, and other items which properly should be considered in the final choice of any one type of supply.

The principal method of study has been to determine the effects of pumpage of given quantities of water upon the water levels in the wells, and, on the basis of certain principles of hydraulics, to consider the effect that would be produced by further increase in pumpage. In doing this it has been necessary to determine the relative effects of several factors, which if not correctly understood might lead to a wrong interpretation of the data obtained. Records were obtained during a period of nearly four years on the water levels in several observation wells and on the pumpage from the entire area from day to day and month to month; also on the fluctuations of the water levels in wells during a series of pumping tests of several hours. The geological conditions were carefully studied and tests were made on samples of sand obtained from wells during the process of drilling to determine the permeability of the water-bearing formations. Conditions in other regions along seacoasts were studied and compared with those in the Atlantic City region to determine whether there is any danger that the water-bearing formations may become contaminated with salt water from the ocean.

In the Atlantic City region ground water of good quality is obtained from two sources. The most productive water-bearing horizon at present is the Atlantic City 800-foot sand, about 80 feet thick, which along the beach from Brigantine to Ocean City is reached at a depth of about 760 feet and at increasing depths south of Ocean City until at Wildwood it is about 900 feet below the surface. The sand rises toward the northwest and on the mainland at the Atlantic City Water Works it is reached at a depth of only 600 feet. The other water-bearing formation consists of shallow sand beds which yield potable water only on the mainland where they lie within about 250 feet of the surface. In 1927 an average of about 9.5 million gallons a day was pumped from the 800-foot sand. It is the sole source of supply for all places along the coast between Brigantine and Stone Harbor, except Atlantic City, and in that city an average of more than five million gallons a day is drawn from privately-owned wells at hotels and industrial plants. For these reasons the most attention has been devoted to this sand.

The first wells were drilled to the 800-foot sand in 1893. At that time the wells flowed naturally and the water was under sufficient pressure to rise 20 or 25 feet above sea level. As the withdrawal of water has continued the water level in the wells has gradually receded until in the summer of 1924 it was below sea level over a large area, about 50 feet below sea level in Atlantic City, and nearly 25 feet below at Longport. By the summer of 1927 it had dropped to 80 feet below sea level in Atlantic City and more than 45 feet below sea level at Longport. It is obviously important to determine whether these facts indicate that the supply is being overdrawn or whether they represent normal drawdown and indicate that additional supplies can safely be developed.

It was found that along the beaches the water level in wells which indicates the head of the water in the 800-foot sand fluctuates continually in accord with the tide, the amount of fluctuation ranging from a few inches to about four feet. Furthermore, in Atlantic City there is a daily fluctuation in head of from about one to ten feet due to differences in pumping, and at points close to wells that are pumped it may be even more. Because of the considerable fluctuation in the water level in any one day it is impossible to determine the nature of seasonal and annual fluctuations merely by occasional single measurements. Rather it is necessary to have as nearly a continuous record as possible to show the highest and lowest points reached during the year.

The seasonal fluctuations of the head on the water in the 800-foot sand in three widely separated localities, generalized to omit daily fluctuations, are shown in Fig. 14. (See page 60.) The head in the three localities shows a typical seasonal fluctuation, and there is other evidence that throughout the region the head fluctuates in much the same way. It is high in winter and as summer approaches it drops until a low point generally is reached during the latter part of August or early part of September. Thereafter the head rises until the highest point is reached, usually between December and March. A significant feature is that during the period of investigation, from 1924 to 1927, inclusive, the head has dropped lower each summer than in the preceding summer, and has not risen as high in the winter as in the previous winter.

To find the cause of the fluctuations of head, comparison was made with the average daily pumpage by months from the 800-foot sand in different parts of the Atlantic City region and in the region as a whole, and with the accumulated departure from normal precipitation in the southern interior section of New Jersey since 1924. A very close relation was found to exist between the changes in pumpage and the changes in head. The marked decrease in head in spring and summer coincides with a considerable increase in pumpage, the increase in head with a great decrease in pumpage. Furthermore, in accord with the progressive dcrease in head from year to year there has been a corresponding increase in pumpage. The evidence strongly supports the conclusion that the head on the water in the 800-foot sand fluctuates primarily in response to changes in the pumpage.

The fact that the head rises in winter as the pumpage decreases is believed to indicate that the limit of development of the 800-foot sand has not yet been reached. To determine the effects of future increases in pumpage there has been computed the ratio between the depth to water, or loss in head, below the original static level in wells in Atlantic City and Longport, and the rate of pumping in certain parts of the region for each month from 1924 to 1927, inclusive. Assuming that future increases in pumpage are distributed as they have been in the period of observation, an increase of 10 million gallons in the average daily pumpage from the 800-foot sand over that of 1927 may be expected to lower the non-pumping level in wells in Atlantic City to a depth of about 200 feet below the surface; and for the same increase the water level in the Longport observation well may drop to a point about 100 feet below the surface. The loss in head may be greater if the increase in pumpage is largely from wells nearer the localities mentioned, and it may be less if it is at points farther away than the centers of increase during the period of observation. Obviously, it will be inadvisable to undertake to develop the entire future supply of the region from the 800-foot sand.

In some localities along seacoasts the water-bearing formations have been contaminated by salt water as the head has been lowered by pumping. In Atlantic City several wells have become salty, but it has been definitely proved that the salt water has entered the wells through holes in the casings where they pass through overlying beds that are contaminated. Contamination of the 800-foot sand thus far has been prevented by the presence of about 300 feet of nearly impervious clay. However, there is good reason to believe that the sand outcrops beneath the ocean and there is opportunity for salt water to be drawn in, especially in view of the fact that the head of the water in the bed is many feet below sea level. The relation between the original head of water in the formation and the level of the ocean, which has a greater density, indicates that if a state of equilibrium existed before pumping began, salt water was present in the formation where it lies at a depth of 1,000 feet or less, probably only a few miles offshore opposite Atlantic City. The sand lies at a depth of about 900 feet at Wildwood, and if the conjecture just stated is correct the chloride content of the water there should be higher than at Atlantic City. There is an actual increase in chloride southward along the coast from about 10 parts per million at Atlantic City to between 200 and 300 parts per million at Wildwood. It is believed, therefore, that there is danger of contamination of the sand at Atlantic City although the salt water may still be so far out that it will not reach the city for many years.

In view of the great depth to which the water would be lowered by a considerable increase in pumpage from the 800-foot sand and the possible danger of contamination of the formation, it is concluded that no great additional development of the sand should be made and that other sources should be used so far as possible.

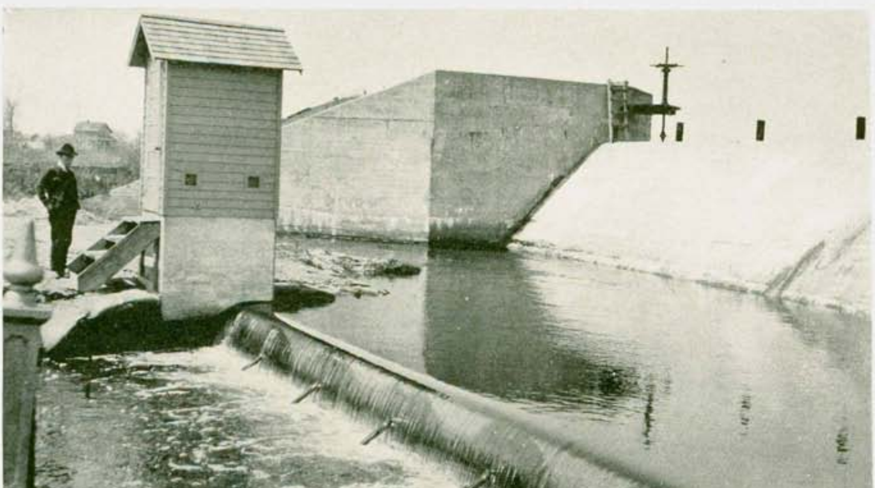
Reliable data in regard to the water-bearing capacity of the shallow horizons of the mainland were obtained only in the well field of the Atlantic City Water Works in Pleasantville. In that vicinity the materials to a depth of 250 feet are principally sand, but clay is present from about 15 to 30 feet and 100 to 120 feet below the surface. Logs of wells in other localities do not show the same sequence of formations as at the water works.

In the well field of the Atlantic City Water Works the water is obtained from 32 wells of which about half are 100 feet deep and the other half about 200 feet deep. The aggregate yield of these wells, when pumped by suction, is about six million gallons a day, of which probably more than half comes from the 100-foot wells. Field tests show that the sands that supply the 100 and 200-foot wells have a much higher water-bearing capacity than the 800-foot sand, as shown by the following facts. The maximum loss of head below the original static level when about three million gallons a day is being pumped from each of the two shallow horizons is only about 30 feet as compared to a loss of head of 75 to 100 feet in the 800-foot sand in Atlantic City for a pumpage of 3.5 to 5.0 million gallons a day. The area of influence of the shallow wells when pumped at the rate indicated is apparently not much more than a mile in diameter, whereas in the 800-foot sand the depression of head when pumping at only a slighly higher rate extends for at least eight miles in all directions from Atlantic City. The head on the water in the shallow horizons responds quickly to changes in pumpage; when the wells are shut off the head rises to the original static level within a few hours, and when they are pumped a constant pumping level is reached in a short time. In contrast to this the head on the water in the 800-foot sand responds very slowly and a state of equilibrium may not be reached for many days.

So little is known of conditions on the mainland, except at the Atlantic City Water Works, that it is impossible to predict how much water can be obtained from the shallow horizons. If conditions throughout the region are as favorable as at the water works at least three times as much water as is now developed may be obtained without causing permanent overdraft. This additional quantity cannot safely be obtained in the present well field, for to do so would produce a considerable lowering of head and might result in the contamination of the sands by salt water. The danger of contamination of the shallow horizons by salt water is even more imminent than in the case of the 800-foot sand, for the sands are not overlain by any widespread protective bed of clay, and there is reason to believe that salt water may occur only a mile or two from the water works. For this reason the new wells should be scattered over a large area and should be situated as far as practicable from any body of salt water. It is believed that a favorable location for the drilling of additional wells is around the borders of Absecon Pond, from which Atlantic City now obtains part of its supply. Conditions in this locality may be favorable for the percolation of water from the pond into the water-bearing sands. If so, a large supply would be assured and some of the flow of the stream that now goes to waste could be recovered. However, in view of the lack of reliable data in regard to conditions outside of the present water works well field, no large development should be undertaken without exploratory drilling and extensive pumping tests.

In view of the expected large increase in consumption of water in the future, and the fact that the problem of providing for this increase may be of great importance to many communities in a large area, observations on pumpage and water levels should be continued.

Absecon Pond, source of part of public water supply for Atlantic City.



Weir and gaging station below Absecon dam, maintained by New Jersey Department of Conservation and Development and U. S. Geological Survey to measure flow of Absecon Creek.

PRESENT WATER SUPPLIES OF THE REGION.

It is not within the scope of this report to make a detailed study of the water supply situation of the Atlantic City region, but certain features of the existing supplies may be mentioned briefly.

Atlantic City.—The present public supply for Atlantic City is obtained from two sources—wells at the Absecon pumping station on the mainland[1] and Absecon Creek. The relative amounts of surface and ground water used are given on page 18.

The water of Absecon Creek is stored by a dam situated about a mile west of Absecon. The capacity of the reservoir is about 300 million gallons, but the reservoir cannot be entirely emptied, and the usable capacity is only about 250 million gallons. Since December, 1923, measurements have been made of the flow of Absecon Creek. The average daily flow for the months of maximum and of minimum discharge, and for the entire year for the years 1924 to 1927, inclusive, is given in the accompanying table.

AVERAGE DAILY FLOW OF ABSECON CREEK ABOVE ABSECON DAM IN MILLION GALLONS.[a]

YEAR	Month of minimum flow	Month of maximum flow	Average for year
1924	13.9	32.4	25.6
1925	9.7	17.1	15.2
1926	12.0	17.0	17.1
1927	11.9	21.2	18.7

From the figures given it is evident that the summer discharge of Absecon Creek at present is no more than sufficient to meet the demand, and in dry years draft must be made on the storage. In order to meet the increase in the consumption in the near future either greater storage must be provided or a large supply must be developed from some other source.

The water from Absecon Creek Reservoir is carried about two miles by a 42-inch wood stave conduit to a small basin at the pumping station. This main is old and is soon to be replaced by a new one. The difference in elevation between the pond and the basin is so small that the rate of flow is limited by the low head. For a few hours on days

[1]The Atlantic City pumping station, although located in the northern part of Pleasantville, is commonly called the Absecon station, and that name will be used in this report.

[a]Corrected for changes in storage from month to month.

of high consumption the pumpage is actually in excess of the flow from the pond. During these periods a shortage is prevented only by draft on the small storage basin maintained at the pumping station.

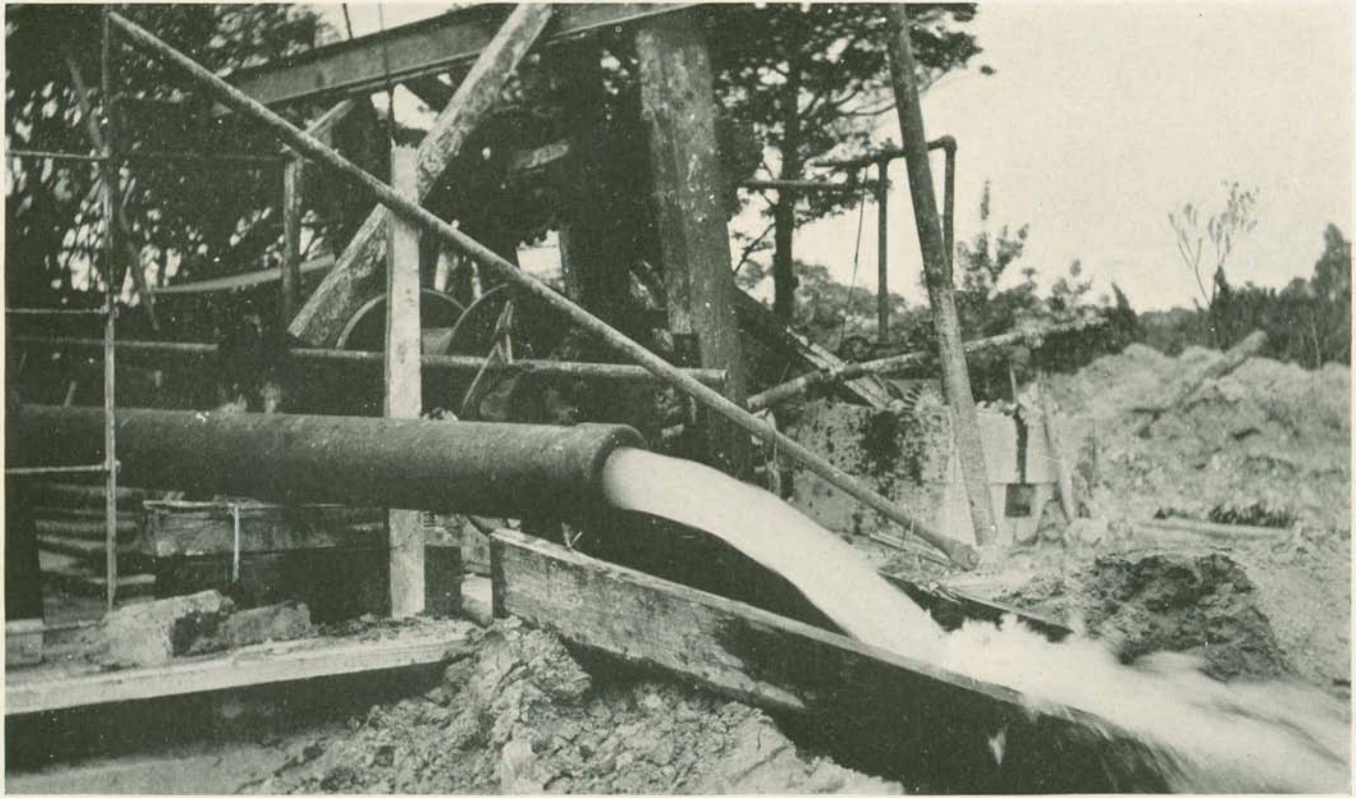
The ground-water supply is obtained from 32 wells 100 to 200 feet deep. The well field is described in more detail on pages 121 and 123. The total yield of the well field is approximately 7½ million gallons a day.

If the dry-period yield of Absecon Creek be reckoned at 10 million gallons a day, the total minimum yield of all systems is a little more than 17 million gallons a day. The Department of Conservation and Development has granted the right to divert a total of 20 million gallons a day of ground water and the construction of new wells needed to obtain this amount was begun in the spring of 1928. When this development is completed the total available supply will be about 30 million gallons a day.

Mainland towns.—The water supply for the several mainland communities lying between Absecon and Somers Point, and including Pleasantville, is furnished by the Atlantic County Water Co. This supply is obtained in part from a small stream that is dammed at Bargaintown, about three miles southwest of Pleasantville, where a pumping plant is located. The capacity of the reservoir is estimated to be 40 million gallons. Water is also obtained from a well nearer the center of Somers Point, which is 118 feet deep, 16 inches in diameter from the top to 80 feet, and 12 inches from 80 to 98 feet. The lower 27 feet is equipped with concrete well screen 11½ inches in outside diameter. It is equipped with a turbine pump which pumps directly into the main and which is controlled automatically so that a certain pressure is maintained. The company also has a well at the Bargaintown pumping station which is 120 feet deep and six inches in diameter. Its yield is small and it is used only an hour or two a day.

Ventnor.—The Ventnor water supply is obtained from six deep wells located at the city water works at Cornwall and Winchester Avenues. The wells are approximately 800 feet deep and range in diameter from 6 to 12 inches at the top with 4½ to 8-inch screens. Five of the wells are situated in an area of about three acres and the sixth is several hundred feet distant. The wells are pumped by air lift and discharge by gravity into a covered concrete reservoir that has a capacity of 574,000 gallons. The system has no standpipe and pressure is maintained by pumping directly into the mains. The peak consumption during certain hours of the day in the summer is considerably in excess of the pumpage from the wells, and storage must be drawn upon.

PLATE III.



Discharge of new well at Margate City Water Works during preliminary test June 19, 1924. Rate of discharge 700 gallons a minute.

Margate City.—The water supply for Margate City is obtained principally from two wells. The wells range in depth from 800 to 812 feet, and are equipped with eight-inch screens. They are equipped with deep-well turbine pumps. Their combined yield is about 1,000 gallons a minute. The pumps are so connected that they can pump directly into the distribution system. Generally, however, the water is discharged into a concrete reservoir in order to provide aeration to remove hydrogen sulphide that is in the water. Two old wells, pumped by air lift, were in use until 1926, but their yield is so small that they have practically been abandoned. If the wells were cleaned out doubtless they would yield more. The concrete reservoir has a capacity of about 125,000 gallons, and a standpipe has a capacity of 83,000 gallons.

Longport.—The water supply for Longport is obtained from a single well in the northern part of the city. This well is six inches in diameter, 835 feet deep, and is pumped by air lift. Its yield is about 400 gallons a minute. This quantity is considerably in excess of the present maximum consumption. The well discharges into a concrete reservoir having a capacity of 60,000 gallons, from which it is pumped into a standpipe having a capacity of 190,000 gallons. The consumption in Longport is not increasing rapidly, and unless the rate of growth of the city increases the well now in use will doubtless be sufficient for several years. When more water is needed it is possible that an old well in the southern part of the city can be cleaned out at relatively slight expense and a good yield obtained with air lift.

Ocean City.—The public water supply for Ocean City is obtained from seven wells, the property of the Ocean City Water Service Co. This company supplies the entire beach extending from the main part of Ocean City at Egg Harbor Inlet southwestward to Corson's Inlet, a distance of more than six miles. The wells range in depth from 825 feet to 840 feet, and in diameter from six to eight inches. One of the wells is at Third and West Avenue, in the northern part of the city; four wells are distributed at distances of a few hundred feet around the main pumping station at Ninth and Haven Streets; one well is at Thirty-fifth Street about half way down the beach, and the sixth well is at Fifty-fifth Street near the southern end of the island. The wells at the main pumping station are pumped by air lift into two nearby reservoirs. The other three are equipped with turbine pumps with automatic controls which discharge directly into the mains. The distribution of the wells makes it possible to maintain proper pressure in all parts of the city without great loss of head in the mains such as would result if the water had to move from a distant pumping station. The capacity of the receiving reservoirs at the main pumping plant is 624,000 gallons. Two standpipes at the plant have a capacity of 657,000 gallons.

Brigantine Beach.—A new water-supply system was put into service on Brigantine Beach in April, 1925. The water is obtained from a well 798 feet deep, which is equipped with a turbine pump that discharges directly into the distributing main.

Other municipalities.—The water supply for the municipalities of Corson's Inlet, Sea Isle City, Avalon and Stone Harbor is obtained from deep wells in each of the places named. These wells all go to the 800-foot water sand which is used for the public supplies in the beach cities from Brigantine to Ocean City. The city of Wildwood obtains most of its supply from shallow wells on the mainland, but in summer it gets some water from a well on the beach to the deep horizon just mentioned and from three other wells on the beach that are about 325 feet deep.

Most of the towns and cities on the beaches and nearby mainland north of Brigantine as far as Asbury Park obtain their water supply from wells. The formations utilized, however, are mostly, if not all, different from the shallow horizons used in Pleasantville or the deep horizon used in Atlantic City and the cities south thereof. The present study accordingly has not been extended north of Brigantine.

Private wells.—In addition to the public supplies a large quantity of water is obtained in the Atlantic City region from about 35 private wells that are mostly from 760 to 840 feet deep. The wells range in diameter from 6 to 16 inches at the top with screens 4½ to 8 inches in diameter. The majority of the wells are pumped by air lift, but several are pumped by deep well turbine pumps and two by deep well reciprocating pumps. The location of these wells is shown on Fig. 1. In addition to the deep wells a few shallow wells, less than 150 feet deep, are used in the city. Since these wells yield only brackish water, they have been neglected in the present investigation. Several wells, mostly not more than 150 to 200 feet deep, are used on the mainland at industrial plants in Pleasantville, the Atlantic County Hospital for Mental Diseases, the County Tuberculosis Hospital and the shore golf clubs. The total consumption from these shallow wells probably is only a few hundred thousand gallons a day.

QUALITY OF PRESENT SUPPLIES.

The mineral quality of the different types of waters used for public supply in the Atlantic City region are shown by the accompanying analyses. Sample 1 is representative of the surface water that is used for the Atlantic City supply. The surface water furnished by the Atlantic County Water Co. is probably of somewhat similar composition. The surface water doubtless varies slightly in rainy and dry weather. Samples 2 and 3 are typical of the wells of two different depths at the Atlantic City pumping station at Absecon. The water from other wells on the mainland not over 200 feet deep is probably somewhat similar in quality.

ANALYSES OF SURFACE AND GROUND WATERS IN THE ATLANTIC CITY REGION.

(Analyzed by C. S. Howard, U. S. Geological Survey. Parts per million.)

	1	2	3	4	5
Silica (S_iO_2)	2.0	8.7	12	26	29
Iron (Fe)	.05	.04	.36	.11	.38[a]
Calcium (Ca)	1.6	3.9	3.3	12	11
Magnesium (Mg)	.7	2.1	1.0	2.0	2.0
Sodium and potassium (Na + K)	4.5	10	6.3	28	26
Bicarbonate radicle (HCO_3)	1.2	7.3	4.9	83	85
Sulphate radicle (SO_4)	4.3	7.9	10	15	12
Chloride radicle (Cl)	9.0	15	9.0	11	8.0
Nitrate radicle (NO_3)	Trace	7.3	Trace	Trace	Trace
Total dissolved solids at 180° C.	24	57	51	134	129
Total hardness as $CaCo_3$ (calculated)	6.9	18	12	38	36

1. Absecon pond, surface water supply for Atlantic City, collected April 17, 1924.
2. Mixed water from three 100-foot wells, Atlantic City pumping station, collected April 4, 1924.
3. Water from 200-foot well, Atlantic City pumping station, collected April 23, 1924.
4. Water from 850-foot well at Chalfonte Hotel, Atlantic City, collected February 21, 1924.
5. Water from four wells approximately 840 feet deep at Ocean City Water Co. pumping station, collected July 9, 1924.

Samples 4 and 5 are typical of the 800-foot sand that is used for the public supplies for Ventnor, Margate, Longport and Ocean City and by private wells in Atlantic City and Ocean City. The maximum difference for any one constituent in the two samples here given is only three parts per million, and the difference in total solids is only five parts. Analyses of samples from other deep wells along the beach show that the water from the 800-foot sand is quite constant as a

[a] Includes 0.32 p.p.m. in sediment that had settled in sample bottle.

whole. A sample from the new well to the same horizon at the Atlantic City Water Works on the mainland contained only 101 parts per million of total solids and samples from Egg Harbor City and Hammonton indicate that the total solids in the water from this formation is slightly less at points farther inland. Locally, in wells along the beach the mineral content of water from the deep horizon has increased for short periods when salt water has entered corroded or broken well casings, but after the trouble has been remedied the content has decreased to the normal. (See pages 98 and 105.) The water from the shallower beds along the beach up to the depths of 200 or 300 feet, is brackish and unfit for domestic use.

As long as ordinary care is exercised to protect the wells from pollution the supplies from both the shallow and deep wells is safe and satisfactory from the sanitary standpoint. The water from Absecon Pond, and from the Bargaintown reservoir of the Atlantic County Water Co., is subject to contamination, but is chlorinated before it is pumped into the distribution main.

Although the surface water from Absecon Pond as served is entirely safe for domestic use, it is generally more or less colored and at certain times of the year has a disagreeable ordor and is turbid. The color is that common to waters that flow from swamps in southern New Jersey. The odor results from aquatic growths that develop in the pond and which it has not been possible to eradicate. The water frequently becomes turbid when storms wash sand and clay into the pond. These conditions at times make the water unsatisfactory for domestic use. The surface water is improved slightly by dilution with water from the wells at the pumping station. The superior quality of the water from the 800-foot sand in Atlantic City, so far as taste and appearances are concerned, has been responsible to a large extent for the well developments by the hotels. The disagreeable features of the surface water doubtless could be removed largely by proper filtration.

For boiler and laundry use there is little preference between the surface water and the well water. The surface water is softer than any of the well waters, but its desirability for washing is lessened somewhat by the disagreeable features mentioned. Although the deep well water is not very hard, some of the hotels use artificial softeners. It is said that the water from the 800-foot wells scales boilers, but that the scale may soften and partly be removed by subsequent use of the Atlantic City public supply. By a judicious alternation of water from the two sources the boilers may be kept in good condition. The city supply used alone tends to corrode boilers.

CONSUMPTION.

The average daily consumption from the various public supplies in the Atlantic City region for the years 1917 to 1927 is given in the accompanying table (see page 18) compiled from quarterly consumption reports that are filed with the Department of Conservation and Development. This does not include consumption in the region between Corson's Inlet and Wildwood. Statistics for previous years are not available.

The table shows some irregular variation in the consumption from year to year, but during the 11-year period from 1917 to 1927, inclusive, there was an increase in consumption from every system. In the 11 years the consumption from public supplies in the entire region increased about 7.4 million gallons and was about 82 per cent above the total consumption in 1917. The consumption in 1927 was actually less than in 1926, because of a decrease in Atlantic City. From 1917 to 1926 the increase was eight million gallons a day, or nearly 90 per cent of the consumption in 1917. The average rate of increase has been a little more than 0.7 million gallons a year.

Of the total increase more than 5.5 million gallons has been in the consumption from the Atlantic City public supply, with only about 1.8 million distributed among the other public supplies. The biggest increase in Atlantic City occurred in 1925, when it was 1.6 million gallons above the consumption of the previous year. The greatest percentage of increase between 1917 and 1927 was in Ventnor and Margate. In Ventnor the consumption in 1927 was 2.8 times that in 1917, and in Margate City it was 6.3 times that in 1917. The figures reflect the large number of new homes that have been built in these places. The irregularties in consumption, with actual decrease in some years instead of a progressive increase, may be ascribed to several causes such as variations in weather conditions or in business conditions which promote or retard home building, and the installation of meters. The low consumption in Longport in 1923 apparently was due to inadequate supply.

In addition to the water consumed from public supplies a large quantity is used from private wells. Data upon which to base an estimate of the consumption from private wells are unsatisfactory. Until 1924 practically none of the well owners kept any records of pumpage. Since that time, at the request of the writer, many have furnished data based largely on the estimated or tested yield of the well at the time of completion and an estimate of the number of

AVERAGE DAILY CONSUMPTION OF WATER FROM PUBLIC SUPPLIES IN ATLANTIC CITY REGION, 1917-1927, IN THOUSAND GALLONS.

	1917	1918	1919	1920	1921	1922	1923	1924	1925	1926	1927
Atlantic City—											
Wells	4,083	5,000	5,533	4,051	4,610	4,175	4,597	4,765	5,866	6,663	6,980
Surface Water	3,544	3,057	2,848	5,534	5,902	6,944	6,265	6,474	6,973	7,371	6,188
	7,627	8,057	8,381	9,585	10,512	11,119	10,862	11,239	12,839	14,034	13,168
Ventnor	411	516	561	581	636	828	989	937	979	1,100	1,153
Margate City	79	95	112	a	94	a	155	189	281	382	497
Longport	62	79	88	79	71	49	33	55	88	91	96
Ocean City Water Co.	397	422	445	513	530	648	750	653	793	824	882
Atlantic Co. Water Co.,	419	370	257	236	351	360	432	517	572	607	613
	8,995	9,539	9,844	a	12,194	a	13,221	13,590	15,562	17,038	16,409

a Report incomplete.

hours pumped daily. In some instances the yield was tested many years ago, and there is reason to believe that it is now much less, but accurate data are not available. For some wells the yield was not known and could not be measured. The writer has endeavored to determine the consumption from the deep wells for the years 1924 to 1927, inclusive, by a careful study of all the information at hand. The results are summarized in the table that follows (see page 21), which shows the consumption of water in the entire region according to source. The data are shown graphically, by years, in Fig. 2. (See also Fig. 14.) The table shows the average daily consumption for the month of February, the month of August, and the entire year. August is usually the month of maximum consumption, and the consumption in February generally is about as low as at any other time during the year, but in different years the conditions may differ slightly.

This table shows a very considerable difference between the winter and summer consumption, due, of course, to the fact that the population of the resorts is very large in summer and dwindles in winter. The average daily consumption in the region from all sources in August, 1927, was about 28.5 million gallons. This was nearly 10 million gallons daily more than in February of the same year, and the increase was 50 per cent over the February consumption.

In 1924 the average daily consumption throughout the year was rather equally distributed among the three types of sources, 38 per cent being surface water, 28 per cent from shallow wells and 34 per cent from deep wells. Since 1924 the consumption from deep wells has increased more than three million gallons, and in 1927 43 per cent of the total was obtained from such wells, as compared to only 27 per cent from shallow wells, and 30 per cent from streams. The relative proportions of average daily consumption just stated are not maintained in the summer months, for while the consumption from surface water and deep wells increases roughly proportionately, there is no great increase in the consumption from shallow wells. This is because the Atlantic City Water Works wells are pumped practically to capacity all the time, in winter and in summer. The increase in consumption in summer from privately owned deep wells in Atlantic City is relatively not as great as from the public supplies, and from deep wells at the other resorts along the beach (see Fig. 14). This is because the hotels that have their own wells attract a large percentage of the winter visitors, and their consumption does not decrease greatly in winter.

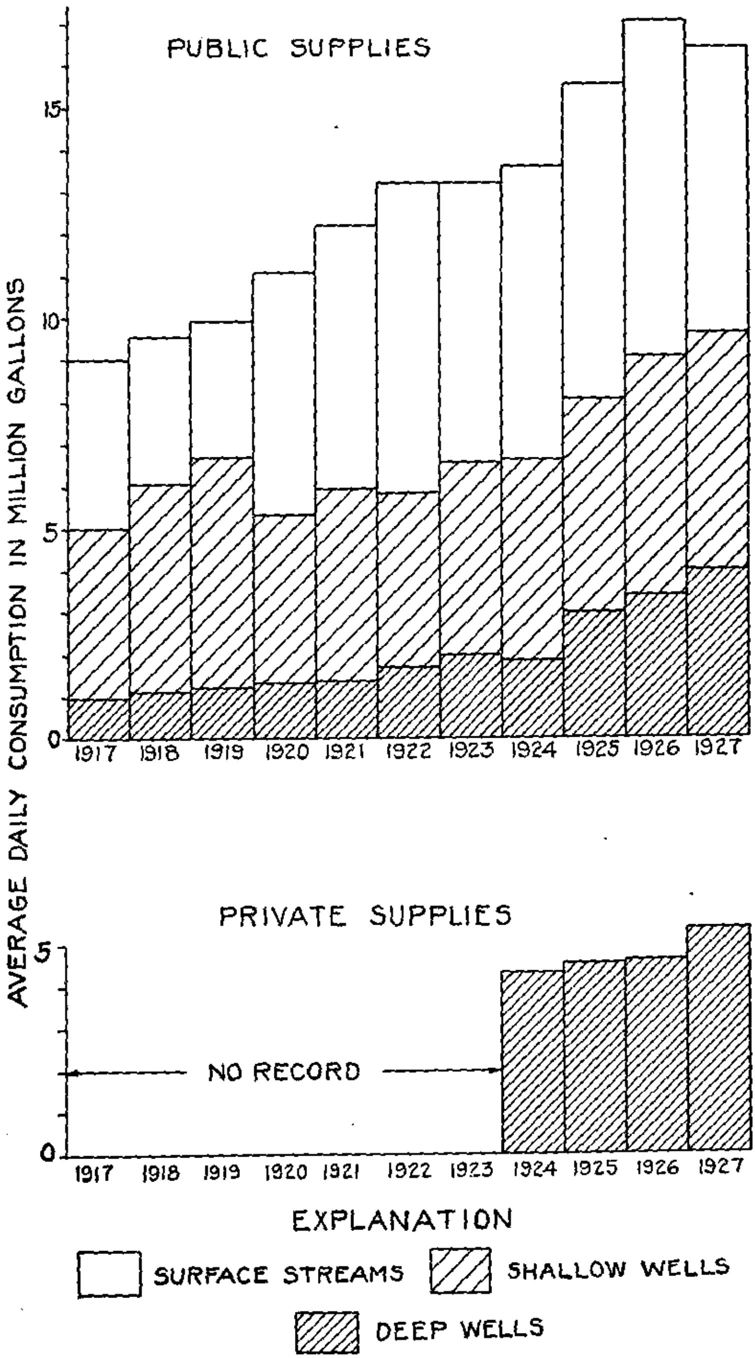


FIG. 2.—Diagram showing average daily consumption of water in the Atlantic City region according to sources, 1917 to 1927, inclusive.

AVERAGE DAILY WATER CONSUMPTION IN THE ATLANTIC CITY REGION DURING MONTHS OF FEBRUARY AND AUGUST, AND DURING ENTIRE YEAR ACCORDING TO SOURCE, IN THOUSAND OF GALLONS, 1924 TO 1927.

SOURCE	FEBRUARY				AUGUST				YEAR			
	1924	1925	1926	1927	1924	1925	1926	1927	1924	1925	1926	1927
Surface water.												
Atlantic City Water Dept.	4,799	6,312	5,666	5,803	10,733	11,365	11,835	9,087	6,474	6,973	7,371	6,188
Atlantic County Water Co.	437	421	477	492	686	639	763	599	494	556	607	585
Total	5,236	6,733	6,143	6,295	11,419	12,004	12,598	9,686	6,968	7,529	7,978	6,773
Shallow wells not over 250 feet deep on mainland.												
Atlantic City Water Dept.[a]	4,750	4,749	5,776	4,533	4,750	5,244	5,342	5,871	4,765	5,016	5,663	5,630
Miscellaneous (estimated)	200	200	225	225	500	500	550	550	250	250	275	275
Total	4,950	4,949	6,001	4,758	5,250	5,744	5,892	6,421	5,015	5,266	5,938	5,905
Deep wells pumping from Atlantic City 800-foot sand.												
Atlantic City Water Works, on mainland (est.)	0	0	1,400	1,410	0	1,340	1,450	1,250	0	850	1,000	1,350
Brigantine Beach	0	0	[b] 20	141	0	71	[b] 75	137	0	[c] 31	[b] 40	136
Ventnor	647	568	699	759	1,892	1,618	1,755	1,730	937	979	1,100	1,153
Margate	172	136	243	263	287	497	598	697	189	281	382	497
Longport	28	39	46	38	165	205	237	187	55	88	91	96
Ocean City Water Co.	343	319	464	534	1,778	1,932	1,851	1,835	653	793	824	882
Atlantic City private wells (est.)	3,618	4,111	3,739	4,735	5,141	5,285	5,438	6,249	4,252	4,351	4,514	5,281
Ocean City private wells (est.)	15	20	25	27	330	345	350	327	108	118	122	124
Total (partly estimated)	4,823	5,193	6,636	7,907	9,593	11,293	11,754	12,412	6,194	7,491	8,073	9,519
Total from all sources in area between Brigantine Beach to Ocean City inclusive (partly estimated)	15,009	16,875	18,860	18,960	26,232	29,041	30,269	28,519	18,177	20,286	22,049	22,197

[a]Consumption from deep and shallow wells at Atlantic City Water Works not reported separately. Figures shown after May, 1925, are based on estimated yield of deep well and total consumption of ground water during the period.

[b]Estimated.

[c]Well put in operation about July 1, 1925.

Unfortunately, no information is available to show the consumption from private wells prior to 1924 so that a comparison of the consumption from all sources over a period of years cannot be made. The increase in average daily consumption from all sources between 1924 and 1927 was a little more than seven million gallons. The greatest increase in draft from any one source was from the deep wells drawing on the 800-foot sand. This was due to an increase of about one million gallons from private wells in Atlantic City, to a pumpage of a little more than one million gallons a day from the new well at the Atlantic City Water works, and to an increase of a little less than a million gallons from public supplies on the beaches.

In addition to the consumption in the area between Brigantine and Ocean City, the average yearly consumption from the 800-foot horizon at places along the coast southwest of Ocean City (which is not shown in the table on page 21) is about 400,000 gallons a day, and in summer it is nearly one million gallons a day. The total maximum draft on the formation between Brigantine Beach and Wildwood in the summer of 1927 was more than 13 million gallons a day.

FUTURE INCREASE IN CONSUMPTION.

An important question in planning the development of a water supply for any community is the probable rate at which the consumption will increase. The present investigation does not properly include a detailed study of this question, but certain general phases of it may be considered.

During the 11 years following 1917 the average daily consumption from public supplies in the region between Brigantine and Ocean City increased about 7.5 million gallons, or a gain of about 82 per cent over the consumption in 1917. If the consumption of the region were to increase in the geometric ratio of 82 per cent every 10 years, in 1938 it would be nearly 30 million gallons daily, in 1948 about 54 million gallons daily, and in 1958 nearly 100 million gallons daily. But if only a uniform increase of 7.5 million gallons in 10 years were maintained, in 1938 it would be only about 24 million gallons, in 1948 about 32 million gallons, and in 1958 about 39 million gallons. It is not likely that the higher rate of increase will continue. The true figures will doubtless be between the two estimates, and nearer the lower than the higher. This does not include consumption from privately owned wells which will also undoubtedly increase. If this increased at the rate of one million gallons in three years, as occurred between 1924 and 1927, the average daily consumption from private wells 20 years hence would be about 12 million gallons. The grand total from all sources in 1948, according to the minimum of the above estimates, would be about 44 million gallons daily. It should be noted that this is the average daily consumption for the year. The consumption in the summer months, according to present ratios, would probably be between 55 and 60 million gallons daily.

In attempting to answer the question as to what will be the future consumption one is naturally faced with other questions as to the trend of the future growth of Atlantic City and its neighbors. The nature of real estate development in the last few years suggest that the population of the region, and, therefore, the water consumption may increase very rapidly, but there are factors that may tend to prevent such a rapid increase. The most suggestive information so far available is the data on annual consumption from the Atlantic City public supply. The average daily consumption in 1900 was about three million gallons. It gradually rose with certain irregularities to nearly 10 million in 1913, but thereafter dropped each year until 1916, when it was only 7.3 million. This derease was in part due to metering and probably in part to stoppage of waste from leaks in the distribution system. Since 1916 the consumption has risen again, as shown in the table on page 18. In a "Report on increased water supply for Atlantic City, New Jersey, covering a period of twenty-five years, 1910-1935," by Lincoln Van Gilder and T. Chalkley Hatton, submitted to the City Council December 11, 1909, it was estimated on the basis of past consumption that the average daily consumption for 1918 would be 17.177 million gallons, and in the month of maximum consumption it would be 25.686 million gallons. Actually the consumption in 1918 fell far below these estimates, and it was still much below them in 1927, nine years later. The estimates for 1935 were 32.078 million gallons daily for the entire year and 53.990 daily in the month of greatest consumption. To reach this point it will be necessary for the consumption of the city to be practically doubled in the eight years following 1927, and this seems very unlikely.

The average yearly increase in the average daily consumption of Atlantic City from 1900 to 1927 has been only about 370,000 gallons. In some years it has been considerably greater as between 1924 and 1925, but these great increases have generally been offset by smaller increases in later years. These figures tell only part of the story, for they do not include data for the neighboring cities, where some of the greatest recent development has occurred, nor for the pumpage from private wells in the city. The records in regard to consumption from these sources cover too short a period to be of much value in considering the future trend of water consumption. However, it is to be expected that there will be a more or less steady, but, perhaps, not very large increase in water consumption each year due to several factors such as closer building up of some parts of the resorts, an increase in the number of hotels, an increase in industries that are necessary to the business of the resorts, and a possible natural increase in per capita consumption. The newer communities doubtless will experience periods of rapid increase in consumption as they are taken up and developed in building booms after which the yearly increase will not be so great. The problem is one that deserves study by those concerned with the future development of water supplies for the shore cities.

POSSIBLE SOURCES OF FUTURE SUPPLY.

The sources that are available for increased supplies in Atlantic City, like the present sources, may be grouped into three classes—streams, wells on the mainland not over 250 or 300 feet deep, and deep wells reaching about 700 feet on the mainland and 850 feet on the beaches.

As stated on page 11, the yield of Absecon Creek during recent dry summers has been barely sufficient to meet the needs of the Atlantic City public supply. In the month of lowest flow in 1924 there was an excess of more than four million gallons a day. This is none too large a margin. However, during the other months of the year the excess was considerably greater, ranging from 8 to 20 million gallons a day. By enlarging the storage the quantity available in the period of low flow could be increased somewhat. Preliminary investigations by the Atlantic City Water Department show that such enlargement of the storage is feasible.

No data are available as to the possibility of obtaining any large additional supply from other streams near Atlantic City, including the one now used by the Atlantic County Water Co. Probably the additional quantity that could be developed would not be great enough to warrant any large expenditures. An investigation for the city by Messrs. Van Gilder and Hatton for Atlantic City shows that a large quantity of surface water, enough for many years, can be obtained at a greater distance from the city, from either Great Egg Harbor River and its branches or from Mullica River and its branches above Batsto.

The relative merits of these several sources of surface water will not be discussed here. Any project for the development of surface water supplies would require the construction of long pipe lines. The quality of the water would undoubtedly be very good and safe from the sanitary standpoint. Nevertheless, a filtration system would probably be required to remove the suspended sediment and the color.

The remaining possible sources are wells to deep horizons on the beaches and to either deep or shallow horizons on the mainland. Shallow horizons on the beaches cannot be used because they yield only salt water. Wells seem to have many advantages over surface water. In the first place, there is a very general prejudice among a large part of the public against surface water and in favor of wells because of the belief that the water obtained from underground sources is purer. Under modern conditions of water works operation this belief is more fancied than real. Nevertheless, it is a psychological factor that often must be reckoned with in obtaining public approval for a new development. Actually in the Atlantic City region the mineral content of the well waters is somewhat higher than that of the surface water, but the difference is so slight that the matter of quality need not be considered.

Where the water is obtained from wells increases in consumption may be met easily from time to time by adding units of one or more wells. The wells can be completed and put in service in a few weeks or a few months, depending upon the quantity to be developed. The cost of new units is comparatively small and absorbed in a short period by the return from increased consumption that is commensurate with the increase in the capacity of the system. These conditions are in contrast to the long time required for the completion of long pipe lines, reservoirs and filter plants that would be needed for a surface water supply. With a capacity that would not all be used for many years, the liquidation of the cost of such a system would necessarily be distributed over a long period. For this reason wells are especially adapted to the needs of the smaller towns.

A ground-water supply also has special advantages from the viewpoint of the beach cities and towns because it can be obtained right in the communities and at practically any point where land is available for wells. The smaller towns can hardly afford to install the long pipe lines across the meadows that would be required to obtain a surface water supply unless several of them unite on a single project. If such a project seemed desirable it could, of course, be brought about by the formation of either a water district or a stock company. The factors in favor of ground water are so weighty that there seems to be no reason to consider surface water if ground water is available. Numerous wells to the deep horizon on the beaches and to shallow horizons on the mainland have proven that ground water of good quality can be obtained.

There is little doubt that a sufficient number of wells drilled in Atlantic City to a depth of about 800 feet would yield enough water, pleasing in appearance and taste and thus far superior to the present supply, to meet the needs of the city for a short time. Similarly, water may be obtained from wells in any of the neighboring towns and cities. The easiest and cheapest solution of the problem of additional water supply for the present would seem to be to put down wells whenever and wherever they are needed. But the question of paramount importance is, will this be the wisest and most economical solution for the future?

The importance of this question—what of the future if the ground water supply is developed without limit—is suggested by the experience of many localities in different parts of the United States. It is emphasized by the conditions now existing in the Atlantic City region. The municipalities of Ventnor, Margate, Longport, Ocean City and of smaller places south thereof, as well as many hotels and industries in Atlantic City and Ocean City, all obtain their water from a single extensive water-bearing bed. As shown on page 129, this is practically the only source of ground water available in these localities unless they go to the mainland. Since the first deep wells were drilled the static head or water level in the wells when not pumping has been lowered many feet over a very large area. If there is a large increase in the draft on this horizon, such as would occur if the deep-well water were substituted for the Atlantic City surface supply, might not the water level be lowered so far, and the yield of the wells decrease so much that many of them would have to be abandoned and a surface supply be developed after all? If this were to happen it might be better and cheaper in the long run to develop a surface water supply from the very first.

If investigation shows that is is not wise to draw too heavily on the deep horizon beneath the beaches there is still the possibility that a large supply may be obtained from deep or shallow wells on the mainland. There also is a question of the effect of pumping a large quantity of water from such wells. It is with these questions of the feasibility, possible results and wisdom of obtaining large supplies from wells in the Atlantic City region that the present report is concerned. It deals primarily with the quantity of water that may be drawn safely from the ground water supply over a long period of time. It does not consider the matter of preference of alternative projects from the standpoint of cost, which is properly the duty of the municipal authorities in consultation with competent engineers.

It may be pointed out that the questions in regard to the possibility of developing additional water from wells is of importance not only to any single town or city where an increase in supply is contemplated but to all of the neighboring towns and cities in the region. There is evidence that a large producing well in the region may not only directly affect other wells within a radius of a few hundred feet, but it may indirectly affect wells several miles distant. The question is likewise of importance to owners of private wells. For example, a great increase in the draft on the deep horizon in either Atlantic City or Ventnor might cause so great a lowering of the water level in some of the private wells that it might not be economical for them to continue to pump them. The natural step would be to turn to the public supply. But if this increased demand was supplied from the already overdrawn horizon the problem would still be unsolved. It is conceivable that the best solution may be the formation of a water district which will undertake to develop the water resources available to the Atlantic City region to the best advantage of all the communities. Such a district need be established only for the purpose of developing water supply without any restriction of the autonomy of the individual municipalities in other matters.

GEOLOGIC CONDITIONS AFFECTING OCCURRENCE OF GROUND WATER.

In order that the problems may be better understood, there is given below a brief resume of the geologic conditions affecting the occurrence of ground water in the Atlantic City region.

The deepest well in the Atlantic City region, drilled in the Atlantic Ocean about 1,000 feet out on Young's Ocean Pier at the foot of Tennessee Avenue, reached a depth of 2,306 feet below the floor of the pier.[2] Samples of this well, one of the deepest along the Atlantic coast, were saved nearly every 10 feet. The following log shows the significant facts that relate to our present study.

2Annual report of the State Geologist for 1901, pp. 110-117, 1902.

RECORD OF WELL AT YOUNG'S OCEAN PIER, ATLANTIC CITY.

DRILLED BY URIAH WHITE IN 1901.

	Thickness feet	Depth feet	Formation
Floor of pier to mean tide level	0	20	Recent and Pleistocene
Beach sand	35	55	
Sandy clay	15	70	
Sand	6	76	
Dark stiff clay	14	90	
Heavy gravel with some thin seams of yellow clay	36	126	
Alternations of light yellow and bright orange and grayish sands and gravels	126	272	Cohansey sand
Brownish and grayish sands with thin clay seams, some lignite	118	390	
Mainly bluish and brownish clays, a bed of coarse sand at about 560	300	690	Kirkwood Formation
Clayey sand	30	720	
Sand and gravel	10	730	
Clayey sand	10	740	
Coarse gray gravel with moderate supply of water	20	760	
Sandy brown clay	20	780	
Dark brown clean sand, some light-colored layers	40	820	
Light brown clean sand, abundantly water-bearing from 780 to 860 (the "800-foot sand")	40	860	
Tough hard brown clay	71	931	
Clay and sand with shells, sand is largely glauconite (greensand)	10	941	Pre-Kirkwood
Sand with a large admixture of greensand, slightly water-bearing	9	950	
Sand and clay	2	952	
Hard tough brown clay with comminuted shell	22	974	
Olive-colored greensand marl	16	990	
Brown clay	12	1012	
Olive-colored sand and marl, moderately fine	42	1054	
Olive-colored sand and marl, considerably coarser	21	1075	
Very clayey olive-colored marl	21	1096	
Sand and marl decidedly dark green in color	24	1120	
Dark marly clay	14	1134	
Light or ash-colored clay with much marl and sand,	26	1160	
Brown micaceous clay	40	1200	
Dull yellow sand	5	1205	
(A little water rose to the surface from about this depth, probably from this stratum.)			
Clay	10	1215	
Greensand marl or marly clay	25	1240	Age?
Very hard and tough light and dark slate or light brown clays	200	1440	
Yellowish calcareous rock sometimes moderately soft and sometimes quite hard, consists two-thirds of a nearly equal mixture of greensand and white quartz sand grains and one-third of carbonate of lime, the latter the cementing material	460	1900	Vincentown Sand
Clay marl, half glauconite at 1913-1923	40	1940	Pre-Vincentown
Clay mixed with a little greensand, thin pebble layer at 2010	70	2010	
Indurated ash-colored clay "hard almost as rock"	60	2070	
Clay marl similar to that at 1900 to 1940 feet[a]	80	2150	
Black or dark micaceous sand clays	156	2306	

[a]Although the fact is not stated in the log as originally published a statement accompanying it says that "a scant supply" of water was encountered at about 2150 feet.

Only a few wells reach the greater depths. The formations to a depth of about 380 to 400 feet consist principally of sand and gravel with some beds of clay. On the beaches the water in these sand and gravel beds is generally brackish, although in some wells water of drinkable quality was obtained. However, heavy pumping would doubtless draw salt water into these wells since there appear to be no thick continuous clay beds to keep out the nearby ocean water. (See pages 119 and 129.) Below these sand beds and extending to about 700 feet the material is principally clay. A 10-foot bed of sand at a depth of about 550 feet is reported in many wells, but it does not appear to be a good water yielder, for it has not been developed in the region. The clay between about 400 and 700 feet is so thick and constant that it is commonly called "the great clay bed."

From about 700 feet to 760 feet (780 feet in the Ocean Pier well) beds of sand, gravel, and clay are reported. These formations apparently are not very regularly distributed. There is quite generally clay at the base of this part of the section.

From about 760 to 840 feet occurs a water-bearing sand that is utilized by practically all of the deep wells in the Atlantic City region. In fact, so important is this bed that it has come to be known as "the 800-foot sand," since the average depth to it at Atlantic City is about 800 feet. In the present report this sand is called the 800-foot sand and the Atlantic City 800-foot sand.

The variation in the depth to the top and bottom of the 800-foot sand is shown by the following typical wells: Brigantine, old town site, top 728 feet, bottom not reached at 798 feet; Old Consumers Water Co. well No. 1, Atlantic City, top 761, bottom 844; Dennis Hotel, Atlantic City, top 775, bottom not indicated at 835; Ocean Pier well, Atlantic City, top 780, bottom 860; Margate City Water Works well No. 3, top 755, bottom 810; Ocean City, Fifty-fifth Street, top 736, bottom 810. South of Ocean City the depth to the sand increases until at Wildwood the top lies about 887 feet below the surface and the bottom 931 feet.[3]

Below the Atlantic City 800-foot sand no reliable water-bearing bed has been developed, and the information afforded by the few wells drilled deeper is unfavorable to the belief that good water can be obtained. In the Ocean Pier well "scant" supplies of water were reported at depths of about 950, 1,250 and 2,150 feet. The exact horizons from which the lower two flows came is uncertain, for at the depths given little or no sand is reported. Sand is reported at several

[3]Report of the State Geologist for 1894, plate opposite page 158 and notes pages 178-179.

depths between 900 and 1,200 feet, but it generally appears to be mixed with clay or greensand marl. With one possible exception the writer knows of no wells in the Atlantic City region that now draw from a horizon deeper than the 800-foot sand. This fact in itself is significant that the beds between 900 and 1,200 feet would not yield large supplies of water, since several of the earlier wells were drilled to that depth, but subsequently abandoned or finished to draw from the 800-foot higher horizon. A public or semi-public supply was obtained from a depth of about 1,100 feet in 1888 and 1889[4] before the 800-foot horizon was developed in 1893, but the deeper horizon has not been used for many years. An analysis shows that the water contained 64.334 grains per gallon (approximately 1,100 parts per million)[5] of total solids and 19.303 grains per million of chloride (330 parts per million). The mineral content of this water is fairly high, and perhaps this caused the abandonment of the wells.

The 800-foot sand has a great areal extent. It has been identified in wells along the coast from Brigantine as far south as Wildwood. Inland it has been traced for many miles. It gradually rises westward and it or strata closely associated with it come to the surface in an elongated zone that passes in a southwest-northeast direction through Kirkwood, about 10 miles southeast of Camden. Because the formation, of which the 800-foot sand is a part, is typically exposed near this town, it is called the Kirkwood formation. The area in which the Kirkwood formation outcrops is shown in Fig. 3.

Among the places where the 800-foot sand of Atlantic City has been tapped inland from the coast are the Atlantic City Water Works in Pleasantville, where it extends from 600 to 675 feet, and Egg Harbor City, from about 300 to 400 feet. It apparently has been reached at Hammonton at a depth of about 300 feet.

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[4]Annual Report of State Geologist for 1888, pp. 73-75; for 1889, p. 90; for 1892, pp..276-277, and for 1901, p. 111.

[5]Annual report for 1888, p. 25.

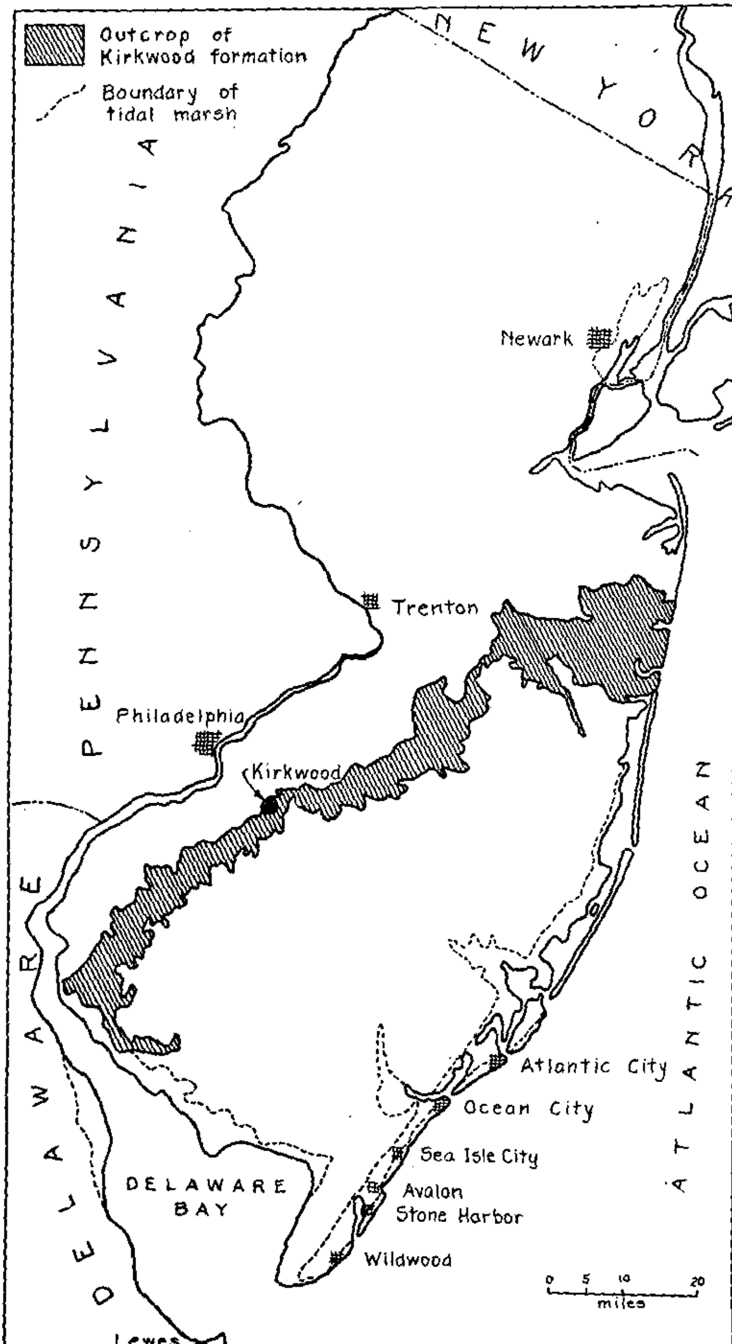

FIG. 3.—Map of New Jersey showing area of outcrop of Kirkwood formation.

On the beaches the 800-foot sand is the only water-bearing horizon of importance. On the mainland, however, water is obtained from higher sand beds which on the beach yield only brackish water. The greatest development of these has been at the Atlantic City Water Works. The log of a test well drilled there in 1903 is given below.

LOG OF TEST WELL AT ATLANTIC CITY WATER WORKS, DRILLED IN 1903.[6]

	Thickness feet	Depth feet
Yellow sand and gravel	18	18
Blue clay, some stones	11	29
Yellow sand, with bark and wood	6	35
White sand, coarse above, fine below	20	55
Yellow sand and gravel, varying sizes	45	100
White and gray clay, some stones	20	120
Layers of sand and clay, sand predominating	18	138
White and red sand	10	148
Red sand (water overflowed casing at 12 feet above sea level)	10	158
No record	10	168
Red sand, finer than water-bearing stratum	32	200
Gray sand, with some clay seams at 230 to 240	50	250
Marl	30	280
Sandy clay	10	290
Marl	20	310
Gray clay	10	320

This log shows water-bearing sand beds between 30 and 100 feet and between 138 and 230 feet. Beds of clay overlie each of these sand horizons, which are utilized at the water works by wells that average some 100 and others 200 feet in depth.

Except at the Atlantic City Water Works, wells on the mainland are few and widely separated. Several show thick sand and gravel beds separated by clay beds, but positive correlation between individual beds in different wells cannot be made. It is impossible to determine, therefore, whether any given clay bed is of wide horizontal extent. If not, there is a possibility that heavy pumping may result in contamination by salt water. On the other hand, discontinuous clay beds favor rapid replenishment of the sand layer from the rainfall.

The geologic conditions governing the occurrence of ground water in the Atlantic City region is shown by a somewhat generalized section in Figure 4, which extends from Philadelphia to Atlantic City. The

[6]Annual report of the State Geologist for 1904, pp. 263-264, 1905. In this log no data are given for the distance between 158 and 168 feet, probably due to a typographical error in the original.

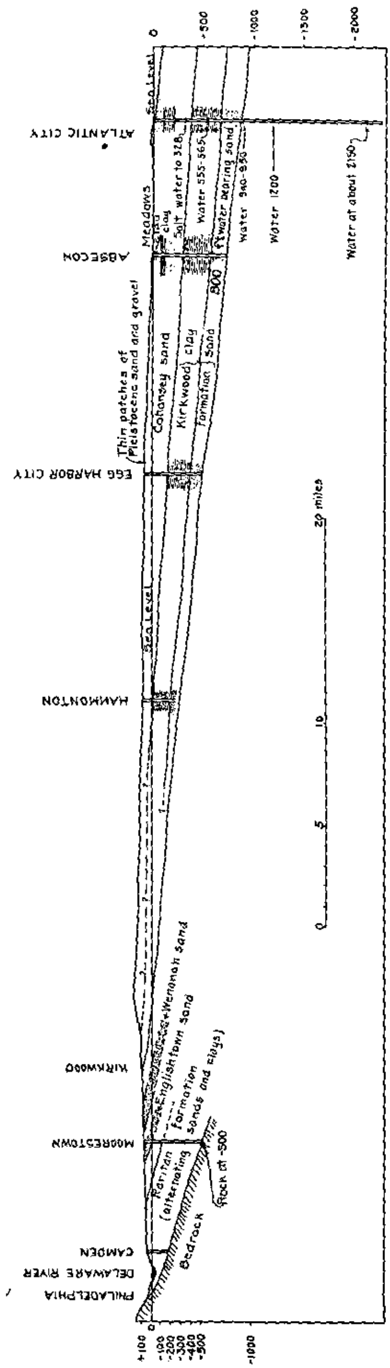

FIG. 4.—Generalized cross section from Philadelphia to Atlantic City showing principal water-bearing horizons.

direction of dip of the beds is practically parallel to a straight line drawn between the two cities.

It will be noted that because the Atlantic City 800-foot sand rises westward and for a considerable distance is overlain by the great clay bed the conditions are favorable for the development of artesian pressure in the horizon. Such is actually the case, for wherever the formation is struck the water rises in the casing. At Atlantic City it rises from a depth of about 750 feet to within less than 100 feet of the surface and some of the wells originally flowed.

In the left-hand part of Figure 4 are shown three horizons, the Wenonah sand, the Englishtown sand and the Raritan formation, all of which are water bearing. The Raritan is one of the best water-bearing formations in New Jersey, and furnishes large quantities of water, especially at Camden.[7] These beds dip eastward, just as does the Kirkwood, and the question arises as to whether they are not available in the Atlantic City region. In the southern part of the State these formations have been penetrated only in wells within a few miles of their outcrop, and no wells east of Kirkwood have reached even the highest or Wenonah sand. The deepest beds penetrated in the 2,300-foot well at the Ocean Pier in Atlantic City cannot be positively identified except that they lie below the Vincentown limesand.

It is possible that all three of the water-bearing formations that are found west of the outcrop of the Kirkwood continue eastward as far as Atlantic City and would be reached if a well were drilled deep enough, but there is no information to show how deep it is to any of them. The Raritan was found at Asbury Park at a depth of about 900 feet and the Englishtown at a depth of about 600 feet. The Raritan is believed to have been reached at a depth of about 1,500 feet in a well completed in the summer of 1925 at Lavalette, about eight miles northeast of Toms River. The facts indicate that the formations lie at greater and greater depths at points farther and farther south along the coast. The conclusion is that, although water-bearing beds may lie below a depth of 2,300 feet at Atlantic City the known conditions are very uncertain. Although it is highly desirable to know conditions to a greater depth, the cost of drilling a test well would be very great, and such an undertaking would of necessity be entirely speculative.

In passing it may be pointed out that, as shown by Figure 4, all of the ground water of the Atlantic City region, as well as of practically all of South Jersey, originates on the New Jersey coastal plain

[7]Ground-water conditions in the Camden area are discussed in a report by the writer in preparation.

or within a mile or two west of Delaware River. Crystalline bedrock, which is practically impervious, rises from beneath the coastal plain deposits a short distance west of the river, and extends westward for many miles. Attention is called to this fact because of a vague notion of some persons that the water obtained from wells in the Atlantic City region has moved underground many miles from the mountains in the interior of Pennsylvania.

THE ATLANTIC CITY 800-FOOT SAND.

GENERAL STATEMENT.

The Atlantic City 800-foot water-bearing sand has yielded uniformly good supplies of water both from the standpoint of quality and quantity, and it is easily available at all places in the Atlantic City region. For this reason it is naturally one of the first sources to be considered in any project to develop additional supplies in any part of the region. It is the sole source of supply for Ventnor, Margate City, Longport, Ocean City and several towns south thereof, except that the first three have emergency connections with the Atlantic City system. In Atlantic City and Ocean City it is utilized by 18 hotels and eight or more industrial plants. Because of its present importance and its probable increasing importance special attention has been given to the study of problems relating to its utilization.

The first deep well in Atlantic City seems to have been completed in 1887.[8] This well, drilled for the Consumers' Water Co., which then furnished part of the public supply, was 1,150 feet deep and the water flowed at the surface. There is some question as to from just what depths the water came, whether from about 960 feet or near the bottom.[9] It seems, however, that the 800-foot horizon, which has since become so important, passed unnoticed. Likewise, it apparently attracted no attention in a 1,400-foot well drilled in 1888 or 1889. Between 1889 and 1892 several wells were drilled which drew upon the sand beds lying betwen 700 and 780 feet—that is, those either above the main horizon or only the upper part of it. It was not until 1893 that the 800-foot horizon was developed in Atlantic City and its value recognized.[10] The same year it was found in Ocean City at a

[8]Annual report of the State Geologist for 1888, pp. 73-76, and for 1889, pp. 89-90.

[9]Annual reports of State Geologist for 1889, p. 90; for 1892, p. 277, and for 1901 footnote, p. 111.

[10]Annual report of State Geoolgist for 1893, pp. 397-399.

depth of 755 to 800 feet, and the following year it was found in Wildwood at a depth of 887 to 931 feet. The value of the horizon was soon realized and during the next few years many wells were drilled to it—two in 1892, five in 1895, six in 1896, only three in 1897 and one in 1898, but six in 1899 and five in 1900, a total of 28 wells in seven years. Thereafter, except for 1901, when four wells were drilled, the number of new wells increased more slowly. In the 20-year period from 1901 to 1920, inclusive, the writer has a record of only 16 wells being drilled, whereas from 1921 to 1927 at least 20 wells were completed to the 800-foot sand.

At least 80 wells have been drilled to the Atlantic City 800-foot horizon at one time or another including those at Stone Harbor, Sea Isle City, Avalon and Wildwood. Only about 55 are now in use and 25 have been abandoned. Of those now in use at least 10 replace abandoned wells. About 10 of the others are known to have been completely abandoned, but the history of several others is uncertain. The location of existing wells drawing from the 800-foot horizon in the region is shown on Figure 1.

As given on page 20 the total average daily consumption from the horizon in the region is estimated to have been about 9.5 million gallons a day in 1927. In the months of high consumption it is estimated that this increased to more than 12 million gallons a day and in winter it dropped to about eight million gallons a day.

The first wells that tapped the horizon flowed naturally and rose in closed pipes as high as 15 feet above the surface (20-25 feet above mean tide), but as more wells were drilled and the pumpage increased the head decreased until they ceased to flow. In the passing years the head has continued to drop until in the summer of 1927 the water level in some wells in Atlantic City when not pumping was 85 to 90 feet below the surface and about 100 feet below the orginal static level. The decrease in head has occurred throughout the entire Atlantic City region, although it is not everywhere as great. The important questions in the consideration of the possibility of determining additional supplies from the Atlantic City 800-foot horizon are: What will happen if more water is pumped from it? Will the static head decrease further? If so, how much will it decrease? Will it decrease only when the draft is increased, or will there be a constant decrease, perhaps at an accelerated rate, even if there is no increase in consumption?

EFFECT OF PUMPING FROM WELLS.

In order that the reader may more clearly understand the discussion on the later pages as to the effect of pumping in the Atlantic City regions certain facts concerning the hydraulics of wells may be stated briefly.

The principal factors that determine the quantity of water that may be drawn from a given formation are three in number, namely: the quantity of water available to recharge the formation; the area of the intake zone, and the permeability of the formation. Brief studies of the first two factors, as they affect the Atlantic City water-bearing horizon, show that the opportunity for water to get into the formation at the outcrop is probably in excess of the present consumption from it so they need not be considered further. Whether the excess will maintain a safe margin with increased consumption, say 25 years hence, cannot be so easily determined. The answer to this question depends upon data yet to be obtained in regard to exact regions of outcrop of the formation, stream discharge, evaporation and percolation and other factors.

A consideration of the third factor, the permeability of the horizon, shows that it may play an important part in limiting the maximum quantity of water that may be obtained in the Atlantic City region. A large quantity of water is being drawn from a comparatively small area through a formation whose pore space is relatively small. It is difficult to get definite information on the permeability of a water-bearing sand. Samples of the material can be obtained from wells, as has been done in the present investigation. (See pages 88 and 96.) However, in testing material so obtained it is impossible to reproduce the same degree of sorting and arrangement of particles as existed under the natural conditions. These factors affect the porosity of the mass and may give a permeability considerably different from the true permeability of the sand in place. Even if the permeability could be accurately determined by tests on small samples of material there would still be uncertainty as to the water-bearing capacity of the formation, for the permeability may vary greatly from place to place, even within a few feet both horizontally and vertically. Variations in the thickness of the formation constitute another factor of uncertainty.

The effects produced by pumping a given quantity of water from a formation obviously are the result of the interaction of all factors that influence the water-bearing capacity. If the effects could be accurately determined they would afford the best means of determining the value of the formation as a source of water supply. However, several factors are involved, and it is seldom possible to evaluate them all accurately. As a result, the water-bearing capacity of a formation seldom can be determined very closely. In the present investigation an effort has been made to obtain as much information as possible in regard to the effect of pumping from the formations under consideration and to draw therefrom conclusions as to the effect of future increases in pumping.

In an artesian bed like the Atlantic City 800-foot water-bearing sand the level at which the water stands in a well is dependent upon the pressure in the bed; in other words, a well is a huge pressure gage. The pressure or pressure head, generally termed simply the head, is referred to a datum plane, such as the ground surface, sea level or any arbitrarily chosen level. The water level in a well when not pumping is generally called the static head. Theoretically the static head shows the pressure on the foundation when the water is at rest. When the water is in motion some of the pressure is utilized in creating the flow and in overcoming friction, and the head on the water is less than when it is not moving. Therefore, when water is flowing through the sand the water level in a well will not be as high as when there is no flow. Observations show that the water in a formation is practically never motionless, but always flowing, perhaps only at an imperceptible rate. Accordingly, a condition of true static head scarcely ever exists. The difference in head produced by natural flow unaffected by pumping ordinarily is so slight that static conditions are generally assumed without introducing any appreciable error. However, where wells are so close together that pumping one lowers the water level in a neighboring well, the departure from the static level in the non-pumping well may be considerable and may fluctuate rapidly as the pumping well is started and stopped. This condition of a continually changing head is present in any region where there is much pumping as in the Atlantic City region. It should be understood, therefore, that when the term "static level" or "static head" is used, it describes a temporary condition, and that due consideration must be given to the degree of change in head that may occur in a period of a few hours, days or months.

Since the head on a formation in a locality is indicated only by the water level in a well, one is inclined to speak of "the water level" or "static level" in the formation. If the water is under artesian pressure these expressions are inaccurate for the formation is saturated with water, and only when a well is drilled into it will the water rise to a point that indicates the true head on the bed.

If the static level in many wells could be connected by a surface, that surface would show the level to which the water would rise if wells were drilled at other intermediate points. Such a surface, necessarily an imaginary one, but, nevertheless, denoting a definite and important condition, is called a piezometric surface. In other words, the piezometric surface is the surface that everywhere coincides with the level of head on the water in the formation. Normally in an artesian horizon where there is no flow the static head is everywhere equal, hence the piezometric surface is a horizontal plane. If there is flow from it the static head is lowest at the point or zone where the water emerges from the horizon and it increases toward the intake area. The piezometric surface accordingly slopes toward the locality of discharge and may be either a plane surface or an uneven surface, depending upon the conditions of discharge.

When the pumping of a well is begun the water level or head immediately drops. The drop is at first rapid, but becomes slower and slower, until finally there is no further apparent drop. The time required to reach the point of stability is generally, at least, several hours, and may be even days or weeks. At the same time the head in the sand around the well drops; the lowering is greatest in the pumping well and decreases in amount at points farther and farther away from it. The piezometric surface showing the head during pumping is approximately that of an inverted cone, the apex of which is at the pumping well. However, instead of the profile of the cone being straight from the apex to the base, it is convex upward, being nearly vertical at the well and away from it changing gradually, until at a great distance it becomes nearly horizontal. Theoretically, there is some decrease in head below its original static position for a very great distance from the pumping well, at least to a place where the area of outcrop affords sufficient recharge to balance the quantity pumped from the well. Actually the loss of head becomes practically negligible within a few hundred or few thousand feet of the pumping well. Near the well water is being drawn in from all directions, and the shape of the piezometric surface is somewhat circular. For this reason the area in which there is an observable lowering in head is often called the circle of influence of the pumping well.

Within certain limits the yield of the well is in direct ratio to the lowering of the water level (generally spoken of as the drawdown). For example, if the drawdown is 10 feet when the well yields 100 gallons a minute, to get 200 gallons a minute it will be necessary to lower the water 20 feet. When the rate of pumping in the well is increased the limiting circle of influence is enlarged and the shape of the cone is changed. When several wells are pumped the ensuing conditions are somewhat comparable to those when only one is pumped, except that they become more and more complicated as each well is added.

When two or more wells are pumped their cones of influence will overlap if they are near enough to each other, and the shape of the piezometric surface will become very uneven. When the circles of influence do overlap the yield of the wells resulting from a given drawdown decreases and the wells are said to interfere with each other.

The principles just stated, namely, that the yield of a formation varies approximately as the lowering of head in the pumping wells, and that an overlapping of the cones of influence causes interference or decreased yield of a given lowering of head, are of great significance. Stated in a different manner, they mean that if more water is to be obtained from existing wells the water level in them must be lowered, or if it is to be obtained from new wells whose cones of influence overlap those of the pre-existing wells, there will be a lowering of head in the old wells.

Some idea as to the shape of the area of influence carried by the pumping of several wells may be obtained by applying the graphic method of showing the direction of movement of water toward wells which is described by Slichter.[11] Two sets of conditions may be assumed—first, when the static head is equal throughout a large area, and second, where there is a constant movement of the ground water in a general direction, it being assumed in each case that the permeability and porosity of the water-bearing bed are everywhere the same. Considering the first condition, if a single well is pumped the water moves toward it from all directions, and the lines of flow are straight lines radiating from the well. If two wells are pumped at the same rate, and each is situated well within the circle of influence of the other, each can no longer draw equally from all directions. The lines of flow will be approximately as shown in Figure 5, A, in which it is assumed that the wells are each pumping the same quantity. The area of influence for the two wells must be somewhat larger than for only one well. The direction of flow into three and four wells situated along a straight line, each pumping the same quantity of water, is also shown in Figure 5. If additional wells are pumped the conditions will approximately reproduce those shown in the diagrams for three or four wells, depending upon whether an odd or even number of wells are in operation. When an odd number of wells, for example five, are pumping, the area of influence of the center well will

[11] Slichter, C. S., Theoretical investigation of the motion of ground waters: U. S. Geol. Survey Nineteenth Ann. Rept., Pt. 2, pp. 368-369.

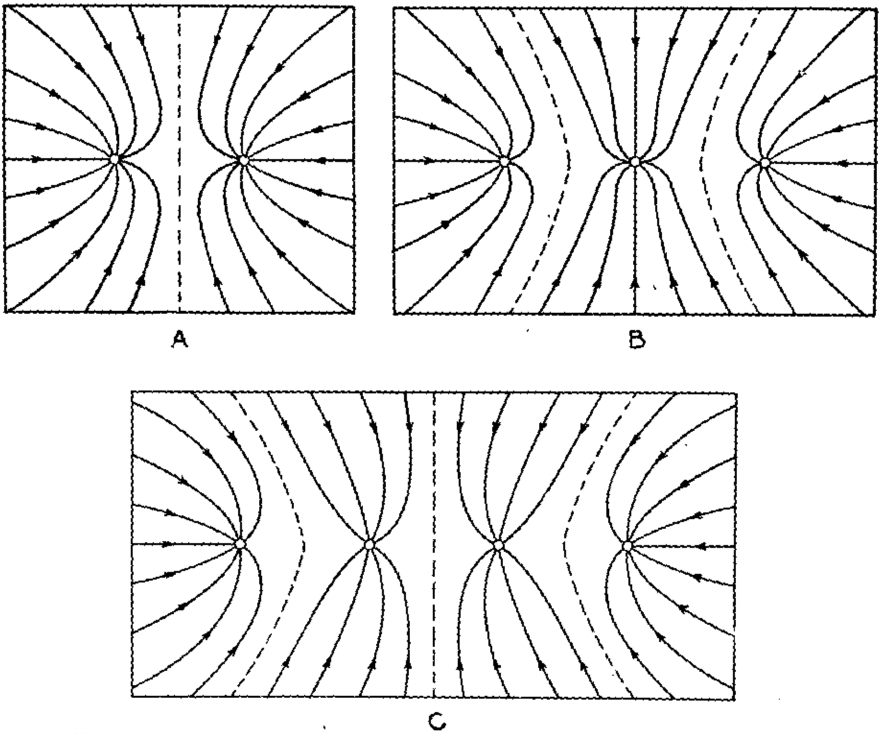

FIG. 5.—Diagrams showing lines of flow for 2, 3 and 4 pumping wells.

be wedge-shaped on either side of the line of wells, and symmetrical to a line at right angles to them. The areas of influence of the wells adjoining the center well will also be somewhat wedge-shaped, but their axes will extend out diagonally from the line of the wells. If an even number of wells are pumped the areas of influence of all the inner wells extend out diagonally, as when four wells are pumped.

When a single well is pumped the decrease in head is the same at all points along a circle having a given radius from the well, because the water is moving at the same rate past all points on the circle. When several wells in a line are pumped, as shown in Figure 5, C, if the rate of pumping is the same from all wells, the water entering the inner wells must move faster than that reaching the two at either end of the line. Therefore, the decrease in head at a given distance from a well in the center of the section must be greater than at the same distance from the outermost wells.

When there is a movement of the water in a general direction, as in the Atlantic City 800-foot sand, the direction of the flow will be much the same as has just been described, but there will be some modifications. When a single well is pumped, as a result of the lowering of the head in it, water will move in from all directions as in the first case described above; but the cone of influence will not extend so far down the dip and the inflow from that direction will be less than from the opposite direction. At some distance down the gradient from the well the general direction of flow will be resumed. When several wells in a line at right angles to the direction of original flow are pumped the general conditions will be the same as for the cases described above except that they create a barrier, as it were, which stops the normal movement down the dip in the well zone. If the original gradient of the piezometric surface is sufficient, water from the upstream side will move around either end of the well zone and thence back to wells in the inner part of the well line. But if the gradient is not sufficient the direction of flow on the downstream side may be completely reversed for a long distance from the well.

When the wells are not situated in a straight line but irregularly distributed, and the rate of pumping is unequal, as in Atlantic City, the conditions are obviously quite complicated. However, the above facts are significant in showing the effect of pumping many wells in a single area. They are especially applicable to conditions in the Atlantic City region where many of the wells are arranged approximately in a line at right angles to the dip of the water-bearing formation. Some of the wells in the city are located northwest of the main line of the wells on the beach. (See Fig. 1.) These wells doubtless capture most of the water that is moving directly down the dip in the city. A large part of the water that reaches the wells nearer the beach, for example, in the vicinity of the Traymore and the Chalfonte Hotels, must come either by a circuitous course around the ends of the long zone of beach wells or it must be drawn landward from beneath the ocean.

OBSERVATIONS ON PUMPING WELLS IN THE ATLANTIC CITY REGION.

General Statement.—In the present investigation efforts were made to determine some of the effects of pumping from the 800-foot horizon by tests on individual wells. The conditions of the tests have not been entirely suitable, for generally some one or two factors could not be sufficiently controlled to make the results conclusive beyond any doubt, but certain valuable observations have been made. The results of some of the tests are described below.

PLATE IV.

Temporary installation of water-level recorder on new well of Atlantic City Electric Co., May, 1924.

At the outset great difficulty was encountered in obtaining any accurate data on the depth to water. Most of the wells are pumped by air lift and covered so tightly that it was impossible to get a measuring tape in them. Very few well owners had given any thought to fluctuations of the water level in their wells. The only definite information they had was the depth to water when the wells were completed, or, perhaps, cleaned out at periods ranging from a few months to 10 or 20 years prior to the time of the writer's visit. Some reported that the depth to water was greater in summer than in winter, and there was a fluctuation with the tide which ranged from a few inches to several feet. Others stoutly maintained that the water level was constant practically all the time, that their starting pressure was always the same. Some engineers said their wells were affected by neighboring wells, whereas others insisted the pumping of nearby wells had no effect, even where there was good reason to suspect some interference. The most generally conceded fact was that the static water level was considerably lower in most places than when the wells were first drilled.

After some study it was found that the depth to water could be determined within a foot or two by means of the starting pressure and shut-in pressure according to methods described elsewhere provided the air-lift installation was made in a certain way. Observations were thereafter made on a number of wells by this method.

It was also found possible to measure with a steel tape wells which had first been reported as tightly closed. As the work progressed several new wells were drilled, and it was possible to make observations on these wells especially during the preliminary tests of the wells.

Atlantic City Electric Co. Wells.—The first observations of value were obtained in May, 1924, when a water-level recorder was installed on a newly-drilled well (No. 1, Fig. 1) through the courtesy of Mr. C. T. Birney, chief engineer of the Atlantic City Electric Co. and of the Layne-New York Co. The fluctuation obtained from this recorder, plotted on a reduced scale, is shown in Figure 6.

The well is about 275 feet from the company's old well which was still in use. During the period of observation the old well, the yield of which is estimated at 330 gallons a minute, was alternately pumped for a few hours and shut off for a few hours. It was immediately apparent that the new well was within the circle of influence of the old. It was found that the water level started to move up or down within about a minute and a half from the time the pump was stopped or started. The downward movement continued as long as pumping

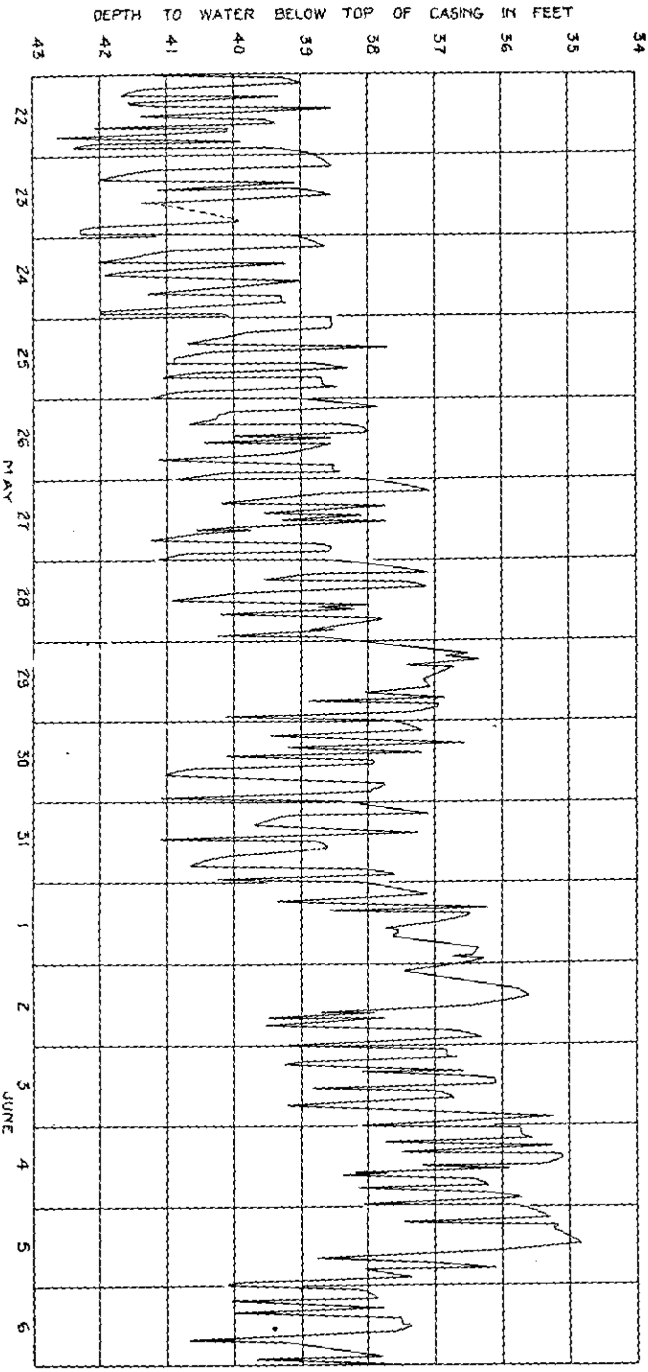

FIG. 6.—Graph showing fluctuation of water level in new well at Atlantic City Electric Company, May 21 to June 7, 1924.

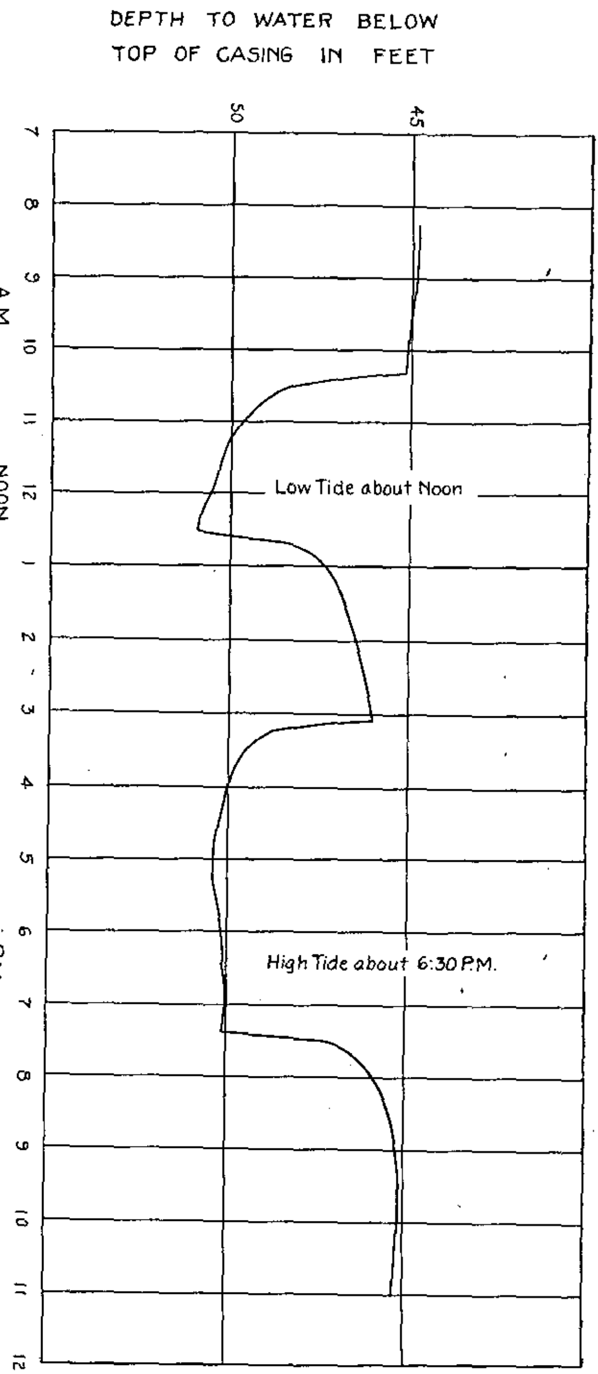

Fig. 7.—Graph showing fluctuation of water level in new well at Margate City Water Works, August 28, 1924.

continued, and the water continued to rise as long as there was no pumping—that is, a condition of stability was not reached, and evidently would not be reached for some time.

During the period of observation the average water level rose several feet. The reason for this was not determined. It may have been due to one or a combination of two or more of the following conditions: less pumping of the old well, less pumping from the horizon as a whole; storms which may have produced high tides which in turn raised the average water level of the well. During the period of observation the maximum difference of the water level was nearly eight feet, and frequently the water rose or fell three feet in as many hours.

Margate City Wells.—On August 28, 1924, frequent measurements at intervals of 5 to 15 minutes were made on a well at the Chalfonte Hotel and on a newly-completed well at the Margate City water works. These were made on the same day to determine whether there was any general fluctuations throughout the entire area. The fluctuation in the Margate well is shown in Figure 7.

The observation well is about 100 feet from the nearest of two wells that were pumped several hours each day. The combined yield of the two wells is probably not more than 200 to 250 gallons a minute. The times of pumping are clearly shown by the marked drop in curve. In this test the wells were pumped long enough for a stable condition to be reached, since the line becomes essentially horizontal. In fact a very slight rise was observed. This came while the tide was rising, and, doubtless, was due to the effect of it. It would have been desirable to have continued the pumping for at least another twelve hours to see if on the next low tide the water level went still lower.

The total fluctuation in the new well during the test was approximately five feet.

Chalfonte Hotel Well.—The Chalfonte Hotel well (No. 19, Fig. 1) is one of several wells situated with a few hundred to a thousand feet of each other. A second well at the Chalfonte is only 60 feet distant; a well at Haddon Hall is about 400 feet distant; one at the Strand Hotel less than 100 farther, and one at the Knickerbocker Hotel is about 700 feet distant. The Chalfonte well was pumped at irregular intervals as were all the others. The depth to water in the Chalfonte well was measured with a steel tape both when it was pumping and when it was at rest. The fluctuation of the water level during the test is shown on Figure 8.

The time when the Chalfonte well was started and stopped is clearly shown by the sharp drops and rises in the line. As the pumping or the period of rest continued the rate of drop or rise decreased

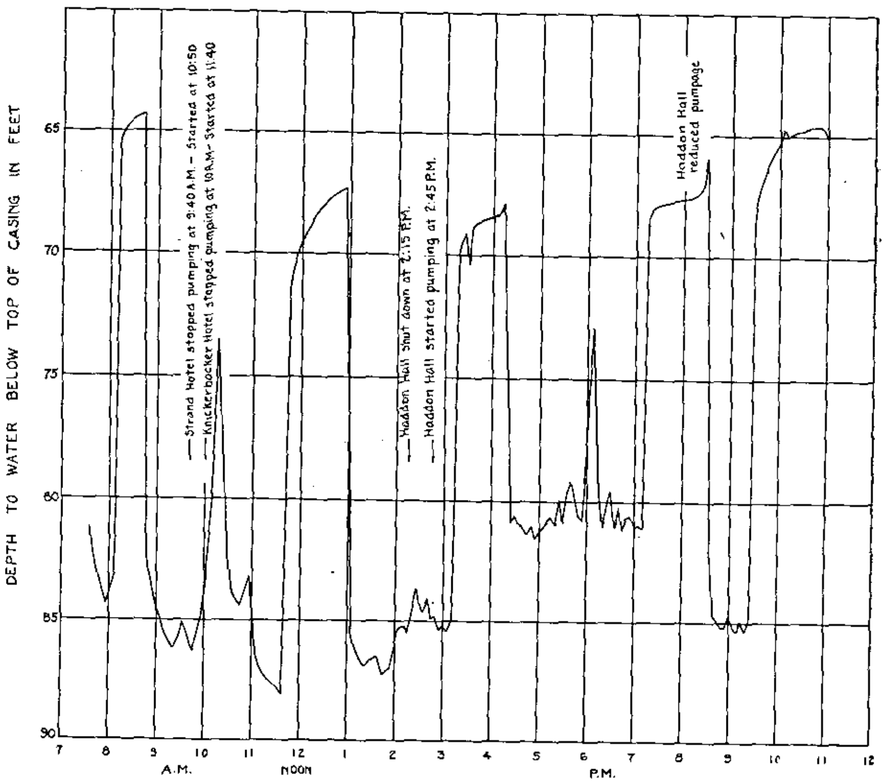

FIG. 8.—Graph showing fluctuation of water level in well at Chalfonte Hotel, August 28, 1924.

and the line began to curve toward the horizontal, but as in the Electric Company well it never reached a point of stability. Numerous irregularities are shown in the curve. Some of those of small magnitude, for example about 5 P. M., appear to be due to variations in the speed of the air compressor, but the major fluctuations are doubtless due to the starting or stopping of neighboring wells.

The highest point reached during successive periods of rest was two to three feet lower during midday than during the morning and evening. Observations on the starting pressure before and after the test show that the level was still higher during the very early morning and late evening. This is shown in Figure 9, on which are plotted the depths to water each time the well was started after a period of rest. It was thought at first that this variation in the so-called static level might be due to the effect of the tide, but this is disproved by the plotting of the predicted times of high and low tide. The interval between successive high tides as recorded by the Coast and Geodetic Survey was about 13 hours, whereas the interval of the highest water in the well was approximately 24 hours. Furthermore, the maximum observed range in the tide was only 5.2 feet, whereas in the well it was about 7.5 feet. As shown by observations at Longport (see page 57) the fluctuations of the water level in the 800-foot sand due to the tide is less than the range of the tide. It therefore appears quite conclusive that part of the fluctuation between the high and low static levels in the Chalfonte well on August 28 were not wholly due

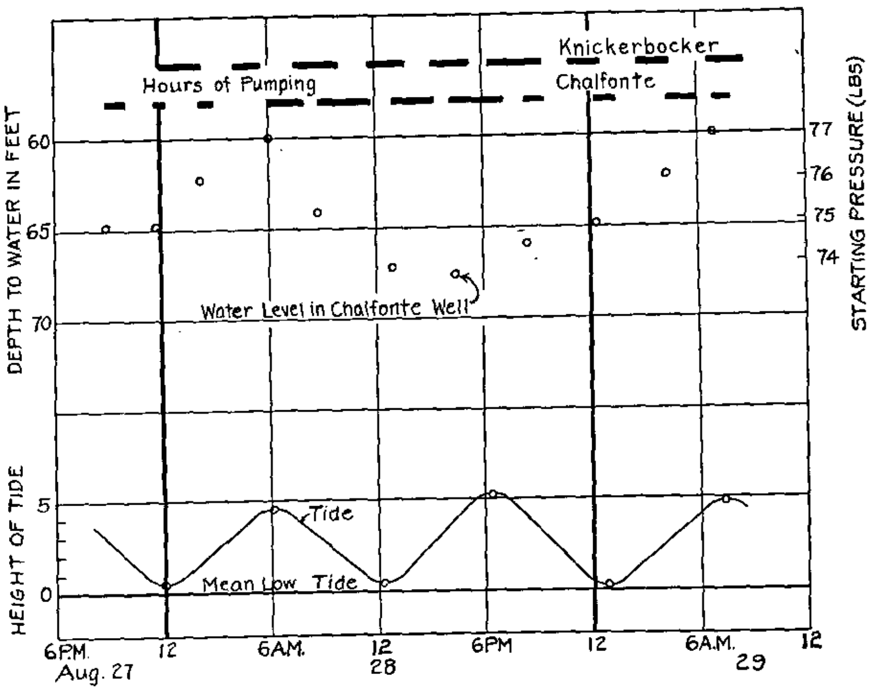

FIG. 9.—Graph showing depth to water in Chalfonte Hotel well at times of starting pump; hours of pumping from wells at Chalfonte and Knickerbocker Hotels, and fluctuation of tide, August 27 to 29, 1924.

to the tide. Nevertheless, the high points doubtless were higher and the low points lower than they would have been if the tide had been in the opposite phase.

Subsequent observations of the starting pressure taken daily for several months at the Chalfonte Hotel and at the Hotel Brighton, show that during the day the water level is generally from two to seven feet lower in midday or late afternoon than it is in the period from midnight to 6 or 7 A. M. This lowering of the static water level during the day is explainable by the fact that the pumping from many wells in the city is heaviest at that time and lightest at night. During the night the periods of rest are longer and the periods of pumping shorter than during the day.

Guarantee Trust Building Well.—Evidence obtained in other tests suggests that the piezometric surface, which represents the hydrostatic pressure on the formation, drops throughout a large part of the city during the day, except where it is affected directly by the stopping of wells that are pumping. This fact is indicated by the movement of the water level in a well (No. 8, Fig. 1) at the Guarantee Trust Building. On December 17th, 1924, measurements of the depths to water were made every 15 minutes from 8:45 A. M. to 5:30 P. M. This well is about 1,500 feet from the nearest wells that were pumped on the day of the test. The water level dropped continuously from 8:45 A. M. until 4:30 P. M. After 4:30 it rose as long as the measurements were continued. The rate of drop during the day was somewhat irregular, with a noticeable slackening in the rate especially between 12 and 1 P. M., when several wells doubtless were shut off. The total drop was almost two feet. The period during which observed lowering occurred was fully seven and three-quarter hours, or fully an hour longer than the interval between high and low tide. Furthermore, on the day of the observations high tide occurred at about 11 A. M. and low tide at about 6 P. M. There is little doubt that at least part of the lowering was due to the effect of pumping in the city.

Ritz-Carlton, Ambassador, and Chelsea Hotel Wells.—Valuable information was obtained during the test on January 20, 1925, of a new well (No. 12, Fig 1) at the Ritz-Carlton Hotel, when frequent measurements were made on a well (No. 11) at the Ambassador Hotel, and on a well (No. 10) at the Chelsea Hotel, 360 feet and 585 feet, respectively, from the Ritz well. The movement of the water level in the wells is shown on Figure 10. The data at this locality are especially valuable, because the observation wells were farther from other working wells, about 3,200 feet southwest, than any to be found elsewhere in the city.

The Ambassador well was shut down for the entire period of the test as well as for two hours previous. The Chelsea well was shut down as long as possible, but it was necessary to pump it for two periods, and the well then could not be measured. It was not possible to measure the depth to water in the Ritz well. The static level before pumping was about 43 feet below the top of the casing and

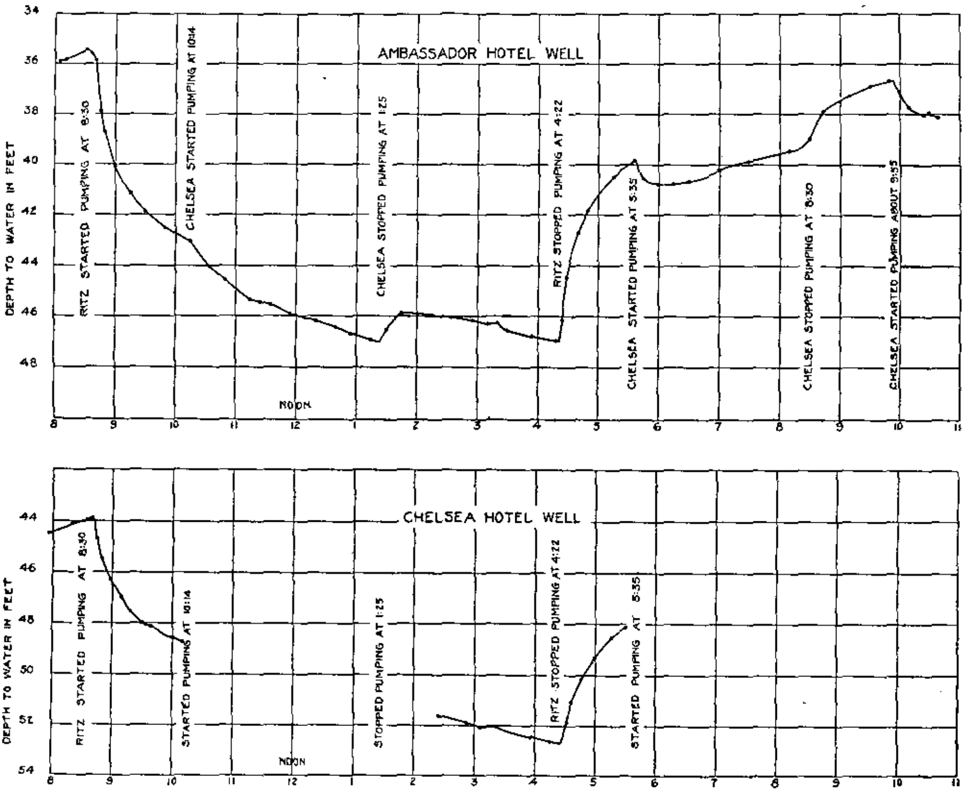

Fig. 10.—Graph showing fluctuation of water level in wells at Ambassador and Chelsea hotels during pumping test of new well at Ritz-Carlton Hotel, January 29, 1925.

the pumping level was estimated to be little more than 91 feet below the same reference point. During the test the yield of the Ritz well, measured by an orifice, ranged from 655 to 730 gallons a minute, but during most of the time it was between 660 and 695 gallons a minute.

The most striking feature of these graphs is that the water level in the two observation wells dropped as long as the test lasted, nearly eight hours; and as soon as the Ritz well stopped pumping the water level in the other wells rose continually except for short periods, when the Chelsea well was pumped. The rate of drop in the Ambassador well was slightly accelerated when the Chelsea well began pumping and the water rose about a foot in 20 minutes when that well stopped, but thereafter the downward movement began again. The latter half of the pumping test coincided with a falling tide in the ocean, and some of the lowering may have been due to this. However, during the test a heavy storm with easterly winds developed, and the afternoon low tide level of the day was more than a foot higher than the early morning low level. The effect due to tide would probably be not more than one to one and a half feet. Incidentally, as shown by Figures 12 and 13, the static water level in the entire region at the time of this test was about as high as at any time in many months.

Pumping of the Ritz well caused an observed lowering of about 11 feet of the water level in the Ambassador well and of nearly nine feet in the Chelsea well. It would have been quite desirable to continue the test for at least another 12 hours to see if the level in these wells continued to drop, but this was not possible. Pumping of the Chelsea well affected the water level in the Ambassador well only about a foot. This slight effect is apparently due partly to the fact that the Chelsea well does not yield nearly as much water as the Ritz well did during the test, and partly because the pumping of the Ritz well had already caused such a lowering of the water level in the Ambassador well that the Chelsea well had relatively little effect on it. Subsequent measurements when the Ritz well was not pumping showed that the Chelsea well alone caused a lowering of two to two and one-half feet in the Ambassador well, or nearly twice as much as when the two wells were operating. The effect of the Ritz well on the other two under ordinary conditions of operation is probably not as great as described, because the rate of pumping is only about 500 gallons a minute, and pumping doubtless does not continue for so long at a single stretch as during the test.

An attempt has been made to determine the radius of the cone of influence of the Ritz well during the test by means of formulæ given by Turneaure and Russell.[12] The calculations give a radius of approximately 3,000 feet when pumping 700 gallons a minute. There is, however, a question as to whether the Turneaure and Russell formula can be correctly applied to pumping tests in the Atlantic City region where the temporary static head is many feet below the original or true static head and the head is also affected by many pumping wells. This problem requires further study before definite conclusions can be reached.

If both the Ambassador and Chelsea wells had been pumping during the test the radius of the circle of influence undoubtedly would have been somewhat greater, and the combined area of influence of these three wells would overlap the circle of influence of the nearest wells in the central part of the city. Judging from the data obtained

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12Turneaure, F. E., and Russell, H. L., Public Water Supplies; John Wiley & Sons, 1924, pp. 254-265.

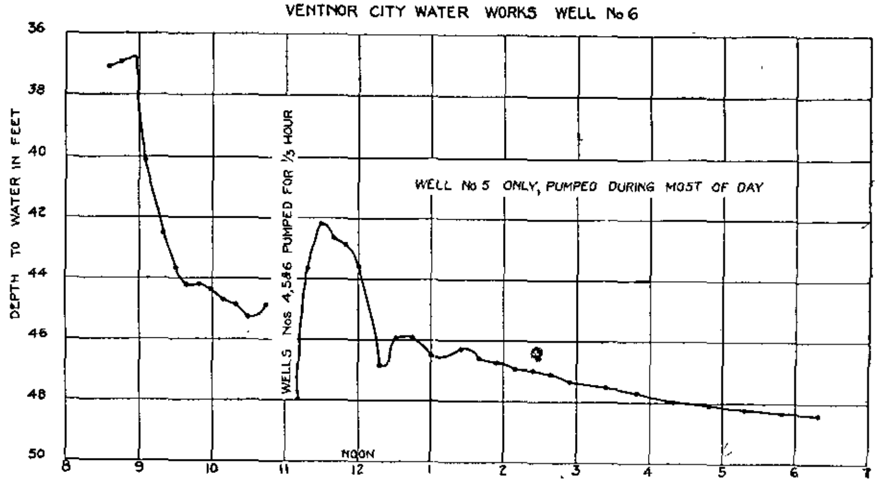
in the test at the Ritz there is no area in the city where the static head is not affected more or less directly by the pumping of wells in other parts of the city.

Ventnor Wells.—On January 15, 1925, a test similar to that at the Ritz was made on wells at the Ventnor Water Works, with somewhat similar results. One well, No. 5, was pumped at a rate of about 600 gallons per minute, and measurements were made on two wells, Nos. 4 and 6, at distances of approximately 260 and 380 feet, respectively, from it. The fluctuations of the water level in the observation wells is shown in Figure 11.

As in the Ritz test the water level in the observation wells continued to drop as long as No. 5 was pumped. Also, as at the Ritz, low tide occurred near the end of the test. There is some reason to believe that if the test had been prolonged the level in the observation wells would have dropped further during the succeeding period of low tide. The total decrease in head in the nearest well, No. 4, was about 14 feet, and in No. 6 about 11 feet.

Significance of Observations.—The tests described above show certain facts. All the wells measured during the tests are affected by neighboring wells. The observed decrease in head in observation wells due to the pumping of neighboring wells has ranged from a foot or two, where the distance to the nearest wells was as much as a thousand feet, to maximum of 14 feet where the wells were only 280 feet apart. The decrease in head varies according to the quantity of water pumped. Since the area of influence of single wells extends a thousand feet or more, and since practically all of the wells in the city are within a few hundred feet of one or more neighboring wells, the problem of determining the effect of individual wells becomes quite complicated. In a locality where several wells are within a few hundred feet of each other there must be several interfering areas of influence. Actually, as shown on page 72, the pumping of so many wells in the city has created an immense area of depression of the head on the formation.

Wherever tests have been made the water level in the observation wells has continued to drop as long as pumping continued, although the rate of pumping was practically constant. Unfortunately in some of the most important tests it was impossible to measure the water level in the pumping well, and it is not certain whether the water level also continued to drop in them. Any further lowering of the water level, if it occurred, would likely be so small that it might be detected only by very careful measurements covering a considerable period. There is abundant evidence that when one or more wells are pumped the head does not immediately become adjusted to the pump-



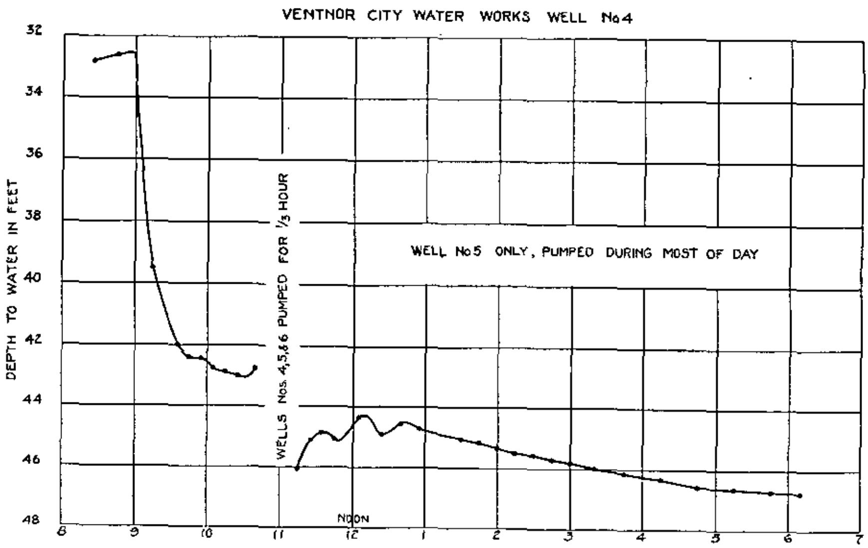


FIG. 11.—Graph showing fluctuation of water level in wells Nos. 4 and 6 at Ventnor Water Works during pumping of well No. 5, January 15, 1925.

ing conditions, but that there is a considerable lag. If the rate of pumping during the tests had been greater it is probable that the time required to reach a stable condition would have been much longer than for the rate that actually obtained. The lag in the lowering of the head when a well is pumped is a condition that has been observed in many tests and in different formations in other regions, so that it seems to be a characteristic of water-bearing formations under artesian pressure. The reasons for this lag are not fully known, but they are believed to be due in large part to the phenomena of compressibility and elasticity of the water-bearing strata.[13]

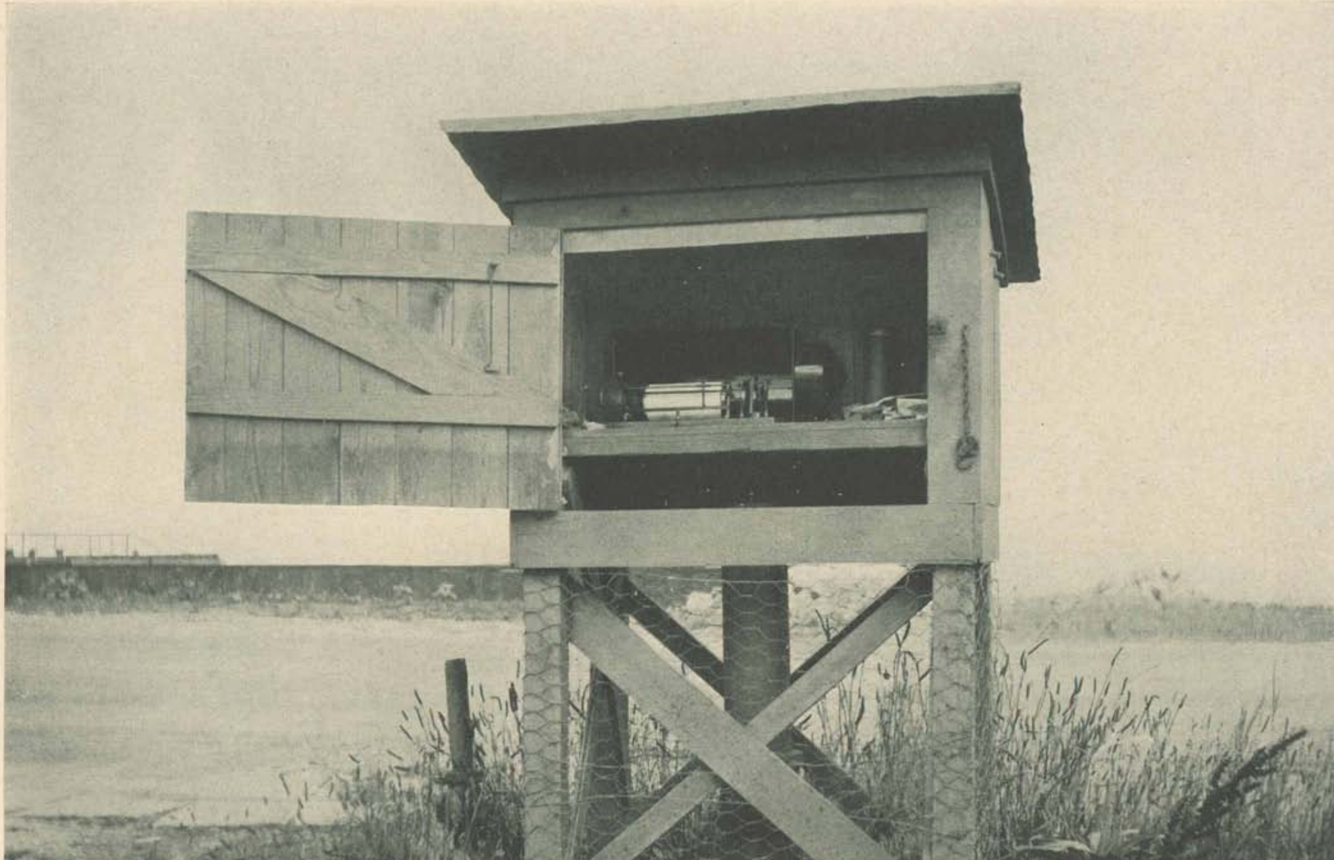
There is good evidence that the so-called static head on the Atlantic City 800-foot sand in different parts of the region rises and falls each day from one to several feet as the pumpage decreases or increases. One of the important results of the observations on individual wells, therefore, has been to show that a true static head in the region does not exist in the sense that the water reaches a stationary level when pumping is stopped. A single measurement has definite value only in so far as information is available as to the length of time elapsing after the well was pumped previous to the time of measurement, as to whether near-by wells were in operation or idle, and as to whether the tide was high or low.

SEASONAL FLUCTUATIONS OF HEAD IN WELLS.

Observations in Atlantic City.—An important phase of the investigation in the Atlantic City region has been the making of observations in regard to seasonal fluctuations of the head on the 800-foot sand. It was first thought that occasional measurements at intervals of a few weeks on favorably situated wells would be sufficient to show any seasonal trend in the static head on the formation that might occur. However, the results of the tests described above showed that there might be a difference of several feet in the water level at different times of any day. If, then, the fluctuations due to differences in seasonal pumpage were not great, it might not be possible to distinguish them from the daily fluctuations.

Preliminary observations at the Chalfonte Hotel showed that the static water level, and, accordingly, the starting pressure, was higher in the early morning hours than during the day. Beginning on July 26, 1924, the engineer on duty recorded the pressure each day when he started the pump between 3 A. M. and 7 A. M. Beginning on January 8, 1925, in order to obtain a more satisfactory record the pressure was read, not only at the early morning start, but each time the well was started and also the shut-in pressure was read each time it was shut down. Similar observations on the starting pressure and shut-in pressure on the Brighton Hotel well were begun on January 28, 1925.

13Meinzer, O. E., Compressibility and elasticity of artesian aquifers: Economic Geology, vol. 23, No. 3, pp. 263-291, 1928.



Installation of water-level recorder on 14th Street 800-foot well of Borough of Longport.

The observations on these two wells are shown graphically up to December 31, 1925, in Figure 12. Only the starting pressure is shown for the Chalfonte, for the record of shut-in pressure during the period covered by the graph is incomplete. The single line for the Chalfonte pressure from July 26, 1924, to January 8, 1925, represents a single reading taken betwen 3 and 7 A. M. each morning, when the water level was presumably as high as at any time during the day. The double lines in all other parts of the diagram shows the highest and lowest starting or shut-in pressure, as the case may be, for each day. The depth to water for a given pressure is shown at the left of the graph.

The graph shows considerable variation in the water level from day to day, due in part to the variable conditions of pumping near-by wells. With several wells to be considered, it is evident that a considerable variety of possible conditions may be obtained. The variations also may be caused in part by the changing effect of the tide. A further reason for the variation in water level from day to day is that the consumption undoubtedly varies from day to day.

In addition to the observations on the wells at the Chalfonte and Brighton Hotels valuable observations covering from a few days to several months have been made on several other wells in Atlantic City. These include the operation of an automatic water-level recorder on a well at the Atlantic City High School (No. 9, Fig. 1) for several weeks in the summer of 1925; regular daily readings on static and shut-in pressure on a well at Galen Hall (No. 25) since July, 1926, and the operation of an automatic recorder on an abandoned well of the Citizens Ice Co., on Baltic Avenue near Massachusetts Avenue, from January 17, 1928, on. These observations show fluctuations from month to month that are essentially similar to those observed in the Chalfonte and Brighton Hotels. Curves showing the fluctuation of water level in wells in Atlantic City from February, 1924, to April, 1928, inclusive, are shown in Figure 14. No one record is complete for the entire period, so the curves are a composite, based largely on the pressure records of the wells at the hotels mentioned. The depth to water at a given time, as shown by the curves, is that existing in the area of heaviest pumping in the city, and, therefore, represents approximately the lowest head in the entire Atlantic City region. The significance of these curves is discussed on pages 59 and 67.

Observations on Longport Well.—In the latter part of August, 1924, through the courtesy of the borough officials, an automatic water-level recorder was installed on a well belonging to the Borough of Longport. The well is located in the south end of the town near Four-

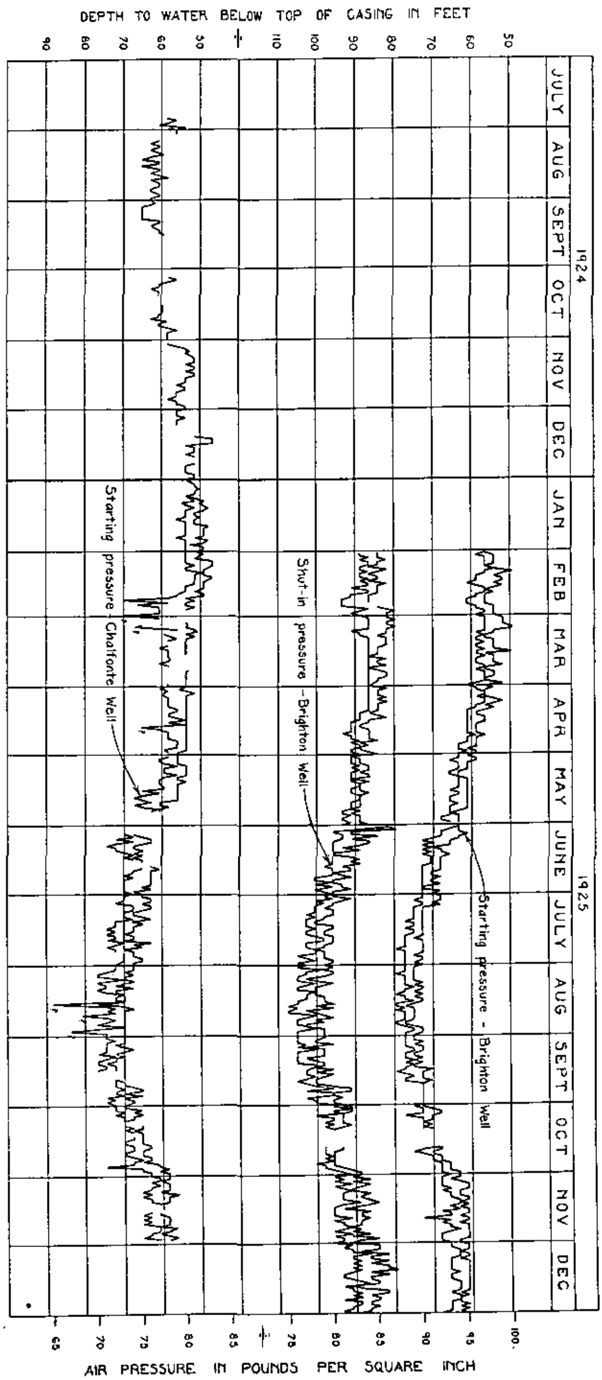


FIG. 12.—Graph showing highest and lowest starting and shut-in pressures on Brighton Hotel well and highest and lowest starting pressures on Chalfonte Hotel well, 1924-1925.

teenth Avenue, and is about a mile from the nearest pumping well at the borough water works at Thirty-first Avenue. The well is one of the oldest in the region, having been drilled in 1895. It had been pumped with a suction pump until the summer of 1924, when the water level dropped so low that suction could not be maintained, and the well was temporarily abandoned. A recorder has been maintained on the well continuously since the date stated, but because of trouble with the mechanism the record is incomplete for certain periods, especially prior to April 1, 1925.

The records from this well show a rise and fall twice each day. These fluctuations agree with the tide in several ways, and there is little doubt that they are directly due to the tide. The periods of rise and fall are practically that of the ocean tide. The amount of fluctuation is a little more than half that of the tide and ranges from about one to three feet, depending upon tide conditions. The daily fluctuation is greatest during spring tides and least during neap tides. Generally, every other low is lower and every other high higher than the alternate lows and highs, just as with the ocean tide. The record from this well shows many features of scientific interest which need not be described here.[14]

The charts show no evidence that the well is directly affected by pumping of the nearest wells. The record of the Longport well, therefore, is especially important. However, in order to determine as far as possible the extent of fluctuations not due to tides, it is necessary to eliminate the tidal fluctuations as far as possible. This has been accomplished partly by computing for each day the mean of the two high and two low levels. The results for 1924 and 1925 are shown graphically in Figure 13. Circles show the mean water level where the record is complete for only a single day, or prior to August 24, 1924, individual measurements with steel tape, corrected so far as possible for tide.

The water level shows many sharp ups and downs which are due principally to irregular fluctuations in the mean-tide level. This is readily shown by a comparison of it with the mean-tide level at the Steel Pier in Atlantic City, which is the average of the two high tides and two low tides recorded by the United States Coast and Geodetic Survey tide gage. The sharp peaks and trough of the two curves are found to coincide in a remarkable manner, although they do not always agree. The fluctuations in the mean-tide level, as is well

[14]Some of these features are discussed by Schureman, Paul, Tides in wells: Geographical Review, vol. 16, pp. 479-483, 1926; and Meinzer, O. E., Compressibility and elasticity of artesian aquifers: Economic Geology, vol. 23, pp. 273-276.

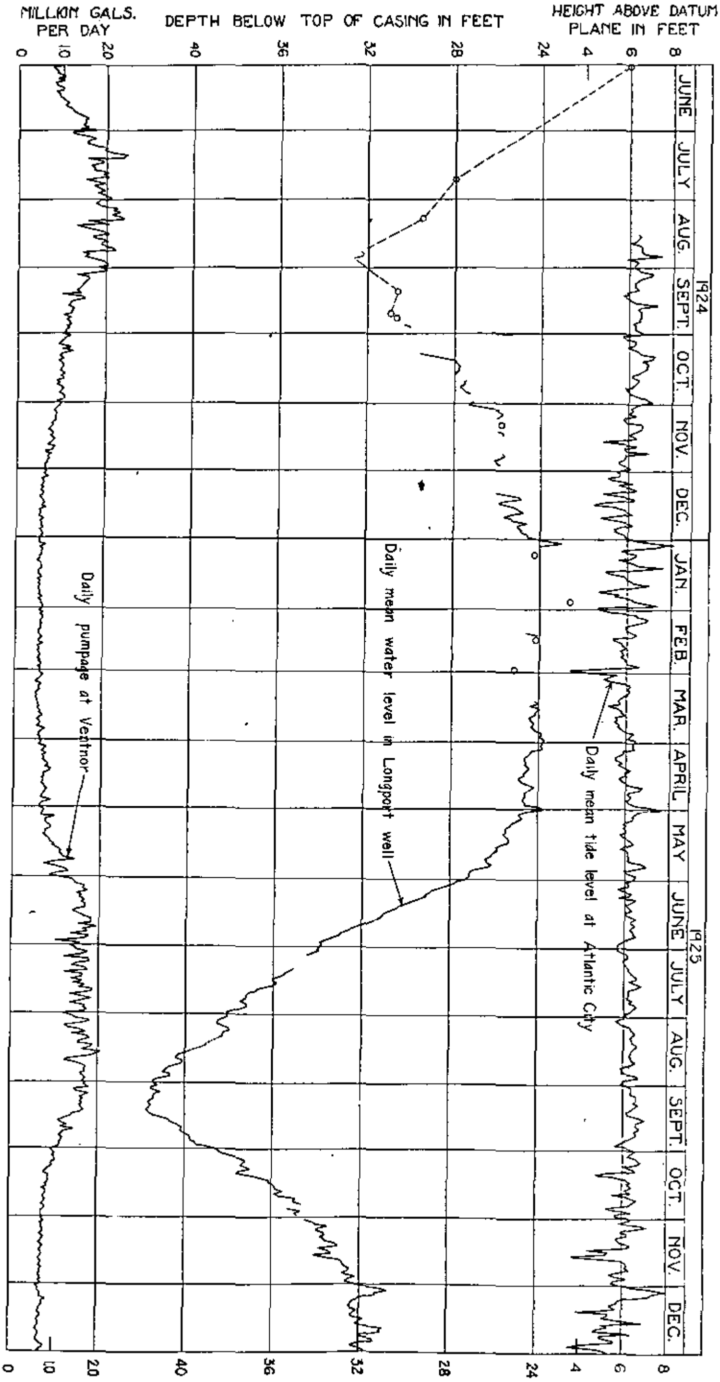


FIG. 13.—Graph showing daily mean water level in 14th Avenue well, Longport, mean tide level at Steel Pier, Atlantic City, and daily pumpage at Ventnor.

known, are due principally to weather conditions, easterly winds blowing water in and causing the mean-tide level to be higher and westerly winds having the opposite effect. The range of these irregularities in the well line is about .55 of that in the tide line. By the use of this ratio, and determining the departure of the tide line from the mean-tide level, it has been possible to eliminate a large part of the irregularity when shown in Figure 13, but certain minor irregularities still persist. The corrected line, with these minor irregularities eliminated, is shown as the second line on Figure 14.

Atlantic City Water Works 600-foot Well.—A water-level recorder has been maintained over a well about 600 feet deep at the Atlantic City Water Works on the mainland, which has shown the fluctuation of head on the 800-foot sand at that locality. The sand at that place lies about 600 feet below the surface, so that the well presumably only enters the top part of the sand. The well is about 650 feet from the 675-foot well at the water works that is pumped almost constantly. The curve shows minor fluctuations each day, mostly from less than an inch up to three or four inches, which are presumably due to the tide. The fluctuation of the water level day by day from March 26 to December 31, 1925, is shown graphically in Figure 17, and the generalized curve for March 26, 1924, to April 30, 1928, is shown on Figure 14.

SIGNIFICANCE OF SEASONAL FLUCTUATIONS OF HEAD.

In order to study the nature of the seasonal fluctuations in the head on the water in the 800-foot sand, the curves of the water level in the Longport well, the Atlantic City Water Works 600-foot well, and of the pumping level and non-pumping level in Atlantic City as determined from two hotel wells, for 1924 to 1927, inclusive, have been plotted together on the same diagram, Figure 14. For further comparison there is shown on the same diagram the pumpage from the 800-foot sand in the area between Brigantine and the southern end of Ocean City, including the Atlantic City Water Works well on the mainland, and the accumulated departure from normal precipitation in the southern interior section of New Jersey since January 1, 1924.

The pumpage is shown for three sections of the region separately, namely, for the well at the Atlantic City Water Works in Pleasantville, for the private wells in Atlantic City and a single well at Brigantine Beach, and for the public and private wells in the stretch from Ventnor to the southern end of Ocean City. The total for the whole area is also shown. The pumpage from the wells of public supplies is largely metered and daily records are kept for each supply, so that the data are rather accurate. The figures for pumpage from private wells

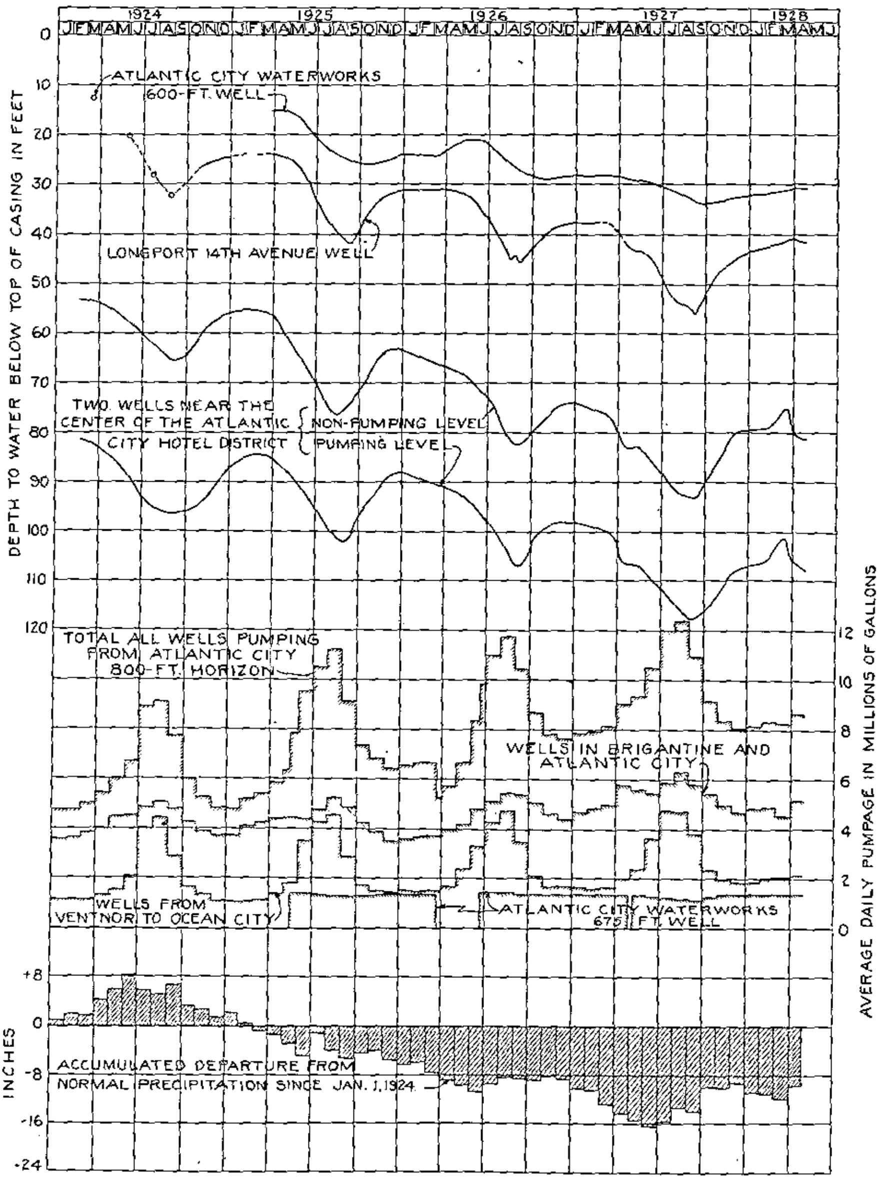


FIG. 14.—Diagram showing fluctuation of water level in, and pumpage from, wells tapping Atlantic City 800-foot sand in the area between Brigantine, Pleasantville and Ocean City, and accumulated departure from normal precipitation in southern interior section of New Jersey since January 1, 1924.

are to a large extent only estimates and much less accurate than those for the public supplies. Only one private supply is metered. Prior to July 1, 1926, daily records were available of the pumpage from one to four wells, and after that date such records were obtained from 15 to 18 of the private wells. With this information, and with some knowledge of the character of general fluctuations of use of water from the other wells, an estimate was made of the average daily consumption by months from each of the 28 private wells in Atlantic City and four private wells in Ocean City. For most of the wells it was not possible to measure the yield, and the assumed yield is generally that reported from a test at the time of completion or when the well was cleaned, in most cases several years prior to 1924. With the recession of the water level during the period elapsed since those tests were made the yields have presumably declined. Therefore, the estimated consumption from private wells is probably too high. Furthermore, since the water level is much lower in summer than in winter, the consumption in summer is probably relatively more in error in being too high. The departures from normal precipitation are based on records of the United States Weather Bureau for the so-called "southern interior section" of New Jersey.[15]

The curves of water-level movement in Figure 14 show two significant features. There is a very distinct seasonal fluctuation —a decrease in head in summer and an increase in winter— and there has been a progressive lowering of the head in successive years. The curves for the water levels in the observation wells in the three widely-separated localities—Atlantic City, Pleasantville and Longport—are very similar except for minor details. Observations on several other wells for shorter periods of a few weeks to a few months show similar trends. There is much evidence that the major seasonal fluctuations occur over a large area and that they are due to the same cause.

The most evident cause of the seasonal fluctuation on head, as well as of the permanent decrease in head from year to year, is changes in the rate of pumping. The decrease in head from winter to summer is concurrent with a considerable increase in pumpage from the wells in the region. Furthermore, there has been an increase in the average daily pumpage in each successive winter and summer. This is just what is to be expected from a consideration of the principles of hydraulic flow involved in the movement of underground water, for, as

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[15] U. S. Weather Bur. Climatological Data, New Jersey section, for years 1924 to 1927, inclusive. Certain errors in the published records have been corrected in Figure 14 in consultation with G. Harold Noyes, meteorologist in charge of New Jersey section.

has already been stated on page 39, the head on the water in a water-bearing sand decreases approximately as the rate of movement of the water increases.

In seeking other possible explanations as to the cause of the fluctuations of the static head on the 800-foot sand variations in the precipitation must be considered. Since the head on the formation in the Atlantic region is dependent largely upon the elevation to which the water fills the formation at its outcrop, a change in the elevation of the water table at the outcrop might produce a change in the head elsewhere in the formation. To consider the possible effect of changes in rainfall from month to month, comparison may be made with the monthly departures from the normal precipitation in the "southern interior section" of New Jersey, as shown in Figure 14.

The "southern interior section," as used by the Weather Bureau, includes all of the coastal plain section of New Jersey, which is that part of the State that lies south and east of a line drawn between Metuchen and Trenton; but it does not include the several stations directly on the coast, including Atlantic City. The records of the southern interior section have been used, rather than those of the coast section, because fluctuations in rainfall could produce a direct effect on the head in the 800-foot sand at Atlantic City only through changes in the water level in the outcrop area. Rainfall in the Atlantic City region cannot reach the 800-foot sand because the 300 feet or more of clay overlying the sand prevents percolation to it.

In Figure 14 positive departures from the normal precipitation, representing excessive precipitation, are plotted up, and negative departures, representing deficient precipitation, are plotted down from a line that represents the theoretical total normal precipitation since January 1, 1924. It is assumed that the precipitation conditions at that time were normal. Actually this may not have been true. The value of the diagram, however, lies in the fact that it shows the conditions at a given time in the period shown as compared to some other time. It shows that the precipitation was above normal in nearly every month from January 1, 1924, to July 1 of the same year. Thereafter, with some minor variations, the precipitation was notably below normal for two years, until July 1, 1926. During the next six months there was not much departure from normal, but from January 1 to July 1, 1927, it was notably below normal. In the last six months of 1927 the precipitation was sufficiently above normal to more than offset the deficiency in the first half of the year. In the whole period from January 1, 1924, to December 31, 1927, however, there was a net deficiency of about eight inches.

The trend of the curve for departure from normal precipitation, with a downward trend from June, 1924, reaching a maximum in June, 1927, suggests that the progressive decrease in the head on the 800-foot sand has been due to a deficiency in rainfall. However, a close examination of the data shown on Figure 14 leads the writer to conclude that, although it is entirely probable that some of the loss in head is due to deficient rainfall, the loss due to such condition is only a small part of the total loss in head.

If the head on the 800-foot sand fluctuated entirely in accord with the departures from precipitation the water level lines in Figure 14 should show a trend similar to that of the accumulated departure line. It is true that at certain times the direction of the lines is the same, but there are radical differences at critical times. For example, the water level dropped from February to August, in 1924, although there was an increasing excess in precipitation through June. Although there was an increasing deficiency of rainfall from October, 1924, to June, 1925, inclusive, except for a slight excess during January, the water level either arose or was approximately stationary at a high level through March. And despite a considerable excess of precipitation in July, 1925, the static head continued to drop through that month. Thereafter, there was an almost continuous progressive deficiency until June, 1926, but during part of this period the water level rose. The theory may be advanced that the high and low points in the water level curves do not coincide exactly with similar points in the precipitation curve because of a lag in the response of the ground-water head to the rainfall. If this were true, it is to be expected that the same lag would be evident after each marked departure from the normal condition. A study of the diagram shows very obviously that there is no such relation.

If the net decline in the water level from 1924 to 1927, 20 to 25 feet along the beach, is considered to be due to deficient precipitation, it is then a logical conclusion that the decline of 30 to 60 feet below the original static head between Longport and Atlantic City prior to 1924 must also have been due to the same cause. This decline has been more or less gradual throughout the period, but there is no evidence of a progressive deficiency in rainfall throughout the entire period.

If deficient rainfall has produced the loss of head in the Atlantic City region amounting to 20 to 25 feet, it seems that there should have been an equivalent lowering of head in the outcrop area. No data are available showing fluctuations in the water table in the outcrop area of the Kirkwood formation. However, if there had been any such great drop in the water level in wells in the outcrop area, as just stated, it seems certain that the fact would have received wide comment. There has been no indication of such a condition in southern New Jersey. As indicative of the probable effect on the water table, of the deficient rainfall in southern New Jersey, certain observations in the northern part of the coastal plane may be cited. Since August, 1923, records of the movement of the water level from a shallow well in the outcrop area of the Raritan formation near Runyon have been obtained by an automatic recorder, and some 20 wells in an area of about 25 square miles have been measured periodically about once a month. The depth of the wells range from about 5 feet to 50 feet, and they are located in a variety of topographic situations. Taking into consideration the geologic conditions, it is believed that the fluctuations of the water table in the Kirkwood outcrop area directly up the dip from Atlantic City will not be greatly different from those in the Runyon area. The water level in the wells in the Runyon area shows more or less response to precipitation, rising after rains and dropping during the intervals between rains. But in the summer months there is some departure from this rule for the water level drops more or less continually except after unusually heavy rains. In this respect the water table curve is somewhat similar to that of the head in the Atlantic City region. The summer drop in the shallow wells, however, is due principally to an increase in the evaporation over that of the colder months.

Although the water table in the wells in the Runyon region in summer shows a trend similar to that of the head in the Atlantic City region there is this difference. The maximum difference in the water level in different wells in the Runyon region between January, 1924, and January, 1926, was about 7.5 feet, and in most of the wells it was only two or three feet; whereas in the same period the difference in head in observation wells in the Atlantic City region was about 30 to 40 feet. The greatest difference in the low level of the summer of 1924 and that of 1925 in any of the Runyon area wells was only about four feet, and for most of the wells it was less than 2.5 feet—the water in 1925 being lower. In the wells in the Atlantic City region for the same period the difference was about 10 feet. Even if the fluctuation of the water table in the outcrop area of the Kirkwood formation were as great as the maximum fluctuation in the Runyon area the fluctuations of head on the 800-foot sand during the same period were so much greater that they cannot be attributed solely to fluctuations at the outcrop based on excesses or deficiencies in the precipitation. Each winter the water level in the Runyon wells has come back to practically the same level, and only in the different summer seasons has there been any great difference in the water level. The lowest level was reached in 1925, and the summer levels of 1926 and 1927 were considerably above that of 1925.

It is believed that a given fluctuation in the water table at the outcrop will not produce as great a fluctuation in the head in the Atlantic City region. For reasons given on page 113 it is believed that the 800-foot sand has a more or less free outlet beneath the ocean. This being the case, the static head at the outlet is practically constant, and a change in head at the outcrop will produce no noticeable change in the suboceanic outlet. At places between the outcrop and the outlet the change in head would bear a relation to the change at the outcrop somewhat in proportion to its distance from the two end points. Considering the greatest possible distance from the outcrop of the Kirkwood formation to its suboceanic outlet (see pages 30 and 113), it appears that the fluctuation in head at Atlantic City could be no more than two-thirds that occurring in the outcrop area. Assuming that the deficiency in precipitation may have caused some of the excess lowering of head, the data presented suggest that only two or three feet at the most, or not more than a third of the decline in 1924-1925 could have been due directly to this cause. It may be pointed out, in this connection, that if a deficiency of rainfall of only about eight inches—the net deficiency from January 1, 1924, to December 31, 1927—has been sufficient to cause a loss of head of 20 to 25 feet in the Atlantic City region, the recharge capacity of the intake area of the 800-foot sand must be extremely limited. If this is true, with future increases in consumption the head may be expected to decline at an increasingly rapid rate, and there is no possibility of developing additional supplies without causing an overdraft on the formation.

The close agreement between the major fluctuations of the head on the 800-foot sand and of the pumpage from the sand has already been pointed out. That the head over a large area is affected by local changes in the draft is shown by certain details of the curves. The fluctuation of the water level in observation wells in Atlantic City has been greater than in the area between Ventnor and Ocean City, but the fluctuation in pumpage has been much less. It appears, therefore, that some of the very considerable increase in pumpage in summer in the Ventnor-Ocean City area is responsible for some of the loss of head in Atlantic City. This is consistent with the principles of hydraulics that govern the flow of ground water, for an increase in flow to the wells in the Ventnor-Ocean City area would lower the head between Atlantic City and Ventnor. This would decrease the gradient toward wells in Atlantic City and reduce the yield of the wells. To maintain the gradient necessary to produce a given flow to the Atlantic City wells a still further lowering of head would be necessary.

The pumpage from the 675-foot well at the Atlantic City Water Works has been nearly constant, but it has been slightly lower in successive summers as a result of a decrease in the rate of yield. (See Figs. 14 and 18, and pages 86 and 87.) In spite of the fact that less water was pumped each year, there has been a loss of head in the 600-foot observation well amounting to about eight feet between September, 1925, and September, 1927. This is attributed to the increase in pumpage in Atlantic City or the Ventnor-Ocean City area. There was an even greater decline in head, about 10 feet, between May 1 and September 1, 1925, but a large part of this is believed to be due to the fact that the 675-foot well was first put into operation about May 22, and there was a lag of several weeks before a stable pumping condition was reached. That such a lag probably occurred is shown by the following conditions. On March 22, 1926, the 675-foot well was shut down and was not started again until about May 15, when it was operated for one day. Thereafter, it was not operated until the latter part of June. From the time the well was shut off in March the water rose steadily until the middle of May. During this period the pumpage in the Ventnor-Ocean City area was practically uniform and in Atlantic City it increased slightly. Therefore, the rise in the 600-foot well cannot be attributed to changing conditions elsewhere, but must have resulted from a lag in adjustment to stable conditions after the 675-foot well was shut down. There is other evidence of a lag in adjustment to changes in pumping conditions. For example, the highest or lowest level in the seasonal movement of water level in the several observation wells generally is not reached until some days after the corresponding points in consumption. The explanation of this phenomenon is suggested on page 84.

In August, 1927, the average daily consumption from wells in the area between Ventnor and Ocean City was less than it was the preceding month. In spite of this fact the water level in the Longport well continued to drop throughout the month and reached its low point after September 1. Alternative explanations of this condition are either that there was considerable lag in the movement of the water level after the maximum pumpage was reached, or else the increase in pumpage from wells in Atlantic City during August was effective in lowering the head as far away as Longport. A third possibility is that on certain days in August, especially near the end of the month, pumpage may have reached a maximum for the season, and this was sufficient to cause a continual lowering of head, even though on other days the pumpage may have been so low—because of rain or cool weather—to make the average for the entire month less than that of August.

In the latter part of March and during April, 1927, there was a rather sharp drop in the head in the wells in Atlantic City and the Longport well. This, apparently, was due to a considerable increase in pumpage in Atlantic City. Most of the increase was from a single well, which was put into service with a yield of about 700,000 gallons a day. It is noteworthy that the head declined in the Longport well about as much as in the Atlantic City wells, although the increase in pumpage in the Ventnor-Ocean City region was not nearly as great as in Atlantic City. On the other hand, in May, 1927, the curves for the wells in both regions became flatter. This evidently was due to a reduction in pumpage from certain wells in Atlantic City. The pumpage in the Ventnor-Ocean City area increased more in May than in April, and yet the increase was not sufficient to offset the effect of the decrease in pumpage in Atlantic City. In the latter part of February and early part of March, 1928, there was a sudden rise of about five feet in the water level in the wells in Atlantic City. This apparently was due to the fact that between February 7 and March 17 the well previously referred to, which usually was pumped at a rate of about 700,000 gallons a day, was shut down. The decrease in pumpage was reflected by a slight rise in the water level in the Longport well. It is noteworthy that the rise of the water level in the Atlantic City wells was about the same as the drop in the same wells in March and April, 1927, when the same well was started.

It is apparent from the facts just cited that the pumpage from the 800-foot sand in any one section of the Atlantic City region produces changes in the head on the water in the sand. When the change in pumpage is considerable, the charge in head may be sufficient to be noticed over a large area. However, since the water level in the 600-foot well at the Atlantic City Water Works did not show as great changes in head as in the other parts of the region, it appears that the local distribution of draft may have some influence in determining the extent to which the effect of pumping is felt in different directions. The evidence as a whole indicates, however, that changes in pumpage, and not fluctuations in precipitation, are the principal cause of changes in the head on the water.

REGIONAL EFFECTS OF PUMPING.

Original static head.—In order to appreciate the significance of the present conditions of the static head on the water in the Atlantic City 800-foot horizon it is necessary to know what the original static head was before pumping was begun in the region.

The first wells, two in number, that are definitely known to have drawn from the 800-foot horizon were drilled in 1893.[16] No information is available as to the head in the one of these drilled at Atlantic City. In the other, at Ocean City, the water rose in the casing 15 feet above the surface. No data as to the static head are available for the single well drilled to the 800-foot horizon in Atlantic City in 1894. It is reported that this well "flowed" seven feet above the surface at the rate of 40 gallons a minute.[17] This probably means that the top of the casing was seven feet above the surface and not that a stream spouted seven feet into the air. If the water were confined in a pipe it would have risen several feet higher. Mr. Scott Price has informed the writer that the head on a well drilled at Brigantine in 1895 was so great that the water rose into a tank 14 feet above the surface at the old railroad station. In a well at Longport, completed in the same year, the water rose 14 feet above the ground, which is reported to have been about two feet above high tide (probably at least five feet above mean sea level).[18] In the following year the water in a well drilled to the 800-foot horizon at Sea Isle City rose 14 feet above the surface.[19] In the published reports the statement that the water rose to a certain height above the surface appears to mean that it rose and stood at the elevation given in a pipe that extended still higher, so that there was no flow. The figures given, therefore, represent the true static head. In all of these wells, for which definite information is given, the original head was 14 or 15 feet above the surface. If the ground level was only five feet above mean sea level the head was fully 20 feet above sea level. The surface elevation may have been a few feet higher, but probably no more than 10 feet above sea level. The wells mentioned are scattered at intervals along a stretch of coast of about 25 miles and at the completion of drilling were not near any pumping wells. It is therefore reasonable to believe that the original static head on the 800-foot sand in the Atlantic City region was between 20 feet and 25 feet above mean sea

[16]Annual report of the State Geologist for 1893, pp. 397-399.
[17]Annual report of the State Geologist for 1894, p. 180.
[18]Annual report of the State Geologist for 1895, pp. 83-84.
[19]Annual report of the State Geologist for 1896, pp. 175-176.

level. As a result of the rapid development of the horizon in the next few years the head decreased over the entire area so that data from later wells are not indicative of the true head.

No data are available as to the original head on the 800-foot sand on the mainland in the vicinity of Absecon and Pleasantville. Prior to 1924 only one well was drilled to the Atlantic City 800-foot horizon on the mainland, that being completed in 1899 at the Atlantic County Hospital at Smith's Landing.[20] The water rose in the well to within 17 feet of the surface, the elevation of which is reported to be 30 feet. The static level was therefore about 13 feet above sea level. This is not as high as reported at the beach wells originally, but it may be due in part to an error in reporting the altitude which is doubtless only approximate, and in part to the fact that pumping had been going on in the region for several years and the head on the formation had been lowered considerably in Atlantic City. For example, the water in wells drilled at Atlantic City and Sea Isle City in 1899 barely rose to the surface, showing a loss of head of about 15 feet.[21] Conceivably, there may have been likewise some lowering of the head on the mainland by this time.

Since the head on the formation is due to the greater elevation of the formation at its intake many miles west of the coast, the original head ought to have been greater and greater at points farther and farther west. Therefore, the head on the mainland must have been fully as great and even a little greater than in the beach wells. In wells at Egg Harbor, which are believed to have reached the horizon, the water stood within a foot or two of the surface in 1897. The elevation of the wells is reported as 50 feet above sea level, but from the topographic map it is estimated to be only about 35 feet above sea level. At Hammonton, at a surface elevation of 120 feet, in 1902 the head in a horizon that is believed to be the same as the 800-foot sand was about 30 feet below the surface or about 90 feet above sea level. At Winslow Junction the water level stood about 86 feet above sea level in 1916.

On the basis of the data given above, the gradient of the head appears to have been about five feet per mile between Hammonton and Egg Harbor City, but only about one foot per mile between Egg Harbor and Atlantic City. It must not be supposed that there was a sudden change in the gradient at Egg Harbor City, but this apparent change is due only to the fact that data are available at the points mentioned. Doubtless there was a gradual change over a considerable area. The original head near the coast possibly was affected by rela-

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[20]Annual report of the State Geologist for 1899, pp. 104-105.
[21]Idem, pp. 106-109.

tions between salt and fresh water in the horizon off shore as shown on page 115 in the discussions of salt-water problems. These statements in this paragraph are based on the assumption that the data given for places on the mainland represent the original head. It will be noted, however, that they show conditions at different dates, all of which are some years later than the date when pumping of the 800-foot sand had begun. It is possible that the head at Egg Harbor City in 1897 had been reduced as a result of pumping in Atlantic City, and this might account for the apparent difference in gradient northwest of Egg Harbor City and southeast thereof. However, unless the 800-foot sand is a very poor water-bearing sand, it hardly seems possible that the pumpage in Atlantic City in 1897, doubtless much less than at present, would cause any great lowering of head some 18 miles from the city.

Present conditions.—Bearing in mind the results of the observations described in the previous pages consideration may now be given to the effects of pumping throughout the entire region.

On the basis of the data that were collected in 1924 a profile was drawn showing the piezometric surface from Brigantine Beach southwestward to Corson's Inlet. This is reproduced in Figure 15, A. This line shows the static water level in existing wells, and between them it shows approximately the level to which the water would rise if wells were drilled.

Necessarily the profile is only approximate. As shown by the observations at several points the so-called static level, even several hours after a well has stopped pumping, is slowly rising or falling, and the difference from day to day or week to week may be several feet. It was not possible to get observations on some of the wells during the late summer when the head was lowest, and the only available measurements were on dates considerably earlier or later. In order to make these comparable to late summer measurements some allowance was made for the change in water level during the intervening intervals in accordance with observations on other wells. Observations in 1928 showed that the profile then had much the same outline, but throughout its length it was from a few feet to 20 feet further below sea level in different places.

There is no means of determining just what the head is at localities some distance from pumping wells. Doubtless the water level immediately surrounding wells that are pumped frequently is not quite as high as some distance from them—that is, the cone of depression of the head is perhaps never completely eliminated before the well is started again. However, after a study of the data obtained in several

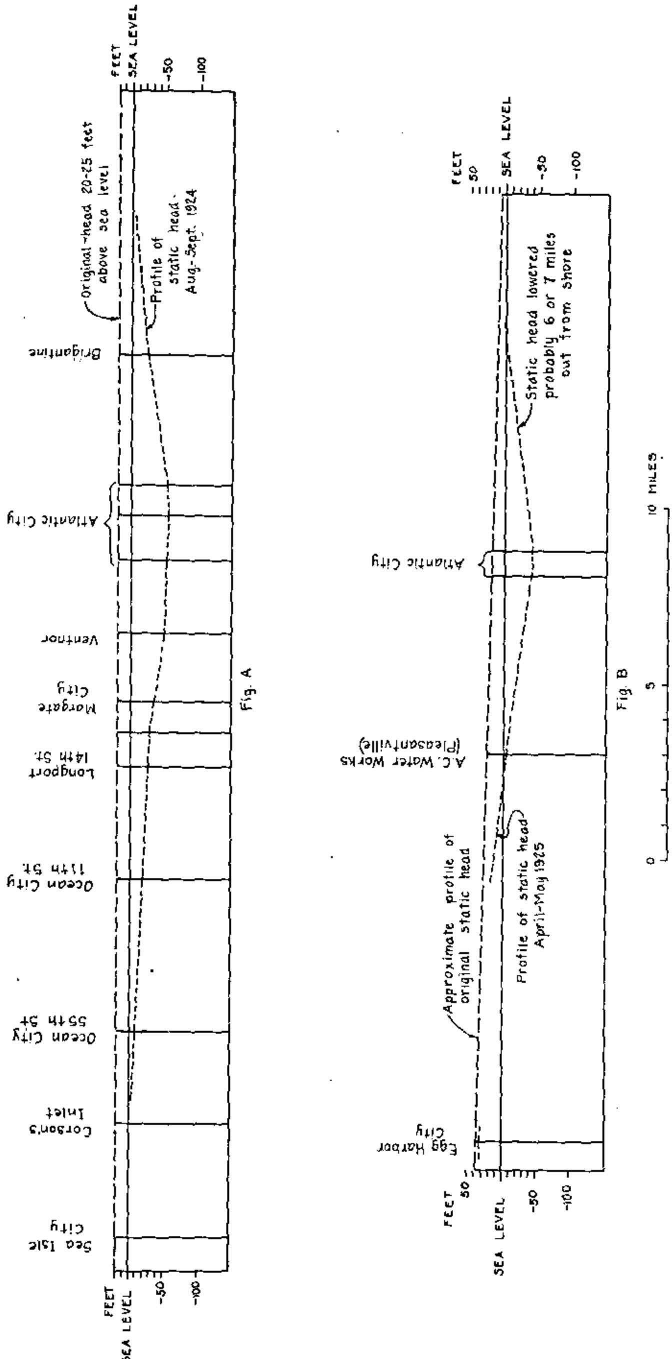


FIG. 15.—Profiles of piezometric surface of 800-foot horizon in the Atlantic City region. *A*.—Profile parallel to coast. *B*.—Profile at right angles to coast.

tests, it is the belief of the writer that the difference in the static level at points midway between two observation wells, for example, is not very different from the average of the head in the two wells. This, of course, depends upon conditions in each locality. Confirmation of this opinion was obtained in 1925 when a well was drilled at the Atlantic City High School, and the depth to water was found to be about as would be expected from the profile, allowing for the diffenence in water level in the entire region between 1924 and 1925.

Figure 15, A, shows that since the first wells were drilled the static head has been lowered more or less over a very large area. The greatest lowering has been in Atlantic City, where, as shown by the table on page 21, the pumping is heaviest. The following data give some idea as to the extent of this decrease in head.

The lowest static observed in the present investigation was about 90 feet below the top of the casing or 80 feet below mean sea level in wells in Atlantic City. Northeast of Atlantic City the only well known definitely to reach the Atlantic City 800-foot horizon is at Brigantine. Measurements on an old well made for the writer in August, 1924, through the courtesy of Mr. H. I. Eaton, engineer for the Island Development Co., showed a depth to water of about 28 feet below the top of the casing. In April, 1925, the depth to water in a new well was 26 feet below the top of the casing or about 16 feet below sea level. Presumably during the summer the water level was several feet lower. The profile northeast of the Brigantine well is necessarily hypothetical, being drawn mainly by connecting the levels in that well with the level in the Royal Palace well. Actually the piezometric surface probably is not a straight line, but rises in a curve, the slope of which becomes more gradual at points farther and farther from the area of heavy pumping. Therefore, the slope of the profile is probably not as steep as shown, and the area of influence extends farther northeast than shown.

The following rather meager data relate to the water level in wells along the coast southwest of the Fifty-fifth Street well in Ocean City. Mr. Warren Smith, Superintendent of the Ocean City Water Co., and also in charge of the Corson's Inlet Water Co., states that the well at Corson's Inlet flowed until the summer of 1924, when it became necessary to use a pump. The static water level doubtless was only a few feet below the surface. Further south, at Sea Isle City, the water level in two wells drawing on the 800-foot sand was 7.5 feet below the surface on November 7, 1925, and it was at about the same depth in wells at Avalon in October of the same year. A. H. Van de

Pol, Superintendent of the Stone Harbor Water Department, reports a measurement of 32 feet to water below the top of the casing in August, 1925. The reference point is six to eight feet above the general land surface, and probably at least 12 to 15 feet above sea level, so the corrected depth was between 15 and 20 feet below mean sea level. On March 5, 1926, it was 12 feet below the top of the casing and probably about at mean sea level. In a well at Pine and Holly Beach Avenues, in Wildwood, the depth to water in the fall of 1924 is reported to have been 10 feet below the surface. When the well was completed in 1894 the water rose seven feet above the surface,[22] or to an elevation of about 15 feet above "tide level." In the fall of 1925 the water stood at the surface, or not more than 8 or 10 feet above sea level, in a new well drilled to the Atlantic City 800-foot sand in Wildwood Crest, about two miles farther southwest. On April 25, 1928, the water level in this well was four feet below the surface.

The observations show that the head on the 800-foot sand has declined wherever wells have been pumped. The minimum decline, at Wildwood, has been some 10 or 15 feet considering the winter level, and probably at least 10 feet greater in summer. The greatest depression has occurred between Atlantic City and Ocean City. There is little doubt that this is due to heavy pumping in this area. Whether the effect of pumping of the wells in Atlantic City alone would cause the depression to extend as far as Wildwood is uncertain. However, pumping in the city doubtless has an indirect effect in that it causes the depression to be so extensive. In winter the Wildwood wells are not pumped and the consumption from the wells south of Ocean City is very small. It therefore seems likely that some of the depression even so far southeast as Wildwood is due to pumpage farther northeast. The hydraulic profile apparently arises more rapidly from Atlantic City northeastward than it does southwestward. This is to be expected, since pumping at each well field southwest from the city lowers the head a little more than if there were no pumping there, whereas in the opposite direction there has been no pumping.

Until a well was drilled to the Atlantic City 800-foot water-bearing horizon at the Atlantic City Water Works in Pleasantville, in April, 1925, no data were available as to the extent of the lowering of the static head in that direction. When that well was completed the water stood 9.5 feet below the top of the casing or 3.9 feet below mean sea level referred to a datum used by the city water department. It

[22] Annual report of State Geologist for 1894, p. 159. In one place it is stated that water flowed "seven feet above the surface," and in another that "the water flows over the surface, and will rise above it seven feet."

has not yet been possible to correlate this datum with the United States Coast and Geodetic Survey datum at the Absecon lighthouse, but there is probably not much difference between the two. The fluctuation of the water level in this well, as obtained by the automatic recorder, is shown on Figure 14.

In Figure 15, B, an attempt has been made to determine graphically the extent of the area in which the head in the Atlantic iCty water horizon has been depressed at right angles to the coast. The profile of the piezometric surface as it was in April and May, 1925, has been drawn as a practically straight line from a well on the west side of Atlantic City through the Atlantic City Water Works well. Actually, the curve doubtless becomes flatter at points farther and farther from the city, so that the area of depression probably extends somewhat farther than shown. As shown by Figure 15, B, the head has been lowered somewhat below its original position at least some 10 miles inland.

There seems to be no reason why the head should not be depressed for some distance beneath the sea, just as it is inland. The distance to which the area of depression will extend seaward probably will not be as great as in the opposite direction, because the original piezometric surface sloped seaward. However, as indicated in Figure 15, B, it seems likely that the area of depression extends at least six or seven miles out beneath the ocean.

Rate of lowering of static head.—Information in regard to the rate of lowering of the static head in the past is obtained partly from the annual reports of the State Geologist and partly from data obtained in the present investigation. The information available must be considered in the light of the observations described on pages 42 and 59, which show that the measurements on the static level may differ by as much as 10 to 20 feet at different times in the year, and in different wells by several feet, even at the same time, depending upon whether the observation well is near or far from pumping wells.

As shown in the discussion on page 68, the original static head on the Atlantic City 800-foot horizon was sufficient to cause the water to rise at least 14 or 15 feet above the surface or between 20 and 25 feet above mean sea level. It evidently began to decrease soon after the first wells were drilled in 1893. In 1895 the water in a well at the old Atlantic City Cooling Co.'s plant rose only 9.5 feet above the surface, whereas in the same year at Brigantine, some distance from the area of pumping, it rose 14 feet.[23] In 1896 the water level at Haddon Hall rose six feet above the surface. By 1899 the head

[23]Annual report of the State Geologist for 1895, p. 82, and information furnished by Mr. Scott Price.

had dropped so that the water barely rose to the surface in three wells in different parts of the city.[24] By this time the head seems to have been reduced over a large area. A new well at Ocean City overflowed, but in one at Sea Isle City the water rose only to within one foot of the surface.[25] In 1901 the static level on the 800-foot horizon in Young's Ocean Pier well is reported as about 10 feet above tide level. After 1901 few records of value have been published.

The trend of the decline in head is well shown by the following data. Mr. Scott Price, formerly chief engineer of Haddon Hall, states that when the first well was drilled at that hotel in 1896 the water rose about six feet above the surface. The well was pumped entirely by a suction pump. At times during the summer of 1901 the water level fell to 30 feet when pumping 250 gallons a minute. In June, 1904, it was necessary to install an air lift for pumping when the water level was low in the summer. The suction pump, however, was used in winter until January, 1909, when the water level had dropped so low that it could no longer be used. Further data are not available for Haddon Hall until 1924, but in 1913 the depth to water in a new well at the Chalfonte Hotel, across the street, was 39 feet. In February, 1923, the writer obtained a measurement on the Chalfonte well of about 50 feet to water. During the year from July, 1924, to February, 1925, inclusive, the highest water level in the Chalfonte well during periods of rest at different times of the year ranged from about 45 to 65 feet below the surface. (See pages 54 and 55 and Fig. 12.) In the late summer of 1925 it dropped to 76 feet, or 11 feet lower than at any time during the previous summer. Observations are not available for 1926 and 1927, but by comparison with the movement of the water level in the well at another hotel in the summer of 1927 the water was probably about 90 feet below the surface.

The history of pumping in other parts of the region has been somewhat similar, except that different stages were reached at earlier or later dates, according as to whether there was much pumping in the vicinity. For example, at Longport the water level rose 14 feet above the surface when the first well was drilled in 1895. When another well was drilled in 1911 the water rose to within a few feet of the surface. It was possible to use direct suction pumps on both of these wells until 1924, when the water level fell below the limit of suction. As late as March, 1926, the water level was still within the limit of suction lifts at points from Corson's Inlet southwestward. However,

24Annual report of the State Geologist for 1899, p. 102.
25Idem, p. 109.

in the summer of 1925 at Stone Harbor, where the consumption is greater, it would probably have been impossible to use suction pumps.

The rate of lowering of the water level in wells at Haddon Hall and Chalfonte Hotel, and the well at Longport from 1893 to April, 1928, is shown graphically in Figure 16. The exact trend between the few scattered dates prior to 1924 is uncertain, but it seems certain that the head has dropped much more rapidly since that date than before it.

PROBABLE FUTURE LOSS OF HEAD.

The history of pumping in the region shows that there has been a more or less continual lowering of the water level, but it does not show whether it has been at a uniform rate from year to year, or whether it has been greater in some years than in others. From a study of the available data it appears that if the curve of lowering were definitely known it would be somewhat irregular, but in general it would show the water to have gone down in accordance with increase in consumption. In years when the increase was great the lowering doubtless was more rapid than in other years. In other words, the water level in the whole region appears to fluctuate with changes in the pumpage from the formation, much in the same way that the pumping level in a well fluctuates with the rate of pumping. If this theory is correct, a further lowering of the head on the horizon may be expected whenever there is an increase in the pumpage. If there is any definite mathematical relation between the rate of pumpage and the regional static head, it may be possible to determine rather closely the effect of a given increase in the pumpage. In an effort to determine whether any such exists the following analysis may be made.

If all of the water drawn from the 800-foot sand were pumped from a single large well it is probable that the head would fluctuate essentially directly with changes in the rate of pumping. A consideration of the principles of hydraulics involved leads to the belief that, if changes in pumpage were distributed equally among all wells, in a given observation well the head would vary practically directly as the rate of pumping. This condition does not hold in the Atlantic City region. For example, in the Ventnor-Ocean City area the consumption in summer is from 3 to 3.5 million gallons more than the consumption in winter, whereas in the Atlantic City-Brigantine area it is only from 1.5 to 2 million gallons a day more. Also, from time to time, a sudden draft is begun in a single locality when a new well

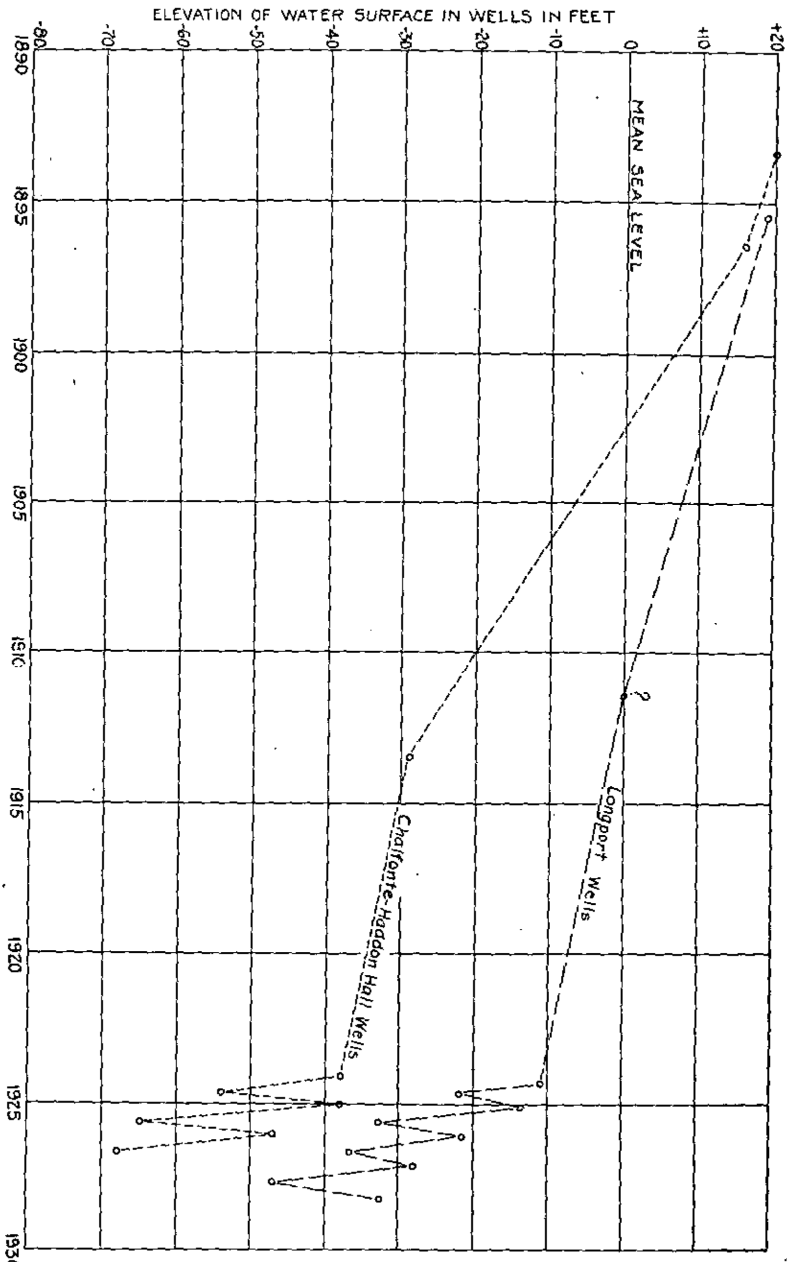


FIG. 16.—Graph showing rate of lowering of static water level in wells at Haddon Hall and Chalfonte Hotel and at Longport, 1893 to 1928.

is put into service. For these reasons it is impossible to determine accurately any exact relation between changes in pumpage and changes in head in the region. Nevertheless, certain relations have been discovered which may be of value in determining the effects of future increases in pumpage.

For each month for which data are available there has been calculated the ratio between the depth to water below the original static level in the Longport observation well and the rate of pumping in the entire region and in the Ventnor-Ocean City area. Similarly, there has been computed the ratio between the depth to water below the original static head, when pumping, in observation wells in Atlantic City, and the rate of pumping both in the entire region and in the more restricted Atlantic City-Brigantine area. The data in regard to water level are based on the composite curve of the pumping level for wells in Atlantic City shown in Figure 14. The values for the depth to water used in the computations is that at the end of each month. A different value might have been used by taking the average between the level at the beginning and end of the month. This would have given different actual values, but the relative results would have been essentially the same. The depth to water at the end of each month has been used, because if there is any lag in adjustment of water level to pumping conditions—and there is good evidence of this—the water level at that time is more nearly in adjustment than earlier in the month. The base data and resulting calculations are given in the accompanying tables. To simplify the headings algebraic notation has been used, and the symbols are explained in footnotes appended to the tables.

RELATION BETWEEN DEPTH TO WATER, BELOW ORIGINAL STATIC LEVEL, IN LONGPORT OBSERVATION WELL, AND AVERAGE DAILY PUMPAGE FROM 800-FOOT SAND IN ENTIRE ATLANTIC CITY REGION AND VENTNOR-OCEAN CITY REGION, 1924-1927.

MONTH	aD_1	bQ_1	c$\frac{D_1}{Q_1}$	dQ_2	e$\frac{D_1}{Q_2}$
1924					
May	30.0	6.058	5.0	1.556	19.3
June	35.0	6.702	5.2	2.136	16.4
July	39.5	8.906	4.4	4.027	9.8
August	42.0	9.593	4.4	4.474	9.4
September	39.5	7.746	5.1	2.925	13.5
October	36.5	6.058	6.0	1.728	21.1
November	35.0	5.309	6.6	1.394	25.1
December	34.5	4.869	7.1	1.107	31.2

RELATION BETWEEN DEPTH TO WATER AND AVERAGE DAILY PUMPAGE—*Continued.*

MONTH	aD₁	bQ₁	$\frac{cD_1}{Q_1}$	dQ₂	$\frac{eD_1}{Q_2}$
1925					
January	34.0	4.817	7.1	1.077	31.6
February	34.0	5.193	6.5	1.086	31.3
March	34.0	5.446	6.2	1.133	31.3
April	35.0	5.865	6.0	1.398	25.0
May	37.0	7.201	5.1	1.849	20.0
June	43.5	9.529	4.6	3.612	12.0
July	48.0	10.509	4.6	4.323	11.1
August	51.5	11.293	4.6	4.582	11.2
September	49.0	9.167	5.3	2.903	16.9
October	44.0	7.386	6.0	1.760	25.0
November	42.0	6.801	6.2	1.485	28.3
December	41.5	6.421	6.5	1.485	27.9
1926					
January	41.0	6.561	6.2	1.528	26.8
February	41.0	6.636	6.2	1.468	27.9
March	41.0	6.692	6.1	1.495	27.4
April	42.0	5.729	7.3	1.699	24.7
May	43.5	6.654	6.5	2.436	17.9
June	47.5	9.777	4.9	3.392	14.0
July	52.5	10.958	4.8	4.302	12.2
August	55.5	11.754	4.7	4.787	11.6
September	52.5	10.415	5.0	3.566	14.8
October	49.5	8.681	5.7	2.156	23.0
November	48.0	7.826	6.1	1.751	27.4
December	47.5	7.592	6.3	1.728	27.5
1927					
January	47.0	7.829	6.0	1.710	27.5
February	47.0	7.907	5.9	1.623	29.0
March	48.0	8.120	5.9	1.691	28.4
April	53.0	9.046	5.9	1.917	27.6
May	54.0	9.375	5.8	2.453	22.0
June	59.5	10.510	5.7	3.676	16.2
July	63.5	12.014	5.3	4.796	13.2
August	65.5	12.412	5.3	4.775	13.7
September	62.5	10.950	5.7	3.846	16.3
October	57.5	9.192	6.3	2.394	24.0
November	55.5	8.392	6.6	2.036	27.3
December	53.5	8.081	6.6	1.917	27.9

aD₁=Depth to water, in feet, below estimated original static level in Longport observation well. This is depth to water below top of casing plus five feet.

bQ₁=Average daily pumpage from 800-foot sand, in million gallons a day, in entire Atlantic City region (not including area from Corson Inlet to Wildwood).

$\frac{cD_1}{Q_1}$=Loss of head, in Longport well, for a pumpage of one million gallons a day, assuming loss to be due to pumping in the entire region.

dQ₂=Pumpage in area from Ventnor to Ocean City, inclusive.

$\frac{eD_1}{Q_2}$=Loss of head in Longport well for pumpage of one million gallons a day, assuming loss to be due to pumpage from Ventnor-Ocean City area only.

RELATION BETWEEN DEPTH TO WATER, WHEN NOT PUMPING, BELOW ORIGINAL STATIC HEAD, IN OBSERVATION WELLS IN ATLANTIC CITY AND AVERAGE DAILY PUMPAGE FROM 800-FOOT SAND IN ENTIRE REGION AND IN BRIGANTINE-ATLANTIC CITY REGION, 1924-1927.

MONTH	[a]D_2	[b]Q_1	[c]$\frac{D_2}{Q_1}$	[d]Q_3	[e]$\frac{D_2}{Q_3}$
1924					
January	....	4.772	....	3.593	....
February	59.0	4.823	12.2	3.618	16.3
March	59.5	5.012	11.9	3.863	15.4
April	61.0	5.417	11.3	4.058	15.0
May	63.5	6.058	10.5	4.502	14.1
June	66.0	6.702	9.8	4.566	14.5
July	68.5	8.906	7.7	4.879	14.0
August	71.0	9.593	7.4	5.141	13.9
September	70.0	7.746	7.3	4.821	14.5
October	66.0	6.058	10.9	4.330	15.2
November	63.0	5.309	11.9	3.915	16.1
December	61.5	4.869	12.6	3.762	16.3
1925					
January	61.0	4.817	12.7	3.740	16.3
February	61.0	5.193	11.7	4.121	14.8
March	62.5	5.446	11.5	4.313	14.5
April	67.0	5.865	11.4	4.467	15.0
May	71.5	7.201	9.9	4.502	15.9
June	76.0	9.529	8.0	4.482	17.0
July	80.5	10.509	7.7	4.806	16.7
August	81.0	11.293	7.2	5.315	15.2
September	77.5	9.167	8.5	4.914	15.8
October	72.5	7.386	9.8	4.276	17.0
November	69.0	6.801	10.1	3.931	17.6
December	69.0	6.421	10.7	3.576	19.3
1926					
January	70.0	6.561	10.7	3.663	19.1
February	71.0	6.636	10.7	3.759	18.9
March	72.5	6.692	10.8	3.797	19.1
April	73.5	5.729	12.8	4.030	18.2
May	76.0	6.654	11.4	4.218	18.0
June	79.0	9.777	8.1	4.885	16.2
July	84.5	10.958	7.7	5.165	16.4
August	88.0	11.754	7.5	5.513	16.0
September	86.0	10.415	8.3	5.439	15.8
October	82.5	8.681	9.5	5.105	16.2
November	80.0	7.826	10.2	4.655	17.2
December	80.0	7.592	10.5	4.444	18.0
1927					
January	81.5	7.829	10.4	4.709	17.3
February	82.0	7.907	10.4	4.876	16.6
March	88.0	8.120	10.8	5.029	17.5
April	90.0	9.046	9.9	5.819	15.5
May	90.5	9.375	9.7	5.612	16.1
June	94.0	10.510	8.9	5.534	17.0
July	98.0	12.014	8.2	5.918	16.6
August	99 5	12.412	8.0	6.385	15.6
September	96.0	10.950	8.8	5.904	16.3
October	91.0	9.192	9.9	5.498	16.6
November	86.0	8.392	10.2	4.956	17.4
December	85.5	8.081	10.6	4.764	17.9

RELATION BETWEEN DEPTH TO WATER AND AVERAGE DAILY PUMPAGE—*Continued.*

[a] D_2=Depth to water not when pumping, in feet below estimated original static level, in observation wells in Atlantic City. This is depth to water below top of casing plus 10 feet.

[b] Q_1=Average daily pumpage from 800-foot sand in million gallons a day in entire Atlantic City region (not including area from Corson Inlet to Wildwood).

[c] $\frac{D_2}{Q_1}$=Loss of head in wells in Atlantic City for a pumpage of one million gallons a day assuming loss to be due to pumping in the entire region.

[d] Q_3=Average daily pumpage from 800-foot sand in million gallons a day, from wells in Atlantic City and Brigantine only.

[e] $\frac{D_2}{Q_3}$=Loss of head in wells in Atlantic City for pumpage of one million gallons a day from Atlantic City-Brigantine area only.

The ratio of the rate of pumping divided by the depth to water below original static level $\left(\frac{Q}{D}\right)$ is in a way comparable to the specific capacity of a well, for it is the quantity of water obtained by lowering the head one foot. Of course, since the water is not all coming from the observation well—and none of it is obtained from the Longport well—the comparison is only a general one.

The ratio would have a maximum value if all the water came from one well—that is, if the ratio actually were the specific capacity. It would have a very small value if the observation well in which the head were determined were situated at a very great distance from the pumping wells. Obviously, the value of the ratio will depend in part on the situation of the observation well with respect to the centers of pumping. The ratio of the depth to water divided by the rate of pumping gives the number of feet that the water must be lowered to produce one million gallons a day. It would have a maximum value if the water were all pumped from a single well and the loss in head were measured in that well; and its value would be very small when based on loss of head in a well at a great distance from the pumping wells.

The ratios given in the two tables show considerable range, not only for the values for different sets of conditions, but even for the same set of conditions in the same month. For example, the ratio of the depth to water in the Longport well to the average daily pumpage from the area between Ventnor and Ocean City ($\frac{D_1}{Q_2}$ in the first table) has a range between 8.3 (August, 1924) and 26.9 (January, 1925). At first glance there appears to be no relation between given depths to water and given rates of pumping. For example, in June, 1925, when the water level was 30 feet below the original static level, the rate of pumping was 2.136 million gallons a day, whereas in April, 1925, with the water at the same level, the rate of pumping was only 1.398 million gallons a day. Even more striking is the difference in the pumping rate in June, 1926, and December of the same year, when the depth to water was 42.5 feet. In June the pumpage was 3.392 million gallons a day or nearly twice that in December, when it was only 1.728 million gallons a day. Considering these facts, are the ratios of any value?

A study of the tables shows that in general the value for $\frac{Q}{D}$ decreases during the spring and summer, and increases during the fall and winter. In other words, in the latter part of the summer the loss in head required to produce a given quantity of water is less than that required in winter. For example, in July, 1925, the loss in head for each million gallons was only 9.9 feet, whereas in January of the same year it was 26.9 feet. This seems to be a very unusual condition, especially considering the fact that the head on the water decreases considerably in summer.

The explanation of this condition is better understood if the monthly data are plotted, using the depths to water and rate of pumping as co-ordinates, and drawing a curve that connects the points in chronological order. Such a curve, for the relation between depth to water in the Longport well and the pumpage in the Ventnor-Ocean City area, is shown in Figure 17. In this curve the direction of progression is shown by arrows. At the beginning or end of certain years the points are so crowded that one or more have been omitted. If the average depth to water during each month had been used instead of the depth at the end of the month most of the points would be situated differently, and the shape of the curve would be altered slightly, but it would be of the same general type.

The curve shows two significant features. The first is the shape of the curve for individual years. The line for the months after August rises toward the starting point for the year, but for a given rate of pumpage it lies at a lower point than for the same pumpage in the first half of the year. This type of curve indicates the condition known as hysteresis, which is a "lagging of one of two related phe-

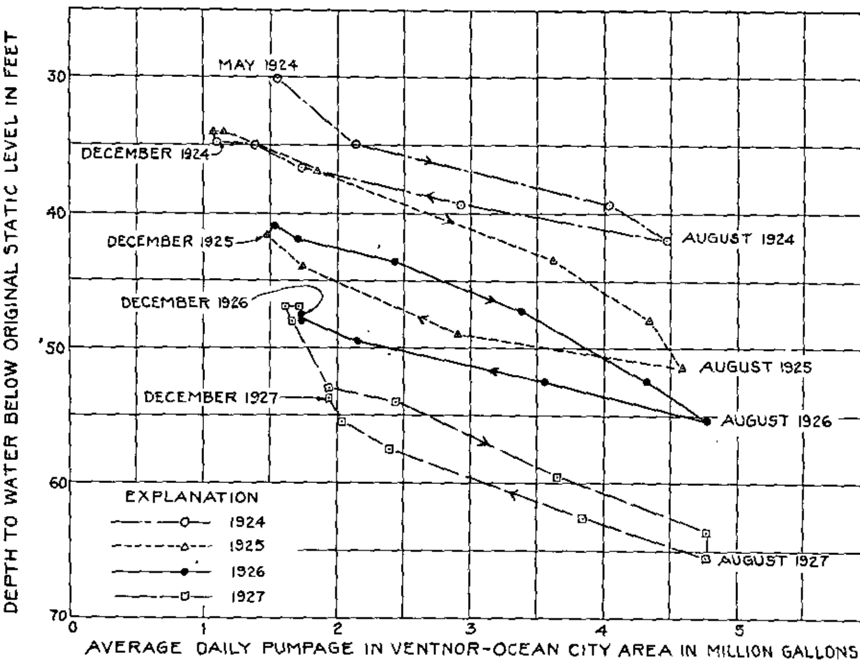


FIG. 17.—Graph showing relation between depth to water, below original static level, in Longport observation well, and average daily pumpage from Ventnor-Ocean City area, by successive months, May, 1924, to December, 1927, inclusive.

nomena behind the other."[26] The condition of hysteresis in the curve in Figure 17 indicates conclusively a lag in the movement of water level following changes in pumpage which has already been suggested from other observations (see pages 53 and 66). It shows that as the pumpage increases in the spring and summer months the head does not fall as rapidly as would be expected if the law of direct relation rate of flow and head held without modification. On the other hand, when the pumpage decreases rapidly in the fall, the head does not rise as rapidly as it should. If the average pumping rate during the month of maximum consumption were maintained long enough the water level would drop lower than it does. However, the maximum rate is reached generally in the later part of August or fore part of September, and immediately thereafter there is a very great decrease in pumpage. So great is the decrease, in fact, that the head cannot respond as rapidly. In winter, generally from December to March,

[26]Century dictionary.

there is not much change in pumpage, and the head has a chance to "catch up" and reach a condition where it is more in the proper position corresponding to the existing rate of pumping. During the other months of the year the head that would correspond to a given rate of pumpage, if stable conditions were reached, would be shown by a line drawn approximately half way between the two lines of the curve for each year.

It is noteworthy that studies of the elasticity and compressibility of sands and clays by Terzaghi have shown a condition of hysteresis or lag in the adjustment of the material to change in pressure.[27] This fact favors the suggestion on page 54 that the lag in the adjustment of the head in the 800-foot sand is presumably related to the phenomena of elasticity and compression of the water-bearing material.

The second significant feature of the curve shown in Figure 17 is the fact that each year the head has dropped to lower and lower levels for a given rate of pumping in the Ventnor-Ocean City region. The data given in the table on pages 78 and 79 show that if the pumpage from the entire region is considered, instead of that from the more restricted region, the same condition is found. In other words, in so far as the Longport well is concerned, the lowering of head in that well, resulting from an increase in a unit quantity of water pumped, is increasing from year to year. The reason for this is not fully known, but it appears that it may be due to one or more of several possible factors. Conceivably it may be due to a loss of head in the outcrop area resulting from deficient precipitation; to a reduction in the porosity, and hence permeability of the water-bearing sand as a result of withdrawl of water from storage and subsequent compression of the sand; or to an increase in pumpage near the observation well relatively greater than that in other parts of the region. In the years covered by the record there has been an unusual increase in the consumption from the 800-foot sand at the Margate City Water Works, and it is believed that this may be largely responsible for the increasing loss in head. The data in the table on pages 80 and 81 in regard to the observation wells in Atlantic City do not show such definite evidence of a progressive increase in loss of head per unit quantity of water pumped. In fact, at certain times the ratio $\frac{D_2}{Q_1}$ and $\frac{D_2}{Q_3}$ vary irregularly. This is probably because there have been sudden changes

27Terzaghi, Charles, Principles of soil mechanics: Eng. News-Record. vol. 95, pp. 743-744, and 987, 1925; Principles of final soil classification: Mass. Inst. Technology Publications, vol. 63, pp. 41-53, 1927.

in the pumpage in Atlantic City resulting from the starting of new wells or shutting down of wells for long periods.

Bearing in mind the factors described above, which affect the ratio between the loss of head in the observation wells and the pumpage in different parts of the Atlantic City region, the results in the tables may be applied to determine approximately the effect of future increase in pumpage. Using the winter values of $\frac{D_2}{Q_1}$ it appears that if future increases are distributed in the region as they have been during the period of observation the loss of head in Atlantic City will be some 10 to 12 feet for each increase of one million gallons a day. If the pumpage in winter, which in 1927 was about eight million gallons a day, is increased by 10 million gallons, the non-pumping level in the observation wells in Atlantic City may be expected to be lowered to a depth between 180 and 220 feet below the original static level or 170 to 210 feet below the surface of the ground. The level in pumping wells will be 25 to 50 feet or more lower, depending upon the rate of pumping. If the greater part of the increase in pumpage occurs within Atlantic City the loss in head will be even greater, and if it occurs largely in more distant parts of the region it will be less.

The loss in head in the Longport well per million gallons per day of pumpage in the entire region in winter months has ranged between six and seven feet. Accordingly, assuming the pumpage to change proportionately in all parts of the area as it has done between 1924 and 1927, an increase of 10 million gallons a day to a total of 18 million gallons would lower the head in that well to a point from 110 to 125 feet below the original static level or 100 to 115 feet below the surface. The true figure likewise may be greater or less than that stated, depending upon whether the greater part of the increase takes place near the observation wells or at a distance of several miles from them.

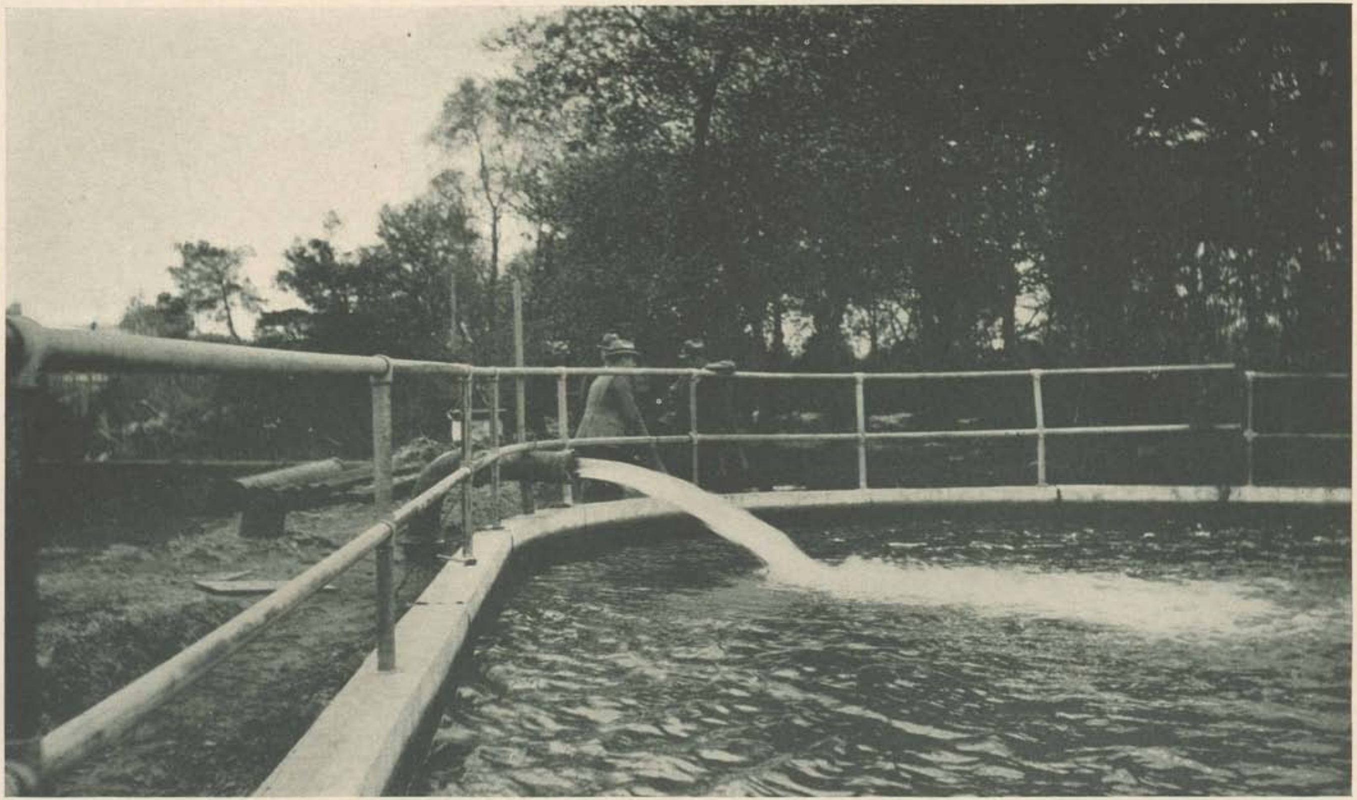
If the maximum rate of 18 million gallons a day is maintained for only a month or two in the summer, the loss in head probably will not be as great as indicated in the above estimates because of the lag in the change of head.

It cannot be expected that the estimates given above will be verified within the limits given, for too many factors are involved concerning which our knowledge is quite uncertain. It is believed, however, that the estimates are of considerable value in indicating the magnitude of the loss in head that may result from an increase in pumpage of 10 million gallons a day, or other quantities in proportion. They are of especial significance in considering the possibility of developing future public supplies from the 800-foot sand. According to estimates on page 22 the increase in consumption from all public supplies in the region in the next 20 years may be expected to be at least 20 million gallons. If this were all developed from the 800-foot sand, the head would be lowered several hundred feet below the surface. In fact, it might be drawn down to such a great depth that the cost of pumping would become prohibitive if the wells were not in the meantime contaminated by salt water.

EFFECTS OF FURTHER LOSS OF HEAD.

If consumption from the 800-foot sand continues to increase and the head to decrease the final effects will be several. Probably the first noticeable effect will be a decrease in the yield of wells. This has already occurred to some extent, but methods of testing the yield in most cases have been so crude that the decrease has not been evident. The ability of a well to yield a given quantity of water may not be impaired, but the yield with the original equipment will decrease. In order to maintain the original yield it will be necessary to lower the cylinder if the pump is of the reciprocating type, or the bowls if it is of the turbine type, or to increase the length of the air pipe and compressor capacity if air lift is used. In any case, more power will be required to obtain a given quantity of water and the pumping cost will increase. If the water level is lowered far enough, and no other factor places a limit on pumping, it is probable that eventually a further increase in the draft in the horizon would be prohibited by the rising cost of pumping the water to the surface.

The decrease in the yield of a well as the head decreases is well illustrated by the results of rather accurate observations on the new well drilled at the Atlantic City Water Works in April, 1925, which draws on the Atlantic City 800-foot water-bearing horizon. When the well was tested on May 13, 1925, by the drilling contractor, the yield as measured by an orifice was 1,050 gallons a minute. Subsequently the orifice was checked with a pitometer and the discharge was measured at intervals of about a month by one or the other of the two methods. The results computed to a uniform speed of pumping are shown graphically in Figure 18. The graph also shows the fluctuations of the water in an old well nearby, 600 feet deep (see page 59). The fluctuations in water level are due largely to fluctuations in the draft from the formation in Atlantic City and other coast towns (see pages 66 and 67). Although there are minor irregularities, it is appar-



Discharge of 675-foot well at Atlantic City Water Works, May 13th, 1925. Rate of discharge 1,050 gallons a minute.

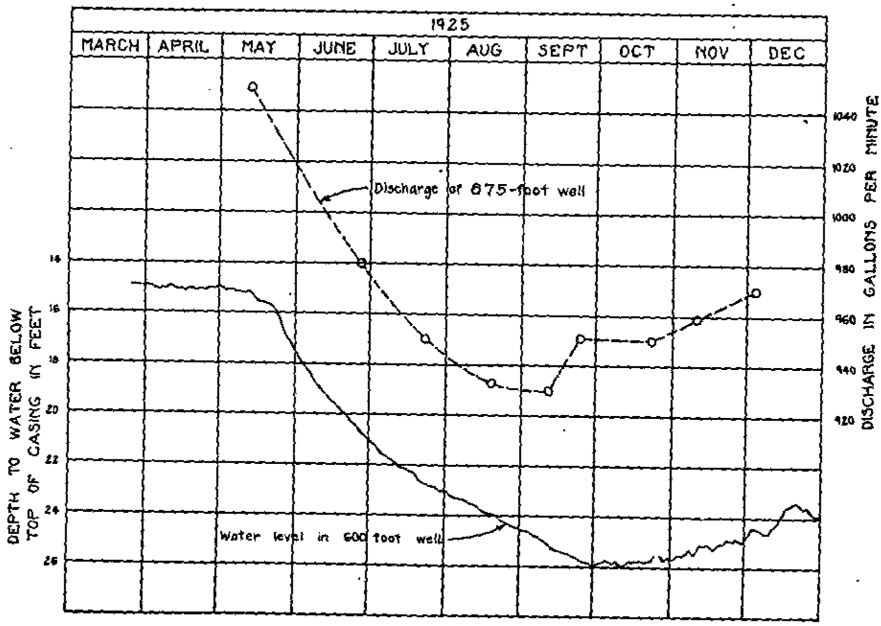


FIG. 18.—Discharge of 675-foot well at Atlantic City Water Works and fluctuation of water level in old 600-foot well.

ent that the yield of the wells changes with the head in the formation, declining when the head becomes less, and increasing if the head increases. At its lowest the yield was 930 gallons a minute, a decrease of 11 per cent from the original yield. On December 4, 1925, the yield was 970 gallons a minute, or about eight per cent less than the original yield. The pump installations have been changed slightly since then so that conditions are not entirely comparable, but the yield on January 13, 1926, was practically the same, 974 gallons a minute. On March 5, 1926, however, it was a little lower, 958 gallons a minute at 1,163 revolutions a minute. During the summer of 1927 the yield decreased still further, and in August it was only about 850 gallons a minute.

As another illustration of the effect of a decline in the static head the experience of a well owner in Atlantic City may be cited. When a new well was completed in April, 1924, the depth to water was about 40 feet. Equipment was ordered to set the pump at a depth of about 50 feet. The pump was not installed until the latter part of the summer. When first started no water could be obtained, but better success was had after the pump was primed. The static water level at that time was about 50 feet from the surface and the pumping level must have been considerably lower. Thus the pump was undoubtetdly operating with a suction lift instead of being submerged as it should be to obtain the geratest efficiency. In the spring of 1925 the pump was lowered to 75 feet from the surface, but difficulty in obtaining water occurred during the following summer. Since observations elsewhere in the city showed the static level then to be about 75 feet below the surface, the pumping level in the well doubtless was so low that the suction could not be maintained.

Several of the turbine pumps in wells in Atlantic City are set only 100 feet below the surface with 10 to 20 feet of suction pipe below the pump bowls. If the decline in head in the next few years is comparable to that in 1925 the water will drop below the limit of suction lift, and the pumps become useless. The difficulty can be remedied by lowering the pump bowls to a greater depth if the casing is large enough to receive them. Because of the possibility of a considerable lowering in head it is desirable, when drilling a new well, that the upper casing be of large enough diameter to receive the pump bowls to a depth of at least 125 or 150 feet. The pump need not be set so low at first, as the loss in head in pumping through the greater length of pipe would unnecessarily increase the cost of pumping the water. In several wells that are pumped by air lift it has already been necessary to increase the length of the air pipe, but this is done comparatively easily.

A factor which may cause a serious trouble before the pumping cost becomes excessive is the possible invasion of salt water. This subject is discussed on pages 112 and 119.

TESTS ON SAND SAMPLES.

More than twenty-five samples of sand have been obtained from wells drilled between 1923 and 1926 to the Atlantic City 800-foot horizon, and tests have been made on them by Dr. Norah D. Stearns in the hydrologic laboratory of the United States Geological Survey. The tests that are of special value in the present investigation include the determination of the mechanical composition, porosity and permeability.[28]

[28]The methods used are described in a report by Norah D. Stearns, Laboratory tests of physical properties of water-bearing materials: U. S. Geol. Survey Water-Supply Paper 596-F, 1927.

MECHANICAL ANALYSES, COEFFICIENT OF PERMEABILITY, AND POROSITY OF SAND SAMPLES FROM THE 800-FOOT HORIZON IN THE ATLANTIC CITY REGION.

Laboratory Number	SOURCE OF SAMPLE	Mechanical Composition (Per Cent)								Coefficient of Permeability	Porosity Per cent
		5–2 mm.	2–1 mm.	1–.5 mm.	.5–.25 mm.	.25–.10 mm.	.10–.05 mm.	.05–.005 mm.	Less than .005 mm.		
109	Layne well, Margate City Water Works, from depth of 745-795 feet.	10.18	45.09	29.87	11.65	3.13	.08	....	....	2,561	41
111	Thirty-fifth Street well of Ocean City Water Co., coarse material characteristic of upper part of 800-foot sand	22.99	35.11	16.05	16.64	6.43	.23	.66	1.89	10,464	38
112	Same well as No. 111, material characteristic of middle part of 800-foot sand	8.35	22.44	35.75	19.66	11.54	.68	.56	1.02	2,554	30
113	Same well as No. 111, fine material in lower part of 800-foot sand	......	16.13	60.42	17.21	4.27	.25	.58	1.14	2,609	36
301	Fifty-fifth Street well, Ocean City Water Co., from sand bed lying between 735 and 810 feet, probably near bottom of horizon	......	7.41	22.60	41.09	26.69	1.34	.46	.41	869	34
316	Atlantic City High School well, from upper part of section between 770 and 796 feet; sample washed in laboratory	5.12	13.76	35.74	26.72	16.03	.78	.51	1.33	616	27
317	Same material as No. 316, but washed by driller	5.03	15.42	41.02	31.87	5.50	Trace	1.15	....	1,944	30

MECHANICAL ANALYSES, COEFFICIENT OF PERMEABILITY, AND POROSITY OF SAND SAMPLES FROM THE 800-FOOT HORIZON IN THE ATLANTIC CITY REGION—Continued.

Laboratory Number	SOURCE OF SAMPLE	Mechanical Composition (Per Cent) 5–2 mm.	2–1 mm.	1–.5 mm.	.5–.25 mm.	.25–.10 mm.	.10–.05 mm.	.05–.005 mm.	Less than .005 mm.	Coefficient of Permeability	Porosity Per cent
318	Same well as No. 316, but from lower part of section between 770 and 796 feet; sample washed by driller...	7.94	23.62	33.92	23.60	4.79	Trace	.41	5.73	1,762	35
319	Same material as No. 318, but washed in laboratory	1.87	10.59	31.83	35.32	18.15	1.03	.85	.35	473	30
324	Atlantic City Water Works 675-foot well, representing material from 598-675 feet	a39.32	30.89	13.47	7.55	.44	Trace	1.02	.30	5,505	34
325	Haddon Hall well, representing material between a depth of 760 and 840 feet	9.90	50.46	24.63	11.57	2.36	Trace	.52	.56	2,419	32
326	Royal Palace Hotel well, at a depth of 768 feet	......	7.91	56.45	33.49	1.96	Trace	.19	....	2,500	34
327	From same well as No. 326 at a depth of 800 feet	3.35	41.67	43.19	10.60	.64	Trace	.41	.14	3,754	36
328	From same well as No. 326, at a depth of 830 feet	7.46	79.18	11.87	1.18	....	....	.30	....	4,362	33
329	Ritz-Carlton Hotel well, from upper part of sand between 779 and 812 feet	26.91	34.73	23.13	13.65	1.06	Trace	.51	....	4,189	33

MECHANICAL ANALYSES, COEFFICIENT OF PERMEABILITY, AND POROSITY OF SAND SAMPLES FROM THE 800-FOOT HORIZON IN THE ATLANTIC CITY REGION—Continued.

Laboratory Number	SOURCE OF SAMPLE	Mechanical Composition (Per Cent)								Coefficient of Permeability	Porosity Per cent
		5–2 mm.	2–1 mm.	1–.5 mm.	.5–.25 mm.	.25–.10 mm.	.10–.05 mm.	.05–.005 mm.	Less than .005 mm.		
330	From same well as No. 329 from lower part of sand between 779 and 812 feet	31.58	35.26	19.79	12.27	.51	Trace	.58	......	3,981	35
335	Guarantee Trust Building well, from a depth of 772 feet, representing upper part of 800-foot sand	......	......	.53	68.52	30.49	Trace	.21	.26	1,321	35
336	From same well as No. 335, at a depth of 815 feet, representing middle of 800-foot sand	1.04	7.32	15.81	39.85	26.62	.64	1.16	7.55	688	29
337	From same well as No. 335, at a depth of 842 feet, representing lower part of 800-foot sand	Trace	2.67	28.84	58.70	8.96	.45	.37	......	1,428	36
340	Atlantic City High School well, typical of sand between 796 and 816 [a]feet; washed by driller	11.98	31.14	32.78	17.06	3.55	......	.57	2.92	3,353	34
341	Same material as No. 340, washed in laboratory	22.91	39.03	21.19	10.10	3.82	.62	1.47	.86	1,146	31
342	From same well as No. 340, between 816 and 827 feet, washed in field	9.84	33.06	20.01	16.99	18.07	.38	1.64	......	2,114	32
344	Same material as No. 342, but washed in laboratory	14.17	33.06	20.84	16.29	14.54	.46	.65	......	972	38
345	From same well as No. 340, from a depth of 836 feet. Sample washed in laboratory	19.02	22.04	20.86	19.02	14.06	1.93	2.77	.20	1,114	29

[a]This sample also contained 7.02 per cent greater than 5 mm., which is not included above.

The "coefficient of permeability" is defined as the number of gallons of water a day at 60° F., that is conducted laterally through each mile of the water-bearing bed under investigation, measured at right angles to the direction of flow for each foot of thickness of the bed and for each foot per mile of hydraulic gradient.[29] Having the coefficient of permeability, and other requisite data as to the temperature of the water and thickness of the water-bearing bed, there may be determined the head necessary to yield a given quantity of water or conversely the amount of water that can be obtained with a given head. Certain practical difficulties are encountered which in the present stage of the work make it impossible to consider the results conclusive. For example, the thickness of the bed may vary from place to place, and the factor of thickness cannot be determined accurately. Furthermore, as shown by samples already tested, the permeability of the sand in different parts of a water-bearing bed varies considerably, even in the same well, so that it may be quite difficult to properly evaluate this factor. Another probable cause of error is the impossibility of getting a sample into the testing equipment just as it was in the sand bed.

In drilling the sand is washed out of the well. If the rotary hydraulic process is used it is mixed with thick mud. If the jet process is used the mud is not so thick. In either case, in order to obtain a sample of the sand the mud is washed out by the driller. It is impossible to wash out all of the mud used in drilling without also washing away some of the finer sand. The upward current in the well during drilling may not be strong enough to carry to the surface any coarse sand or gravel when it is struck. Therefore, the sample may be finer than the water-bearing bed as a whole. It is a well known fact that, other conditions being the same, the greater the variation in the size of material the less is its permeability, and the more uniform its size the greater the permeability. Since the coarser materials may remain in the well and the fine be washed out with the mud, the samples obtained probably show permeabilities higher than the permeability of the formation underground. Despite these difficulties, it is believed that the tests of samples are of some value in showing the relative quantities of water than can be obtained from different formations.

As shown by the table (see pages 89 and 91) there is a considerable range in the coefficient of permeability of the samples tested—from 616 to 10,464. The coefficient of permeability of sample No. 111 is so much higher than that of any other sample that is believed not a true sample

29Stearns, Norah D., op. cit., p. 148.

of the sand. It may have been washed an undue amount. It is therefore not considered in the following discussion. Tests were made on four pairs of samples of the same material (Nos. 316 and 317, 318 and 319, 340 and 341, 342 and 344). In one sample of each pair the mud used in drilling was washed by the driller and the other was washed more carefully in the laboratory. The method used by the driller was to turn a stream of water from a hose into a bucket, stir the sand, and let the fine material flow over the top. By this method some of the fine sand, and perhaps even some of the coarse, was washed out. In the laboratory the sample was stirred in water, it was allowed to settle, and the water carrying the fine material was carefully decanted. This process was repeated many times. In the samples thus washed the fine sand was left in the sample. As shown by the table the result was that the coefficient of permeability of the samples washed in the laboratory was much lower than that of the less carefully washed samples. The average coefficient of permeability of four samples washed in the laboratory was 802, and of the samples of the same material washed by the driller it was 2,293, or nearly three times as great. Since all of the samples, except those otherwise indicated, were washed by the driller, it is probable that the coefficients of permeability are in general too high. With these limitations in mind an application of the results may be attempted.

The average of the coefficient of permeability of 18 samples washed by the driller is 2,662. This means that in one day 2,662 gallons will move through a strip of sand one foot thick and one mile in length, at right angles to the direction of flow when the head is one foot per mile and the temperature of the water is 60° Fahrenheit.

The flow varies according to temperature, a high temperature increasing the rate of flow and a low temperature retarding it.[30] The temperature of water from five wells in the region ranges from 60° to 65° Fahrenheit, with an average of 63°. According to Slichter's table, the flow at 63° is approximately 1.05 times that at 60°, and the corrected average permeability coefficient is practically 2,800. A study of a number of logs shows that the average thickness of the sand is about 80 feet. On this basis, with a head of one foot per mile, the quantity of water passing through a strip one mile long would be 80 x 4,000, or 224,000 gallons a day. If the strip were two miles long the quantity would be twice that much or 448,000 gallons a day, and so on. The distance between the northeastern and southwesternmost wells in Atlantic City is approximately two miles. On this basis

[30]Slichter, C. S., Field measurements of the rate of movement of underground waters: U. S. Geol. Survey Water-Supply Paper 140, p. 13, 1905.

the head required to provide a flow of five million gallons a day would be 11.2 feet per mile. This assumes that the water is moving to the wells from one direction only at right angles to the coast and down the dip of the bed from the west. Actually, some water is probably moving from other directions. Doubtless about half water moves up the dip, being replenished by flow around the ends of the zone. If this is true the quantity coming from the region directly northwest of the pumping area would be about half that estimated, and the head need be only 5.6 feet per mile.

By similar computation a comparison may be made with the head between the new well at the Absecon pumping station and wells in Atlantic City. When completed in May, 1925, the water level in the pumping station well was about five feet below mean sea level. On the basis of the observations at the Chalfonte, in Atlantic City, it is estimated that the static level in the western part of the city was about 35 feet below mean sea level, and that the difference in head or gradient was about 6.7 feet per mile. The average daily consumption from wells in the city, in May, 1925, is estimated to have been about 4.5 million gallons a day (see Fig 14). In the following table is shown the head required to yield this quantity of water using the average coefficient of permeability determined from samples washed by the driller and those washed in the laboratory.

Assuming that the water moves to the wells in Atlantic City from two directions, the gradient in May, 1924, was intermediate between the gradients computed from samples washed in different ways. It was, in fact, not much different from the gradient based on the largest number of samples. Considering factors involved which cannot be accurately evaluated, the results are as good as can be expected. They are believed to indicate that the determinations of coefficient of permeability are useful within certain limits. In the table on page 95, there is given the gradient required for a draft of 10 million gallons a day from wells in the city. If the larger average coefficient is more nearly correct, the gradient required to draw five million gallons a day in Atlantic City would be about 11 feet per mile, and the head in Atlantic City would be about 50 feet lower than at the Atlantic City Water Works on the mainland. If the lower coefficient was correct the difference in head between the two places would be nearly 150 feet. Since the head at the water works would be lower than it is now the head in Atlantic City would be much more than 150 feet below the surface.

Applied in a different way the test data as to the permeability of the 800-foot sand are of significance in showing the area from which

HYDRAULIC GRADIENT, IN FEET PER MILE, REQUIRED TO PRODUCE FLOW EQUIVALENT TO CERTAIN RATES OF PUMPING FROM 800-FOOT SAND IN ATLANTIC CITY, AS DETERMINED FROM PERMEABILITY TESTS ON SAND SAMPLES.

Example Number	Observed coefficient of permeability =C	Coefficient of permeability corrected for temperature = C x 1.05	Rate of flow gallons per day in section 2 miles long and 80 feet thick, and head of 1 foot per mile	Gradient required for [a]4.5 million gallons a day		Gradient required for 10 million gallons a day	
				Water coming from one direction	Water coming from two directions	Water coming from one direction	Water coming from two directions
				Feet per mile	Feet per mile	Feet per mile	Feet per mile
A	2,662	2,800	448,000	10.0	5.0	22.3	11.2
B	864	910	145,600	30.9	15.5	68.7	34.4

A Average of 18 samples washed by driller, coefficient of permeability probably too high.
B Average of 5 samples washed in laboratory.
[a]Estimated average daily pumpage for month of May, 1924.

water is being drawn. As stated on page 69, the original head on the formation near Atlantic City appears to have been only about one foot per mile. As shown on page 73, using an average coefficient of permeability of 2,800, the quantity of water passing through a strip of the formation one mile long under a head of one foot per mile, is 224,000 gallons. To obtain 5,000,000 gallons a day with the natural gradient of one foot per mile, it would be necessary to draw on a strip more than 22 miles long. To obtain 12,000,000 gallons a day, which is approximately the average daily pumpage in summer in the area from Brigantine to Ocean City, water would be drawn from a strip more than 50 miles long. This assumes that the draft is equal in all parts of the strip of water-bearing formation. Actually, since the draft is concentrated in a relatively small area toward which the water must move rapidly, the head required is great where the pumping is heavy, and becomes less along lines radiating out from the pumping wells. Nevertheless, before the intake area is reached the water must be moving in a zone whose length is of the magnitude just stated. That this is actually the case is shown by the profile of the piezometric surface along the coast (see Fig. 15, A).

CONTAMINATION OF WELLS BY SALT WATER.

General statement.—A problem that has given concern to some of the owners of deep wells in Atlantic City has been the contamination of their wells by salt water. The seriousness of this problem is better understood when it is realized that the static water level in the wells in different parts of the city is from 60 to 80 feet below sea level, and that salt water is heavier than fresh water. If sea water in sufficient quantity finds access either to the water-bearing bed or to wells tapping it, a large part of the formation may be contaminated, and this valuable source of water will be destroyed. Therefore, a consideration of the danger of salt-water contamination becomes desirable in a study of the quantity of ground water that may safely be drawn from the 800-foot sand in the Atlantic City region.

Certain general relations between fresh water and salt water along seacoasts are well known, and the literature on this subject has been summarized by Brown.[31] To show the danger that conceivably may

[31]Brown, John S., A study of coastal ground water with special reference to Connecticut: U. S. Geol. Survey Water-Supply Paper 537, 1925. A summary of the principal points in the paper has also been published under the title, "Relation of sea water to ground water along coasts," in the American Journal of Science, 5th series, vol. 4, pp. 274-294, 1922.

confront well users in Atlantic City conditions on Long Island, N. Y., may be cited where heavy pumping of wells near the ocean resulted in the drawing in of salt water and necessitated partial or complete abandonment of certain well fields.[32] However, certain conditions in the Atlantic City region seem to indicate that there is less danger of widespread contamination, at least for the present, than at the Long Island localities, but because of a lack of knowledge of certain factors that may favor intrusion of salt water this problem cannot be neglected.

The relative saltiness of water is ordinarily determined by its chloride (Cl) content, which is one of the two elements of common salt (sodium chloride, NaCl). Ordinary ocean water contains between 19,000 and 20,000 parts per million of chloride. Water containing as much as 1,500 parts per million is intolerable to most people for drinking, and to be acceptable for ordinary household use it should not contain more than 200 to 250 parts per million. As shown by the analyses on page 15, the waters now being used in Atlantic City are very low in chloride, the maximum, with a few exceptions, to be discussed below, being only about 15 parts per million.

The wells in Atlantic City are on a narrow island practically surrounded by salt water. Samples of water collected by the writer from the channel, Main Thoroughfare, where it is crossed by Absecon Boulevard, show a chloride content of about 17,000 parts per million as compared to about 19,000 parts in sea water—that is, the water in the thoroughfare between Absecon Island and the mainland is essentially as salty as ocean water. Salt water is found in the beds overlying the 800-foot horizon, and there is some indication that the water in the formations beneath it, at least below the 950-foot horizon, is at least brackish. With these conditions in mind a perusal of Brown's paper would lead one almost immediately to the conclusion that contamination of the 800-foot horizon by salt water is inevitable, and, in fact, should have occurred long before this. However, the geologic conditions in the Atlantic City region are different from those in other regions where studies have been made, and because of the different conditions there is no precedent to follow in determining the likelihood of salt-water contamination.

The conditions at Atlantic City appear so favorable to contamination that when some wells in the city began to yield salt water the first conclusion was that the heavy pumping was drawing the salt water into the formation, and soon a considerable part of it would be

32Spear, W. E., Long Island sources—an additional supply of water for the City of New York, vol. 1, pp. 144-157, 1912; Brown, J. S., Water-Supply Paper 537, pp. 44-48, 1925.

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spoiled by salt water. There is abundant evidence, however, that such is not the case. In the present investigation samples have been analyzed from about 15 wells situated in the stretch from Brigantine Beach on the northeast to Wildwood on the southeast. With the exception of the water from wells that have been more or less contaminated by leaks in the well casing the chloride content in every case was very low, ranging from 6 to 37 parts per million of chloride.

That there has been no general contamination of the 800-foot horizon by salt water is shown by a comparison of samples taken at different times. Water from the well at the Chalfonte Hotel, analyzed in 1905, contained eight parts per million of chloride, a sample analyzed in 1911 contained 9.7 parts per million, and one in 1924 contained 10 parts per million. In several samples analyzed at intervals between December 3, 1925, and February 24, 1928, the chloride ranged from only from 5.5 to 9.9 parts per million. These differences are so small that they are insignificant. An analysis for a sample from the well at the Hotel Dennis in 1899 shows a chloride content of 10.12 parts per million.[33] No samples from the Brighton well have been analyzed recently, but the results on samples from other wells are so close to the chloride in this very early analysis that it may be said there has been no material change in the many years of pumping.

On the other hand, several wells have become so salty that they could not be used. All of the facts point to local contamination, the salt water entering the wells through openings in the upper part of the casing. When the difficulty has been overcome either by filling the old well and drilling a new one, or by some other expedient, fresh water has again been obtained. The writer has a record of five wells that have gone salty since 1922. It is probable that salt water was the reason for abandoning a number of other wells.

Specific examples of contamination.—In the fall of 1921 a well (No. 4 on Fig. 1) at the Supplee-Wills-Jones Dairy, which had been completed only about six months, began to show signs of salt-water contamination. An analysis on October 13, 1921, showed 16.93 grains per gallon (about 290 parts per million) of sodium and potassium chloride.[34] By May 23, 1922, it had increased to 56.094 grains per gallon (960 parts per million). The well was abandoned shortly afterward and filled, and a new well was drilled by the rotary hydraulic process, using mud fluid about 20 feet from it.

The new well was completed in June, 1923. W. P. Tramel, the

33 Annual report of State Geologist for 1899, p. 147.
34 Analysis by Dearborn Chemical Co.

driller, states that a sample collected after it had been pumped steadily for about seven hours showed the water to be of good quality. A sample collected by the writer on July 14, 1923, contained 37 parts per million of chloride and 183 parts per million of total dissolved solids. Another sample, collected about November 14, 1923, contained eight parts per million of chloride and 132 of total solids. In 14 samples collected at intervals of one to several months between that date and February 24, 1928, the chloride has ranged from 5.0 to 8.8 parts per million, and most of the time it has been less than six parts per million. This is the lowest chloride content found in any sample collected by the writer from the 800-foot horizon, except a sample from the well at the Atlantic City Water Works in the mainland, which contained only three parts per million of chloride. The well has been pumped at a rate of 100,000 to 300,00 gallons almost every day since it was completed. If contamination of the formation was general and the result of heavy pumping, surely it should have proven so at this place; but the evidence shows that after the old well was filled up, water of a quality that appears to be the normal for the horizon was obtained.

The old well was of the type known locally as a "single-cased well." The casing record as furnished by Mr. Osgood, chief engineer of the Supplee Dairy, is as follows: 200 feet of 10-inch, 193 feet of eight-inch, 381 feet of six-inch and 50 feet of four-inch screen. There was a short overlap at the bottom of each string of casing and that of next smaller diameter inside. No data are available as to the length of the overlap, but apparently it was not great. The space between the two casings at these overlaps was pluggged with wood plugs. The reduction from the 10-inch to 8-inch casing was made well above the 400-foot clay bed, and probably was in or near salt-water bearing sand. Although each casing extended to the top during drilling it was cut off and withdrawn. The expense of drilling was thereby lessened by an amount approximately equal to the cost of the casing. It is supposed that the wood plug either did not fit properly when first put in or else broke out in some way and admitted the salt water. In confirmation of this theory it is reported that pieces of wood were pumped from the well. In this connection attention may be drawn to the fact that in a well where the water level when pumping is 50 feet below the ocean level the difference in pressure between the fresh water in the well and the salt water in the upper formations outside it is about 22 pounds per square inch. Unless a plug were very tightly inserted this might easily be pushed out by the pressure on it from the salt water-bearing horizon.

A case of salt-water contamination, concerning which valuable information is available, occurred during 1924 in a well (No. 26 on Fig. 1) at the Royal Palace Hotel. The first evidence of contamination occurred in the spring of 1924. Apparently the leakage at this time was small, and as the pumpage increased during the summer the salt water that entered was sufficiently diluted by fresh water from the 800-foot sand so as not to be noticeable. The first real indication of salt water was observed about the middle of September—that is, soon after the pumpage from the well had increased considerably. It soon became so bad that the well had to be abandoned.

The well stood as it was until about December 1, 1924, when it was filled up just prior to drilling a new well about 25 feet away. Just before it was filled, at the request of the writer it was pumped for one and a half hours and samples taken at half-hour intervals. The first sample, taken when the water first flowed, contained 20,000 parts per million—that is, it was as salty as sea water. The other samples, taken half an hour, an hour, and one and a half hours after starting, contained, respectively, 13,300, 10,650 and 8,450 parts per million of chloride. On plotting the results it is found that the chloride apparently would have continued to be at least several thousand parts per million for some time. Salt water was leaking into the well at this time in such quantity that the dilution by the fresh water was insufficient to reduce the chloride low enough to make it usable.

The new well was completed about January 15, 1925. A sample collected as soon as the water had cleared up, when it was first pumped, showed 490 parts per million of chloride. After a couple of days pumping a disagreeable taste was noticed and the water could not be used for drinking. A sample collected on February 11 showed 567 parts per million. At the suggestion of the driller thereafter the well was pumped into the street about 14 hours daily for several months, and samples were taken at intervals. The chloride content in these samples is shown graphically in Figure 19. As shown by the graph the chloride content declined very slowly, until finally, on October 30, 1925, it was down to 15 parts per million, which, although it is slightly higher than the chloride in most wells in the city, can be considered normal for the region.

During the early weeks of tests of this well the question arose as to the source of the salt water—whether it was leaking into the new well or whether it had entered the formation from the old. If it was from the old well, was that well still leaking or was the salt water residual—some that entered the formation during the two months or more before the well was filled after being abandoned? In an attempt to

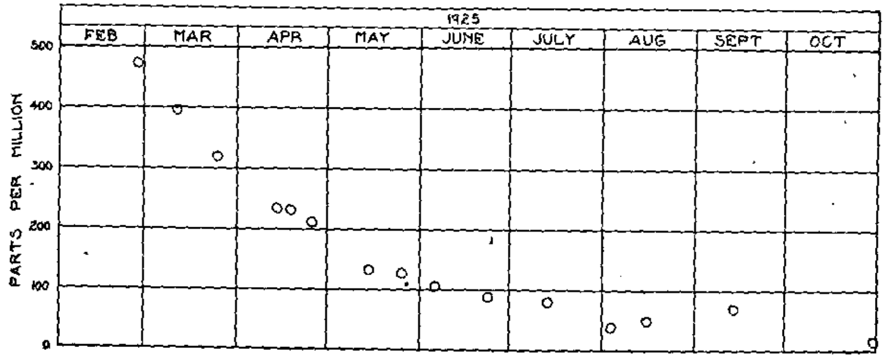


FIG. 19.—Graph showing chloride content in water samples from Royal Palace Hotel.

answer these questions a series of samples were taken at frequent intervals on successive days. The amount of chloride in these samples on one day, March 24, 1925, is shown in Figure 20, A. The first water that came from the well contained 325 parts per million of chloride, but within 10 minutes the chloride dropped to 55 parts. Thereafter it rose again, at first rather rapidly and then more slowly, and when the pump was stopped at the end of 12 hours it was nearly as high as in the first sample. A series of samples collected for a short time on the following day showed a similar rapid drop in the chloride during the first few minutes of pumping and rise thereafter.

The results of these tests are interpreted as follows: If salt water were leaking into the new well through holes in the casing such water

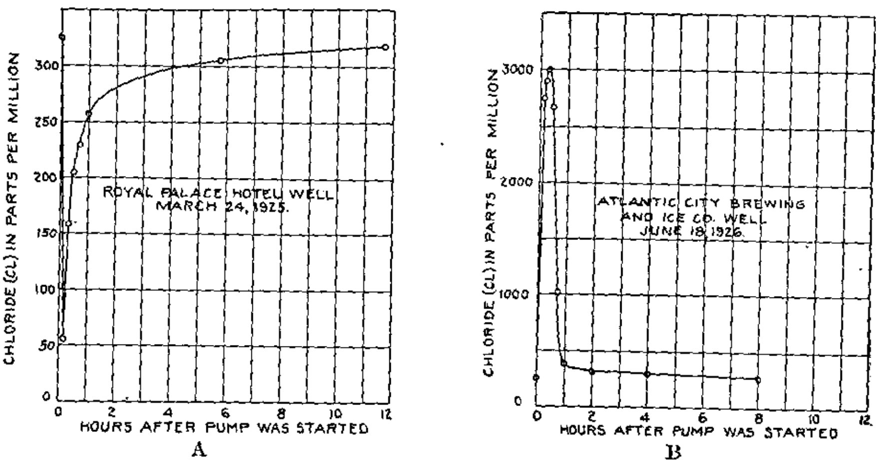


FIG. 20.—Graphs showing fluctuation of chloride content in water samples during pumping from wells of Royal Palace Hotel and Atlantic City Brewing and Ice Co.

of high chloride content would fill the casing from the point of leak to the bottom of the casing, and since salt water is heavier than fresh water, it would spread out into the water-bearing formation. Therefore, water from the lower part of the casing, which would reach the surface after the pump had operated a few minutes, should contain the most chloride, and as pumping continued the salt water would be removed and the chloride content should diminish. This did not happen in the Royal Palace well, and it was therefore concluded that the water of high chloride content did not come from a leak in the new well but from the old well. The first sample was of water left in the casing on the cessation of pumping the previous day, and represented the concentration of the water in the sand at that time. This water had been drawn in from the direction of the old well. The sample that contained only 55 parts per million reached the surface after pumping for several minutes and must have come from the formation. Evidently the water in the formation near the new well had become better in quality during the night, and this could occur only by underflow past the well. The hydraulic gradient in this locality is known to slope in the general direction of the old well, which was nearer the center of heavy pumping in the city. Therefore, conditions were favorable for fresh water moving toward the new well during the period when the well was not pumped. The increase in chloride as pumping continued during the day occurred as water was drawn in from the direction of the old well.

If salt water were still entering the formation from the old well a cessation of pumping would result in an increase, and this increase should show up when the new well was pumped. This did not occur, and it was concluded that there was then no leakage from the old well. The salty water that reached the new well was part of the sea water that had entered the formation before the old well was filled up, and it took several months before that water was pumped out or mixed with fresh water in the formation.

None of the cases of salt contamination that has come to the attention of the writer has showed a chloride content approaching that of the old Royal Palace well. The first sample, which contained 20,000 parts per million of chloride, undoubtetdly was water that entered the upper part of the well. That a considerable quantity of it entered the water-bearing bed is shown by the sample taken after an hour and a half of pumping, which contained more than 8,000 parts per million of chloride. Rough computations show that this water must have come from that part of the formation several feet from the well. If this water were so salty, it would not be surprising that the water as far away as the new well would show some contamination. The cause of the leakage into the old well has not been determined. Nor is it clear why the chloride should be so much higher than in most wells that have shown salt water. Perhaps this apparent difference is really due only to a lack of definite data at cricital times in regard to the other wells. The Royal Palace well is nearer the ocean than most wells and is so situated near the Inlet that the ocean is not far away in two directions. At this locality wave action may have broken protective beds that may be present in other wells, and allowed easier access for water from the ocean.

Another instructive record of contamination is that of a well at the Atlantic Brewing and Ice Co. (No. 7 on Fig. 1). The well is 846 feet deep with a four and one-half-inch screen. The water from it showed the first sign of being brackish in 1922. It is said that an analysis showed 105 grains (equivalent to approximately 1,800 parts per million) of "salt," but it is not certain whether the term was used to indicate sodium chloride or only chloride. An attempt was made to shut out the salt by putting a four and one-half-inch pipe down to the screen and placing a "packer" between the pipe and the casing to prevent the salt water moving down the intervening space to the screen. The "salt" content was reduced to 17 grains per gallon (about 290 parts per million), and a second attempt was made to reduce the chloride still more. In working on the well a string of 380 feet of four and one-half-inch pipe accidentally was dropped in the well and all efforts to pull it out were unavailing. Finally, a special packer, known as a "step expanding gas anchor packer" manufactured for use in oil and gas wells, was put in the well. This packer consists of two parts, a lower section of gum rubber and an upper section of pipe, which is small at the lower end and increases in outside diameter by steps. The upper section telescopes into the lowering, being pushed down by the weight of a string of casing above. As it enters the rubber the latter is squeezed outward until it meets the side of the casing forming a tight seal. The packer was placed just above the 380-foot string of six-inch casing at a depth believed to be about 340 feet, and four and one-half-inch pipe was continued to the surface. When a sample of water was collected about August 10, 1925, shortly after this work was completed, the chloride was reduced to 46.8 parts per million. A sample collected on November 20, 1925, contained only 10 parts per million of chloride and 127 parts per million of total solids, which shows that water of the normal mineral content was being obtained. The salt water had thus been effectively shut out at a cost much less than that of a new well.

Unfortunately, the shut-out was not permanent. In June, 1926, the water was again reported to be salty. A well about 500 feet away was known to have been abandoned several months before, and, according to rumor, was contaminated by salt water. It was therefore thought possible that the salty water might be coming from that well, but the very fact that the well of the Atlantic Brewing and Ice Co. had earlier been known to have a leaky casing in the salt-water zone cast suspicion on it.

A series of samples were collected as during the test of the Royal Palace well, and the quantity of chloride in them is indicated graphically in Figure 20, B. The fluctuation of the chloride is just the opposite of that in the Royal Palace well—low at first, with a very rapid rise occurring within a few minutes after pumping started and immediately thereafter a sudden drop. The curve flattens even more rapidly than in that of the Royal Palace, and apparently the chloride would continue to be between 200 and 300 parts per million for at least many days. In accordance with the decision on page 102 the character of the fluctuation of chloride in the Atlantic City Brewing and Ice Co. well is considered to indicate quite clearly that the salt water was entering through a leak in that well and was not being drawn in from the nearby well.

It is possible that in the future other wells in the region may become contaminated from local sources, either directly by leaks in their own casing or indirectly by leaks in nearby wells. It is believed that the method used to determine the source of the salt water in the Royal Palace and Atlantic City Brewing and Ice Co. wells may be applied to determine the source of contamination in other wells.

A fourth case of local salt-water contamination has occurred at Brigantine Beach. An old well, unused for many years, was cleaned out in the summer of 1924. Samples collected between that time and June 24, 1925, contained from 300 to 700 parts per million of chloride. In June, 1924, a new well close to the old one was begun and water for mixing the mud fluid used in drilling was obtained from the old well. Before the well was finished the old well collapsed and it was impossible to obtain water from it. A large quantity of water is required in the drilling process, and in order to finish the well salt water was pumped from the bay. A sample collected on August 19, shortly after the well was completed, contained 325 parts per million. Thereafter, as the well was pumped a few hours each day, the chloride decreased. Subsequent analyses showed the following chloride content: September 21, 183 parts per million; October 29, 136 parts per million; about November 8, 129 parts per million; January 18, 1925, 85 parts per million, and March 23, 58 parts per million.

There may have been some slight leakage of salt water from an upper horizon in the old well, but the contamination of the new well doubtless resulted largely from the use of sea water in drilling that probably contained 15,000 to 18,000 parts per million of chloride. However, it was used for only a short time and was mixed with mud, and doubtless did not move very far from the well into the formation. Furthermore, a large quantity of the salt water was pumped during the developing and testing of the well. The observations on the Brigantine wells, like those on the Royal Palace well, are significant in showing how long it takes to freshen the horizon when it has once become contaminated even locally and only to a slight extent.

Cause of present contamination.—The evidence is convincing that salt water has not yet been drawn into the 800-foot horizon from its oceanward etxension. The salt-water horizons lie above the great clay bed and salt water enters the well holes above that depth or passes down along the casing. Practically none of the casings have been pulled out, so that the exact causes of the trouble can only be conjectured.

Several persons who have followed the development of the Atlantic City horizon for many years have stated to the writer their belief that salt water trouble was due to the use of reciprocating pumps—that is, pumps in which a cylinder that contains valves is placed in the well, generally below the static water level, and the water is lifted by the alternate raising and lowering of the valves by means of rods connected to an engine at the surface. In support of their contention they stated that every well they knew of which had become salty had at some time been equipped with this type of pump. It was their belief that the reciprocating movement of the pump rods created a jar that caused a strain on the casing to the point where it would break. It was further said that sand carried in the water settles around the cylinder when pumping is started, and when pumping is resumed the jarring drives this between the cylinder and casing like a wedge, helping to break it.

The first examples that came to the writer's attention supported this theory, for reciprocating pumps had been used in the wells. However, three wells which are said never to have been equipped with that type of pump, nevertheless, have become salty. These wells are at the Ventnor Water Works, the Royal Palace Hotel and the Atlantic City Brewery. They were either originally equipped with suction pumps which were abandoned for air lifts when the water level got too low or air was used from the beginning. The reciprocating pump, therefore, must not be blamed for all the trouble from salt water. Although the reciprocating pump has been rather generally discredited for use on the deep wells in the region, for the reason just stated, it still has a few advocates. At least four pumps of this type are known to be in use. One engineer who has studied the situation carefully believes that if casings have been broken by the jarring of the pumps it has been due to the fact that the pump is attached rigidly to the top of the well piping. He has recently installed a reciprocating pump on a new well. This particular pump is not connected to the well pipe, and he believes he will have no trouble. Another engineer, whose well has been contaminated, although only air lift had been used, expects to use a reciprocating pump in his repaired well. It is the opinion of the writer that, although there is circumstantial evidence against the reciprocating pump, the case has not been satisfactorily proved. As shown below, there are other possible causes of holes in the casing that are equally as potent.

In at least one instance it seems probable that the salt water gained entrance into the well through faulty construction where the size of the casing was reduced. Either the plug that was to close the space between the inner and outer casing was not properly placed or it was subsequently forced out by the greater head on the salt water outside the well. Salt water may gain access to the fresh-water bed if proper care is not used in putting in the casing through the upper horizons, for the hole is always necessarily a little larger than the casing. To prevent trouble from this source one string of casing should be set firmly into the great clay bed and below that the diameter of the hole should be reduced. To be doubly sure the hole could be cemented at this point before drilling farther, according to methods used in oil fields to shut out water.[35] However, the fact that most wells have shown no contamination in the early part of their life is believed to indicate that there has been little, if any, leakage along the outside of the casing. Where air lift is used the lower end of the air pipe may vibrate and wear a hole in the casing unless some method is used to prevent this.

Aside from mechanical causes such as vibration and rubbing of pump parts, it seems that corrosion is probably the most potent cause of salt-water contamination. The problem of protection of well equipment against corrosion is especially important in oil fiields, and has been the subject of a comprehensive investigation by R. Van A. Mills

[35]Tough, F. B., Methods of shutting off water in oil and gas wells: U. S. Bureau Mines Bull. 163, 1918.

of the Bureau of Mines.[36] The conclusions reached in that investigation may well be applied to well conditions in the Atlantic City area, for the problem of preventing corrosion in oil and gas wells relates largely to the shutting out of both salt and fresh water from the wells. The following extracts point out important factors in the salt-water problem:[37]

"The corrosion of metal is essentially an electro-chemical process accomplished through the agency of water. The presence of an aqueous solution in contact with a metal is the one condition that is essential to all the electro-chemical reactions involved. * * *

"Corrosion in the wells falls within one or the other of two classes, according to water conditions. These classes are as follows:

"1. Corrosion of well casing from outside. In this phase of underground corrosion the corrosive waters stand around the outside of the casing.

"2. Corrosion of casing from inside, with corrosion of tubing and other equipment inside the casing. The waters that cause corrosion stand either between different strings of casing or inside the inner string of casing, or possibly both. * * *

"If the corrosive waters stand between different strings of casing or around the tubing and other equipment inside the casing, the corrosion of the different strings of pipe is closely analogous to corrosion of the plates in galvanic cells. The wells are, in effect, large galvanic cells in which the casing, the tubing and the other metal equipment immersed in salt water are the electodes and salt water the electolyte. Galvanic action takes place between different parts of the equipment very much as it does between the different plates in ordinary galvanic wet cells. * * *

"Corrosion processes in the wells are self-stimulating, and corrosion tends to become progressively more vigorous as it continues."

Prevention of contamination from overlying horizons.—After salt water has once gained access to a well it may be difficult to shut it out, partly because of the impossibility of knowing just where the leak may be. It may be more expensive to attempt to reclaim the well than to abandon it and drill a new one. It is obvious that care in drilling the wells to shut out salt water is by far more important than attempting to rehabilitate old wells. In pointing out precautions that should be taken the methods of drilling used in the region must be considered briefly.

Until the last two or three years most of the wells have been drilled

36Mills, R. Van A., Protection of oil and gas field equipment against corrosion: U. S. Bureau of Mines Bull. 233, 1925.
37Mills, R. Van A., op. cit., pp. 3-5.

by the so-called jet method. When using this method the casing is put down as the hole progresses and is never more than a few feet from the bottom of the hole. The hole is generally slightly larger than the casing, and there is thus a channel outside of it through which the water from the upper horizons may move. Ordinarily this channel soon fills with caving sand, but if only with sand there is still opportunity for the water to move along it.

It is the common practice to drill the hole with a certain diameter to a depth of 100 to 300 feet, and then reduce the diameter of the hole by about two inches. In many wells a second reduction in size is made at a greater depth. In the earlier wells it was the common practice to have an overlap of only a few feet between the successive casings. The space between them was filled with a wooden plug. Since the driller is working more or less in the dark, he can never be sure that he has made a tight plug, and the point of reduction therefore may be a source of contamination. Because there is only one casing at a given point, except for a few feet at the reductions, wells of this kind have been called single-cased wells.

Most of the wells in Atlantic City that were drilled by the jet method are now of a type called double-cased wells. In these the second casing, instead of overlapping the first or outer casing for only a few feet, extends to the surface. There is thus a double thickness of casing in the salt-water horizons which to a certain extent gives added protection against corrosion. However, Mills points out, with water standing between two strings of casing, the conditions are favorable for producing corrosion similar to that of the plates in galvanic cells.[38] Since it costs several hundred dollars to carry the second casing to the surface, in recent years some persons have omitted this precaution in order to save money. This has proven to be false economy, for when the single casing corrodes the cost of rehabilitating the well or drilling a new one will be far greater than the cost of the additional few hundred feet of casing. Experience shows that when wells are drilled by the jet method they should be double cased through the beds that carry salt water. Since there appears to be no widespread clay bed capable of shutting out the ocean water above the great clay bed in order to be safe, the outer casing should be carried down into that clay several feet. As an added precaution, which will probably eventually prove to be of value far in excess of the small additional cost, cement or mud fluid should be poured between the two casings. The cement serves two purposes—it displaces the water between the two casings which might produce galvanic current; and if

[38]Mills, R. Van A., op. cit., p. 5.

either casing should corrode it forms a pipe independent of the casing. Because of the small space between the casings care must be used in mixing and pouring the cement to be sure complete filling of the space between the casings is obtained.[39]

During the last two or three years a number of wells have been put down in the Atlantic City region by the rotary-hydraulic method. In such wells only a single casing is used through the salt-water horizons. In view of the experience with single-cased wells drilled by the jet method, there has been some question as to whether double casing should not be required in these newer wells. This important question has been given considerable attention by the writer.

The rotary-hydraulic method of drilling differs considerably from the jet method. The hole is scraped out, as it were, by a bit which is rotated on the end of a string of pipe. During the drilling heavy mud fluid is pumped down the pipe and rises up the hole, carrying with it the cuttings. In so far as a mud fluid is pumped down the pipe and rises in the hole outside of it, this method is similar to the jet method. In the rotary-hydraulic method, however, the fluid is much thicker and heavier and much more of it is used. The principal purpose of the mud is to hold up the walls of the hole until the casing is put in. This it does in sand formations by filling in the pore spaces between the sand grains, causing the mass to stick together. The casing is not put in until the hole is completed to the desired depth. The users of the hydraulic-rotary method claim that, in addition to holding up the wall of the hole, the clay forms an effective seal, which prevents the salt water from reaching and attacking the casing.

The rotary-hydraulic method is used very extensively in oil fields where the formations consist of unconsolidated or semi-consolidated materials. In such fields one of the most important problems is that of shutting out water, both fresh and salt, from the wells. Accordingly, information was sought as to the use of mud fluid in shutting out water in oil fields. The subject has been investigated extensively by the United States Bureau of Mines.[40] The value of mud-laden fluid in preventing corrosion is summarized by Mills, as follows:[41]

39For methods of cementing wells see Tough, F. B., Methods of shutting off water in oil and gas wells: U. S. Bureau of Mines Bull. 163, 1918.

40See the following bulletins of the United States Bureau of Mines: Lewis, J. O., and McMurray, W. F., The use of mud-laden fluid in oil and gas wells: Bull. 134, 1916. Tough, F. B., Methods of shutting off water in oil and gas wells: Bull. 163, 1918. Ambrose, A. W., Underground conditions in oil fields: Bull. 195, 1921. Collom, R. E., Prospecting and testing for oil and gas: Bull. 201, 1922. Swigart, T. E., and Beecher, C. E., Manual for oil and gas operations: Bull. 232, 1923. Mills, R. Van A., Protection of oil and gas field equipment against corrosion: Bull. 233, 1925.

41Mills, R. Van A., op. cit., pp. 74-75.

"The use of mud-laden fluids to protect well casing against the corrosive action of waters standing either between different strings of casing or around the outside of casing has been repeatedly described in the literature on petroleum engineering. * * * The three chief features in the use of mud-laden fluid for the protection of casing against corrosion are:

"1. Displacement of corrosive water when the mud fluid is forced into place around or between casing.

"2. The clogging action of mud fluid as it enters the interstices of a sand. This clogging action tends to render the sands around the well impermeable, thus stopping or restricting circulation.

"3. The exclusion of corrosive waters and gases from contact with the casing, not only by displacement and clogging action of the mud, but also by the static pressure of the column of mud fluid standing back of the casing, which continually opposes the movement of the corrosive water back into the well and into contact with the casing.

"Salt brines are sometimes used for mud-laden fluids, but as a rule such waters tend to drop the clays from suspension and to facilitate corrosion. The effort should be made to use waters that are non-corrosive, or that are less corrosive than deep-seated brines. This, with the exclusion of circulating waters and gases from around the outside of casing, affords a valuable protection against corrosion as is indicated by the relatively long life of casing in wells where the mud-laden-fluid method has been applied."

After citing examples of the value of mud-laden fluid in preventing or reducing corrosion Mills states: "The mud-laden-fluid method is undoubtedly one of the most effective as well as one of the most inexpensive methods of protecting water strings against corrosion from the outside."

In connection with the use of mud-laden fluid for the prevention of corrosion the following statements are pertinent: The specific gravity of the average mud fluid is stated to be between 1.05 and 1.30.[42] The lower specific gravity is heavier than sea water, which ranges from 1.02 to 1.03. Therefore, the weight of the mud fluid is sufficient to displace the salt water from around the well. It is believed that the mud penetrates the sand for at least several feet from the well, thus replacing the salt water. In drilling one well at Atlantic City mud was pumped from another well about 20 feet distant, showing that some of it traveled that far. In oil field wells similar evidence shows that the mud in some formations has traveled as far as 1,000 feet.

[42]Swigart, T. E., and Beecher, C. E., op. cit., p. 33.

An essential condition when mud is used to prevent corrosion is that the mud remain in a fluid condition, for the effectiveness depends upon its weight as a fluid to hold back the corrosive water. If the mud were to dry out it would doubtless crack so that the salt water could reach the casing. Experiments show that when air was excluded from tubes containing mud fluid the original condition was still maintained after a period of at least two years.[43] Doubtless this condition would be maintained indefinitely in a well if there were no opportunity for evaporation. In the Atlantic City region the ground is saturated to within a few feet of the surface, so that conditions are favorable for the maintenance of the fluidity of the mud indefinitely. If the mud flued were drained away partly or wholly from the hole the corrosive water could again reach the casing. However, conditions in Atlantic City region are such that, barring some very unusual circumstances, this is not likely to happen.

A fourth important condition to be observed when using mud fluid, as mentioned by Mills (see above), is that the water used in mixing the mud should, so far as possible, be noncorrosive or nonsaline. Salt water tends to cause the mud to settle out of suspension. This factor may conceivably be important in the Atlantic City region if wells are drilled at localities near the ocean, where the public supply or other water of good quality from deep wells is not available for drilling, and water used from temporary shallow wells may be salty. The water from the public supplies and deep wells is noncorrosive or only slightly so, and its use should cause no difficulty.

Mud-laden fluid has been used very extensively in drilling oil wells in California. Probably no state in the country has more stringent regulations in regard to the exclusion of water from oil wells, for a rigid test under state supervision must be made before wells can be put into use. Believing that there should be ample evidence in this state as to the effectiveness of the mud fluid in shutting out salt water, the salt-water problem in the Atlantic City region was described rather fully in a letter to the State Oil and Gas Supervisor of the California Mining Bureau. In his reply the supervisor, Mr. R. D. Bush, states:

> "It is my opinion that if these wells are drilled and cased with one string of casing to the top of the fresh-water sand and a column of mud fluid maintained on the outside of the casing to the surface, the salt water will be effectively prevented from coming in contact with the metal casing, and corrosion thereby

43Tough, F. B., op. cit., p. 59.

prevented. I believe that while drilling the mud fluid will penetrate the porous sands to some extent, but the hydrostatic pressure of the mud fluid is relied upon to keep the salt water back in the formation away from the casing, and, therefore, a well in this condition should be inspected from time to time and the column of mud fluid maintained to the surface.

"I do not know of any cases in California of oil wells drilled in this method where the mud fluid has subsequently disappeared and allowed water to have access to the oil sands. While oil wells are drilled principally in this manner in this State, there is also an additional protection provided by placing cement back of the casing for a considerable distance above the shoe, and in some instances cement has been forced to the surface on the outside of the casing, which, if the casing is in the center of the hole and not touching the sides, forms a protective coating of cement between the casing and the walls of the hole, and it seems to me that this practice would be advisable in the drilling of these water wells, if it is in fact corrosion which causes the trouble, or even if it is the water leaking around the shoe of the casing which causes the trouble.

"I would suggest that in wells that are not drilled by the hydraulic method using mud-laden fluid, two strings of casing should be used to the top of the fresh-water sands, and in the event that the outside string became corroded allowing salt water to have contact with the inside string, which, in turn, would become corroded, the inside string could be pulled out easily and the corroded joints replaced with very little cost."

Summarizing the methods of preventing the contamination of wells by invasion of salt water from the overlying horizons, it is believed that either of two methods will prove effective—namely, (1) double casing the well, using due care to see that the outer casing is set tightly in the big clay bed, and (2) drilling with a heavy mud fluid which will push back the salt water from the casing. Care in drilling and setting the casing is the important thing, for in the long run it will prove to be most economical.

DANGER OF SALT-WATER CONTAMINATION DUE TO HEAVY PUMPING.

Although so far there has been no contamination by shoreward percolation in the 800-foot sand, experience in other localities emphasizes the importance of considering the possibility of contamination from this source. The conditions at Atlantic City present elements of special danger in that the static head is so far below sea level, not only in that city, but also presumably for some distance out beneath the ocean.

The problem is one that does not permit of definite solution with our present knowledge, for the most important factors are related to conditions beneath the ocean concerning which we have no information. Therefore, we must depend upon a more or less theoretical consideration of conditions off shore.[44]

A factor hindering contamination of the 800-foot sand at Atlantic City is the presence of the overlying 300 feet of impervious clay, which prevents the direct access of ocean water. A question of moment is whether the 800-foot sand contains only fresh water throughout its entire extent or whether at some place it carries salt water which may be drawn into the wells at some future time. In view of the practical importance of the problem, the writer has been led to speculate on conditions beneath the ocean with the following results.

The 800-foot sand is a marine bed and must once have contained sea water. The presence of fresh water can be explained only by movement of the original salt water seaward to a sub-oceanic outlet. If the dip of the sand at Atlantic City, about 25 feet per mile, continues off shore, its outcrop would be at the edge of the continental shelf about 90 miles out and at a depth of about 3,000 feet, as shown in Figure 21, A. If the sand is filled with fresh water to the outcrop, the weight of the salt water in contact with it at the outlet, assuming an average density for salt water of 1.025, would create a head sufficient to cause the fresh water to rise at least 75 feet above sea level.[45]

It must be remembered that this head would exist at the outcrop at the edge of the continental shelf. It would be fully as great at Atlantic City, and if the fresh water were moving oceanward it would necessarily be even greater. Thus, if the hydraulic gradient required for movement of the water were only one foot per mile, the static head at Atlantic City would have to be about 165 feet above sea level. When the first wells were drilled no such high head as this existed—

[44]This problem has been considered by the writer in "Ground water problems on the barrier beaches of New Jersey": Bull. Geol. Soc. Amer., vol. 37, pp. 468-474, 1926. Additional data are presented in the present discussion.

[45]According to H. B. Bigelow (Exploration of the Coastal Water between Nova Scotia and Chesapeake Bay, July and August, 1913, by the U. S. Fisheries Schooner Grampus, Bull. Mus. Compar. Zool. Harvard Coll., Vol. LIX No. 4, Sept., 1915, Fig. 59, p. 219) the ocean water in the great abyss beyond the continental shelf abreast of Barnegat, N. J., has a density of about 1.023 near the surface, which increases to 1.025 at a depth of about 120 feet and of 1.029 at a depth of about 1,500 feet. The average density of the column of water to a depth of 3,000 feet is therefore somewhat greater than 1.025 so that the figure given above is conservative.

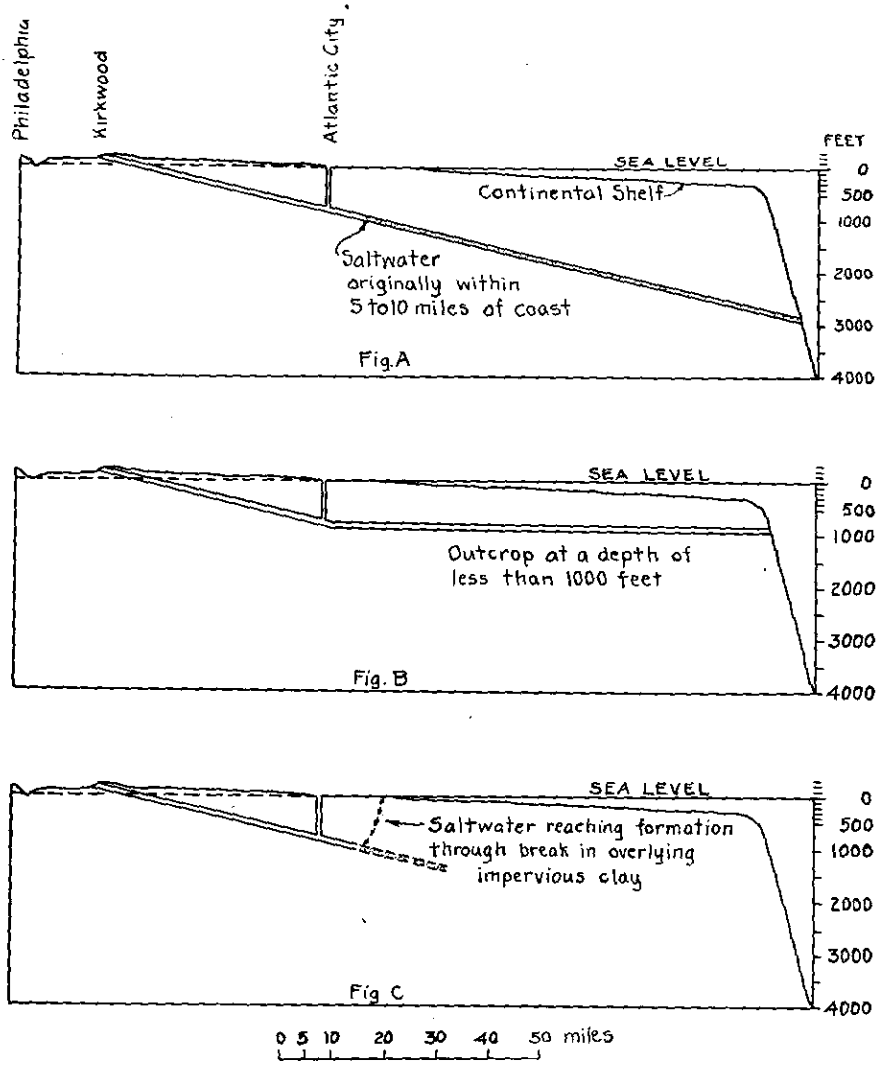


FIG. 21.—Diagrams showing possible alternative conditions that would account for a head of 25 feet on the 800-foot sand at Atlantic City.

nor even as high as 75 feet. It is therefore evident that the 800-foot sand does not contain fresh water to a depth of 3,000 feet.

The original static head of 20 to 25 feet at Atlantic City is equivalent to a column of salt water only 800 to 1,000 feet high and having a density of 1.025. From the facts stated the following alternative conclusions arise: 1. If the sand does outcrop at the edge of the continental shelf at a depth of 3,000 feet, it must be filled with salt water back to a point where its depth is less than 1,000 feet, as shown in Figure 21, A. 2. The dip of the sand off shore may be much less than 25 feet per mile, and the outcrop may be at a depth of less than 1,000 feet, as shown in Figure 21, B. 3. The salt water creating the head on the sand may gain access to it much nearer shore than the edge of the continental shelf through relatively permeable overlying materials, as in Figure 21, C. It will be noted in Figure 3 that the Kirkwood formation is bevelled off beneath the ocean along the coast some 50 miles north of Atlantic City and in the lower part of Delaware river. Doubtless salt water has gained access to the formation at least in the former locality.

In the above discussion no consideration has been given to several questions of a strictly stratigraphic nature, such as the likelihood that the 800-foot sand extends to the edge of the continental shelf, some 135 miles from its outcrop on the land; or the probability that the thick clay bed is continuous over the sand and wholly effective in preventing salt water from reaching the sand except at the edge of the continental shelf; or the possibility that some unsuspected structural condition might give salt water access to the formation at a depth of less than 1,000 feet. Regardless of the reasonableness of any of these possibilities, there seems to be no escape from the conclusion based on hydraulic data that the zone of diffusion between salt and fresh water is at a depth of less than 1,000 feet below sea level.

If the dip of the sand off shore is 25 feet per mile, as at Atlantic City, the diffusion zone must be less than eight miles out, and if allowance is made for loss of head due to flow, probably several miles less. At Wildwood the sand lies at a depth of about 900 feet, and conditions there should be somewhat comparable to those about four miles off shore at Atlantic City. If the salt water is within a few miles of Atlantic City the water in the Wildwood region may be expected to show a somewhat greater chloride content. The following table gives the range of chloride in water from wells drawing on the 800-foot sand as determined by analyses made at frequent intervals during the past 15 years. The localities are arranged in order from north to south.

RANGE IN CHLORIDE CONTENT OF WATER FROM WELLS TO SO-CALLED 800-FOOT SAND.

(From analyses by N. J. State Department of Health, 1906-1925, and U. S. Geological Survey, 1924-1927.[a])

	Depth of wells	Chloride Parts per million Min.	Max.
Absecon (mainland)	675	3	6
Atlantic City	800–840	6	11
Ventnor	825	5	13
Margate	815	3.5	15
Longport	850	5.5	11
Ocean City	840	6.5	12.5
Corson's Inlet	856	14	26.5
Sea Isle City	863–875	15	25
Avalon	925–935	30	36.5
Stone Harbor	890	16	49
Wildwood	931	134	648
Wildwood Crest	930	284	383

South of Wildwood, in a well at Lewes, Delaware, the water from a formation at a depth of 891 to 950 feet, which is believed to be the same as the 800-foot sand at Atlantic City, was so salty that it was not used.[46] The data thus show, as was suggested, a progressive increase in chloride with increase in the depth to the formation.

The situation at Wildwood deserves further consideration. The analyses for Wildwood are of samples of water from a well drilled in 1894 at the corner of Pine and Holly Beach Avenues. The highest chloride content, 648 parts per million, was found in a sample collected on November 2, 1927, and a sample collected on September 28, 1926, contained 534 parts per million. The lowest chloride content has also been found within the same period, 134 parts per million on January 1, 1927, and 172 parts per million on April 29, 1928. However, the chloride in samples collected on nine other days between July 20, 1926, and September 1, 1927, in some cases several samples on the same day, ranged between 198 and 239 parts per million. There is reason to believe that the unusually high samples are due to a slight leak in the casing at some point, and that the unsually low samples are of water that has been forced into the well from the distributing main, for the samples contained the smaller amounts of chloride were of the first water coming from the wells. Samples analyzed in 1906-1907 indicate that the chloride content of water from the Atlantic

[a]Some of the figures in this table differ from those given in the paper by the writer in the Bulletin of the Geological Society of America, additional analyses having been found in published reports of the State Department of Health for the years 1906 to 1910, inclusive.

[46]Woolman, Lewis, Artesian and other wells in New Jersey: Annual report of State Geologist for 1898, p. 83.

City 800-foot sand at Wildwood was even then as much as 180 to 207.5 parts per million.[47] The evidence points strongly to the fact that the normal chloride content in the water at this well is about 200 parts per million, and has been so for at least the past 20 years.

In September, 1925, a new well that draws from the Atlantic City 800-foot sand was completed at Wildwood Crest, about a mile south of the old well at Pine and Holly Beach Avenues. A sample analyzed at that time by the State Department of Health contained 370 parts per million of chloride. In samples collected on 18 different days between March 8, 1926, and July 2, 1927, at intervals of a few days to several months, including several samples on certain days, the chloride has ranged between 284 and 383 parts per million. On only two occasions, however, has it been less than 300 parts per million, and in most of the samples it was more than 325 parts per million.

At first it was believed that there might be some leakage either through a break in the casing or through imperfect packing where the different strings of casing overlapped. The well is double cased to the water-bearing sand and leakage through breaks seemed impossible. The drilling contractor carefully repacked the space between the casing and screen, but the high chloride persisted. Tests according to the method used in determining the source of contamination in the Royal Palace Hotel and Atlantic City Brewing Co. wells (see pages 100 and 104) failed to reveal any condition that would indicate contamination through leakage. The conditions rather indicate that the chloride content shown in the analysis was essentially the normal for the water contained in the formation.

Since the density of salty water is heavier than fresh water, and the salt water tends to seek the lowest part of an aquifer, it was considered possible that water in the upper part of the sand might contain somewhat less chloride than that of the samples. Favoring this hypothesis is the fact that the water was drawn from two separate horizons, between the depths of 810 and 850 feet and 877 and 937 feet. Therefore, the lower part of the screen was plugged off and water entered only through the upper section. Apparently the most of the water comes from the lower horizon, for after that part of the aquifer had been plugged off the supply was so diminished that the pump suction was broken and the water was delivered in intermittent gushes. Subsequently, the yield of the well increased somewhat, indicating either that the upper horizon had opened up or that some water was reaching the well from the lower horizon. The well was pumped for several

[47]Report of New Jersey Department of Health for 1907, pp. 198-199.

days, and although the chloride content mostly ranged between 305 and 315 parts per million—that is, somewhat lower than most of the previous samples—there was no indication of any progressive decline. It was therefore concluded that the upper horizon was also filled with water the chloride content of which was too high for use. The well has been temporarily abandoned, but an attempt is to be made to pull back the screen and develop a water-bearing sand encountered at shallower depth.

The differences in chloride content between Atlantic City and Wildwood are small, but they assume greater significance when it is understood, as has been shown by experience elsewhere, that the zone of diffusion between fresh water and practically pure sea water may be only a few feet to a few hundred feet in width, and that the change from fresh water to salt water in a field that is pumped heavily may occur within a very short time. For example, on the Holland coast the diffusion zone has been found to be only 60 to 100 feet wide.[48] In the Spring Creek well station of the New York Board of Water Supply on Long Island the chloride was found to increase from 10 to 1,400 parts per million in wells only about 20 feet apart.[49] At the Shetucket well field on Long Island the chloride increased from 45 to 100 parts per million in a little more than a year, and in five years it increased to 500 parts per million, although the pumpage had been greatly decreased.[50] A case is recorded of a well at Eastbourne, England, in which the chloride rose to some 2,000 parts per million in 12 months.[51]

In view of the evidence presented it seems entirely possible that salt water may even now be only a few thousand feet from the coast in the Wildwood region. If similar conditions originally existed four or five miles off shore at Atlantic City the salt water may be well within the area in which the head has already been lowered, which, as shown on page 74, probably extends some seven miles seaward. Consequently, the salt water may be moving toward the Atlantic City well. If this is true, it is only a question as to the time required for the salt water to reach the wells. The landward movement of the salt water would not begin until the area influenced by pumping had reached the diffusion zone some years after the first wells were used. At first, the landward

48Brown, J. S., op. cit., p. 36.

49Burr, W. H., Hering, Rudolph and Freeman, J. D., Report of the Commission on additional water supply for the City of New York, p. 419, 1904, wells Nos. 47 west and 50 west: and Spear, W. E., Long island sources of an additional supply of water for the City of New York, vol. 1, 1912, diagram on sheet 56, showing layout of well field.

50Spear, W. E., op. cit., pp. 145-147, and Brown, J. S., op. cit., p. 47.

51Mason, W. P., Damage to wells by sea water: Jour. Am. Water Works Assoc., vol. 8, No. 1, discussion by William Gore, p. 71, Jan., 1921.

movement of salt water would be slow, but it would become increasingly rapid as the head declined. Rough computations show that if the average pumping draft from a two-mile section along the beach in Atlantic City were five million gallons a day, it probably would require about 10 years for the water to move one mile. This rate has not been maintained since the first wells were drilled to the horizon, but in the 35-year period since that time there has been opportunity for it to move at least a mile or more toward the beach. Since the total quantity pumped from the horizon promises to increase the rate of movement will be accelerated. For example, if the pumping rate reaches an average of 10 million gallons a day, the advance of the salt water would be of the magnitude of about one mile in five years. Therefore, even though danger of widespread contamination of the formation may not be immediately imminent, it may conceivably occur within a very few decades. It appears that the danger of salt-water contamination may become fully as important a controlling factor as the economic pumping lift in determining the ultimate safe yield of the 800-foot sand at Atlantic City.

SHALLOW HORIZONS ON THE MAINLAND.

GEOLOGIC CONDITIONS.

On the mainland water is obtained in sand beds within 200 feet of the surface. These beds have been used principally at the Atlantic City Water Works in Pleasantville, and to a much less extent by industries and institutions between the Sea View Golf Club, north of Absecon, and Somers Point. The localities where wells exist are fewer and less definite information is available as to the geologic conditions than for the 800-foot horizon. Accordingly there is a less satisfactory basis upon which to draw conclusions as to the water-bearing capacity of the formations.

Logs are available for wells at the Atlantic City Water Works, at the Sea View Golf Club about three miles northeast of the water works; at the Atlantic County Hospital for Mental Diseases, about 2½ miles southwest of the water works, and in Somers Point, about 7½ miles southwest of the water works. The important features of the log of the water-works well is that the materials down to a depth of 250 feet are dominantly sand with distinct beds of clay from 18 to 29 feet and from 100 to 120 feet, and a mixture of sand and clay from 120 to 138 feet. The logs of the wells in the other localities mentioned likewise show a predominance of sand beds, with several clay beds from 2 to 30 feet thick. But neither on the basis of lithologic character or depth can any of them be said definitely to be continuous over a large area. In contrast to the Atlantic City 800-foot sand, which is easily recognized over a very large area as a distinct formation sandwiched in between clay beds, the shallow horizons in the mainland seems to be mainly a series of sand beds with lenses of clay that thin or thicken from place to place and are not continuous for any great distance. Considering the geologic history of the region, it is probable that the blue clay that lies near the surface at the Atlantic City Water Works covers only a small area along preexisting stream channels. The deeper clay, struck at 100 feet, may be more extensive, but it has not yet been proven to underlie the entire area. The clay lying below 280 feet at the water works is the great clay bed that is reached about 100 feet lower in Atlantic City. It is known to reach to a depth of about 600 feet where the Atlantic City sand is found. At the County Hospital for Mental Diseases this clay bed extended from 310 feet to 640 feet below the surface with practically no water-bearing sand in that thickness. Therefore, unless a well is to be drilled to the Atlantic City 800-foot sand, it is useless to drill deeper than about 275 to 300 feet below sea level at points above the shore road.

MINOR DEVELOPMENTS OF SHALLOW HORIZONS.

With the exception of the Atlantic City Water Works there has been far less development of the shallow horizons on the mainland than of the 800-foot horizon on the beaches. At the Sea View Golf Club about 150,000 gallons per day is pumped from a 231-foot well for use around the club house. In addition, in summer about 734,000 gallons a day is pumped from six wells 85 to 97 feet deep, and one well 195 feet deep on the lower part of the golf links for lawn sprinkling. Doubtless most of the water used in this way returns almost immediately to the formation, so that it cannot be considered an actual draft on it. At the Atlantic County Hospital for Mental Diseases between 50,000 and 100,000 gallons is used daily from wells about 150 feet deep. At the Atlantic County Tuberculosis Hospital nearby a few thousand gallons is used from a 300-foot well. The Atlantic County Water Company uses an average of 46,000 gallons per day from its new well at Somers Point and an old one at its Bargaintown pond with a maximum average daily consumption of 106,000 gallons in July. Water from wells is used at a laundry and an ice plant in

Pleasantville and one or two other places. However, excluding the pumpage at the Atlantic City Water Works, which is considered below, and the consumption of water at the Sea View Golf Club for sprinkling, the maximum daily consumption at the mainland plants described above is probably not more than half a million gallons.

DEVELOPMENT AT ATLANTIC CITY WATER WORKS.

Well data.—At the Atlantic City Water Works, near the dividing line between Pleasantville and Absecon, the shallow horizons are drawn upon by 32 wells distributed over an L-shaped area. (See Fig. 22.)

The actual area occupied by the wells is not more than 20 acres. Two of the wells are 95 feet deep, 16 are 100 feet, 12 are 200 feet, one is 206 and one is 225 feet. The wells are generally considered, however, as penetrating the so-called 100 and 200-foot sands. The wells are mostly 10 inches in diameter with 8-inch screens. The length of screen in different wells ranges from 20 to 50 feet. Four kinds of screens are in use—Cook, Woodbine, which is somewhat similar to the Cook, plain slotted pipe galvanized after cutting, and concrete screen.

The wells are pumped by suction. They are distributed along four separate suction systems, each pumped by a horizontal centrifugal pump. Two of the systems pump 10 wells each, one pumps seven and the fourth pumps five. Three of the systems discharge into a storage basin from which the water is drawn to the pumps of the distribution system. The fourth discharges directly into the suction well from which the force pumps draw.

The 32 wells are so distributed that in general a 100-foot well alternates with a 200-foot well, but this is not true everywhere in the field. (See depths of wells on Fig. 22.) They are mostly spaced 150 feet apart, and with the scheme of alteration two wells of the same depth in most places are 300 feet apart. However, two of the 200-foot wells are only about 55 feet apart and two of the 100-foot wells only 110 feet apart. Several of the other wells are more than 150 feet, but less than 300 feet from the nearest well of the same depth.

From July, 1923, until the Fall of 1925, one system of 10 wells was out of commission, because it was not possible to maintain suction. This difficulty was at first thought to be due either to leaks in the suction main or possibly to an abnormal lowering of the water level in the wells during the unusually dry summer. It has since been proven

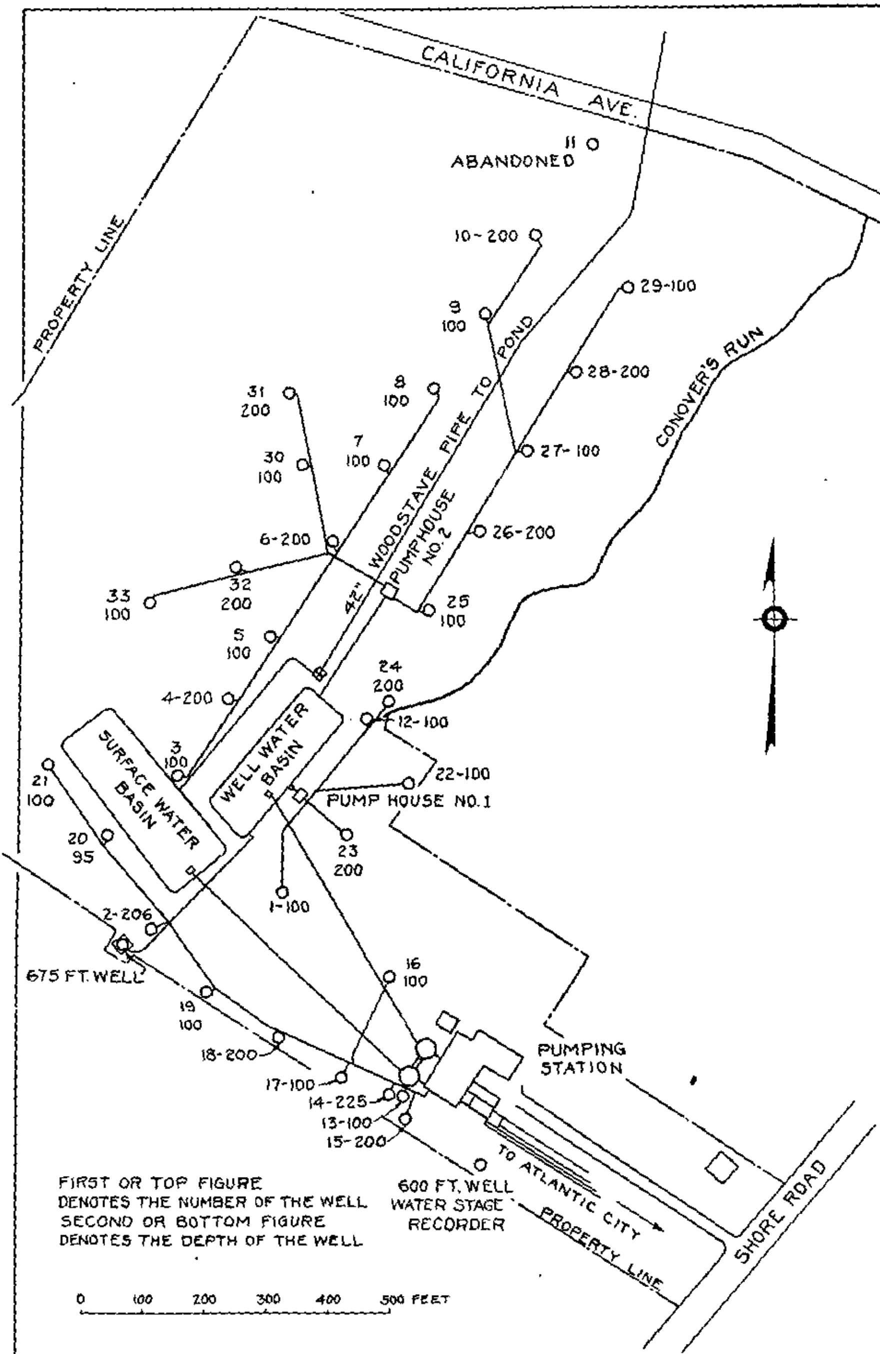


FIG. 22.—Map of Atlantic City Water Works well field.

that the difficulty was due to the clogging of the screens in the older wells so badly that enough water could not enter to supply the pumps. In 1925 and 1926 these wells were replaced by new ones equipped with Kelly concrete screen. These new wells have given such large yields that it is obvious that the water-bearing capacity of the sands has not been impaired.

Yield of wells and effect of pumping.—Measurements made during the spring of 1924 showed a yield from the three serviceable systems of 22 wells of approximately 4.25 million gallons a day. When measurements were made several years ago the yield of all four systems was about six million gallons a day. Since the data for the tests of the three systems in 1924 checked rather closely with that for the same systems during the previous test, it may be safely assumed that since the fourth system has been put in service the original yield of six million gallons a day is now being obtained. This would be an average yield of about 130 gallons a minute from each well. However, the yield from all the wells is not equal. One well is said to have yielded 400 gallons a minute when first put in service, and some have yielded less than 100 gallons.

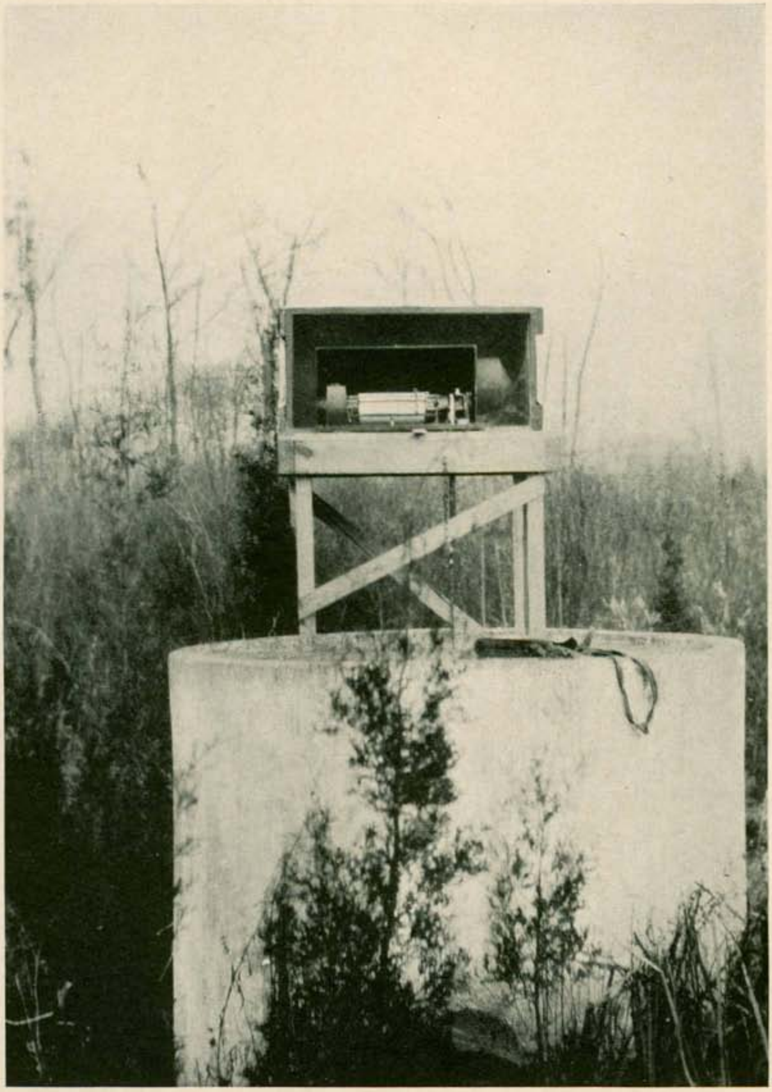
During the present investigation rather detailed tests were made to determine the effect of pumping each of the two horizons and their relative water-bearing capacity. Under existing operating conditions it is very difficult to obtain adequate data as to the yield of individual wells or as to the comparative yield of the 100 and 200-foot horizons. The pumps could not be slowed down enough to pump only one well without losing suction, nor even to pump only two at a time. The best that could be done was to pump, for example, one of the 200-foot wells with all of the 100-foot wells on that system, but with the other systems shut off. Later, a second 200-foot well was added, then a third, and so on. This caused complications. The system pump develops only a constant amount of power. Under theoretically ideal conditions all wells would yield the same quantity and the friction loss between each well and the pump would be the same, but under the existing conditions the friction loss in the pipe lines several hundred feet long naturally differs, depending upon whether wells in operation are near the pump or far from it. Also, it is not known whether a newly added well on the 200-foot horizon yields less water than those previously pumped, for there automatically occurs a change in the yield of the other wells being operated to bring about a balancing of the draft exerted by the pump on different parts of the system. Thus, if a certain quantity of water is discharged when several 100-foot wells and one 200-foot well were pumped, there is no way of telling how much comes from each well; and if a second 200-foot well is added, even though the discharge may increase, it cannot be said with assurance that the increase comes from that one well.

The first tests were made to determine the effects of pumping wells of the 200-foot horizon. All 200-foot wells were shut off for about four days, to allow the head on the formation to reach a true non-pumping static level. The water level in the wells rose rapidly to above the surface. Most of the wells flowed and the level was determined accurately in only one well to which a glass tube was tightly connected. The static level in that well was 9.5 feet above sea mean level, and was constant with less than a tenth of an inch fluctuation for at least three days. However, since there was still discharge from some of the wells, this was not a true static level.

With five 100-foot wells pumping, one 200-foot well (No. 15, on Fig. 22) was turned on and pumping continued about 24 hours until the water level in the observation wells became stable. The draw-down in the 200-foot well was approximately 25 feet. It was not possible to determine the pumpage from well No. 15, but it was probably not more than 285 gallons a minute, and may have been as low as 200 gallons a minute. In the 200-foot well farthest from the pumping well, a distance of 1,200 feet, the head was lowered almost exactly one foot. Without attempting a mathematical solution, but by a graphic solution in which the curve representing the head is continued as a straight line between two of the observation wells, it is estimated that the radius of the circle of influence or point where the loss in head became negligible was approximately 1,800 feet. (See Fig. 23.)

Following this, tests were made with two, three and four 200-foot wells, respectively, in addition to the five 100-foot wells. The details of each test need not be given, but the results are shown graphically in Figure 23. In the diagrams the shape of the profile between pumping wells is necessarily theoretical. The location of the non-pumping wells is determined by their distance from the nearest pumping well, and, therefore, in the different profiles wells 28 and 31 are not always in the same position with respect to well 15. With four 200-foot wells pumping, the water level in the most remote observation well (about 1,125 feet from the nearest pumping well) was lowered about 4.4 feet below the static level. The total yield of the four 200-foot wells during this test was probably not more than 930 gallons a minute, and was very likely somewhat less. By continuing the profile of the piezometric surface for this test line with the same slope as between the two observation wells farthest from the pumping wells, it was found that the radius of the circle of influ-

PLATE VII.



Water-level recorder installation on well No. 28, Atlantic City Water Works well field.

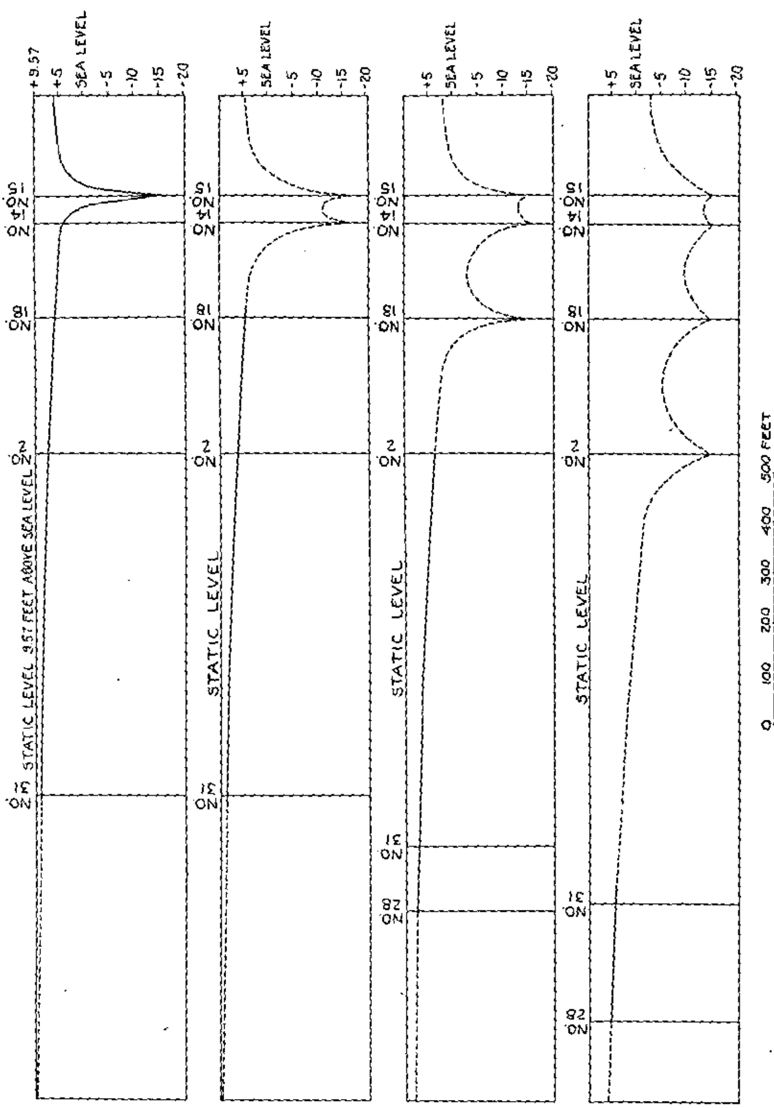


FIG. 23.—Profiles of piezometric surface when pumping 1 to 4 200-foot wells in Atlantic City Water Works field.

ence would be at least 2,000 feet. As a matter of fact, the hydraulic profile is not a straight line with a given gradient between any two points, but flattens away from the pumping wells. Therefore, the radius of influence is actually greater than estimated, probably at least 2,500 feet or about half a mile from the nearest pumping well.

It was not possible to obtain data of any value relating to the 200-foot horizon with more than the four wells pumping at the same time, for the additional wells would have been so close to the observation wells that a reasonably accurate profile could not be developed. From a study of the tests made, however, it appears that with all 15 of the 200-foot wells pumping the influence of the wells would extend probably at least three-fourths of a mile to a mile beyond the borders of the well field. The lowering of the head in the outer part of this area of influence, however, would be only a few inches. The total pumpage from all the 200-foot wells would be probably somewhat less than half of the total pumpage for both horizons—that is, less than 3,000,000 gallons a day; for there is evidence that the 200-foot well yields less water than the 100-foot wells.

Tests similar to those just described, except in somewhat less detail, were made on the 100-foot wells. The essential results are as follows: After all the 100-foot wells had been shut off for nearly 48 hours the static level stood not quite six feet above sea level—that is, about three and a half feet lower than the static head in the 200-foot horizon. When a single well was pumped, with a yield estimated to be between 200 and 275 gallons a minute, at the end of seven hours the head in two wells, each about 1,000 feet distant from the pumping well, was lowered less than four-tenths of a foot. It was evident that the head would not have dropped much farther. When five wells, distributed along a line 800 feet long, were pumped to yield about 1,430 gallons a minute, the head in an observation well 920 feet from the nearest observation well was lowered only about 2.5 feet. This compares with a lowering of 4.4 feet at a distance of 1,125 feet for four 200-foot wells pumping only about 930 gallons a minute—that is, the loss of head was considerably less for pumping 1,400 gallons from the 100-foot horizon than for pumping only about two-thirds as much from the 200-foot horizon. With three systems in operation, comprising nine of the deeper wells and 13 of the shallow wells, charts from automatic water-level recorders on observation wells on each horizon show that the loss in head below static level is at least two feet greater on the 200-foot horizon. Presumably, the 100-foot wells were yielding more water than the deeper wells. There is therefore good reason to believe that the 100-foot sand is somewhat more permeable than the 200-foot bed. This conclusion corroborates the observations of the engineers of the Atlantic City Water Department during the development of the well field.

It was not possible to estimate the probable radius of the circle of influence when the five 100-foot wells were pumping, because the diffence in the observed lowering of the head in the observation wells was so small that the graphic method could not be used with any reasonable degree of accuracy. However, on the basis of the relative lowering of the head on the two horizons, it is evident that the radius of the circle of influence of the 100-foot horizon would be considerably shorter than that of the 200-foot horizon when equal quantities of water were being pumped.

Comparison of shallow and deep water-bearing formations.—Although it has not been possible to determine the actual effects of pumping for more than a few hundred feet from the pumping wells, the tests give valuable data for a comparison of the water-yield capacity of the 100-foot, 200-foot and 800-foot sands of Atlantic City.

When the four systems at the water works are in operation six million gallons is pumped with suction pumps and the drawdown is definitely limited to about 30 feet below static level. Each of the two shallow horizons yields approximately three million gallons as compared to 3.5 to 5 millions gallons in 1924 from the deep horizon in Atlantic City alone. Because of these differences in pumpage exact comparisons cannot be made. Nevertheless, there is good evidence that the effect of pumping is considerably less for the shallow horizons than for the deep one. The pumping level in each of the shallow horizons during the tests was not more than 30 feet below the original static level, whereas for the 800-foot horizon in 1924 it was 75 to 100 feet below the original static head in the city. The area of influence of each of the shallow horizons probably at most extends only a little more than a mile from the well field as compared to the great depression of the head for several miles in every direction from the wells in Atlantic City. In 1925 the decline in head on the 800-foot sand apparently extended at least 8 or 10 miles both to the northeast and northwest, although there has been no pumping in those directions until that year. The shallow horizons respond to changes in pumping conditions very quickly. If all of the wells are shut off the water level reaches a practically constant static level in a few hours, and when pumping is resumed a constant pumping level is likewise reached in a short time. The present static head is not any lower than it was several years ago. On the other hand, when the pumpage from the Atlantic City 800-foot horizon is increased or decreased comparatively rapidly, a stable condition is not reached for many days. On the basis of these facts it is concluded that the water-bearing capacity of the 100-foot and 200-foot horizons is much greater than that of the 800-foot horizon.

Additional supplies from shallow horizons.—Since the shallow horizons at the water works seem to be better water-bearing formations than the 800-foot horizon, and the effect of pumping them has been considerably less than for the deeper horizon, there is little doubt that a considerable additional quantity of water can be developed from them. The data are too inadequate to warrant any accurate estimate as to the ultimate total quantity that can be obtained. If the geologic conditions over a considerable area are the same as in the water-works well field, it is reasonable to suppose that at least two or three times as much water as is now pumped can be obtained without causing a permanent overdraft. However, lacking the necessary information as to conditions outside of the present field, one is not justified in considering this statement as a conclusion upon which to base further development. Much information should be obtained in regard to several important problems which are briefly discussed below.

A very important problem relates to the location of future wells. The pumping level in the existing field at the water works is only about 25 feet below the ground surface. Probably a large quantity of water could be pumped from wells in the same field by increasing the drawdown. For example, on the basis of the well-recognized fact that within certain limits the yield of a well is directly proportional to the drawdown, if the pumping level were lowered to 50 feet about twice as much water could be obtained from the existing wells as at present.

It should be remembered that to obtain an additional quantity of water from the present well field the lowering of the pumping head will be essentially the same whether the water is taken from an increased number of wells or the draft on the existing wells is increased. It is well known that as the number of wells in a field is increased the yield per well decreases, and, therefore, that beyond a certain point the cost of drilling additional wells causes a disproportionate increase in the cost of getting the water. For this reason it has been found to be more economical to spread the wells over a large area than to attempt to obtain too large a supply in a restricted space of a comparatively few acres. An increase in the yield of the present well field by increasing the drawdown cannot be accomplished with the present pumping equipment, which is operating practically at the limit of suction lift, but it would require the installation of air-lift or deep-well turbine pumps. The extent to which an increased supply may be developed economically in the present well field requires a careful analysis of the initial cost of drilling new wells and of additional pumping equipment, and of the increased operating cost of raising the water from a greater depth—factors that are not within the scope of the present report.

A factor that should be carefully considered in developing additional supplies is the possible danger of salt water being drawn into the wells. The 100 and 200-foot horizons dip about 10 feet per mile toward the ocean. Therefore, along the shore in Atlantic City they would lie at approximately 160 and 260 feet below sea level. A study of well logs indicates that probably there is no impervious clay bed that would prevent salt water entering the horizons above the big clay bed along the coast. This conclusion is supported by observations on a test hole put down in Atlantic City in 1891 by J. H. Robinson,[52] which is the only well for which reliable data are recorded as to the fresh or brackish character of the water. In it fresh water was found at a depth of 75 feet, but all the water reported at depths below that to 328 feet was either salty or became so on pumping. It is probable that the water from the 75-foot horizon, if it has not since become salty, would quickly become so if pumped very heavily, for the fresh water in the uppermost horizons must exist only as a relatively thin layer replenished by local rains. A sample of water from a well 100 feet deep at Atlantic City Brewing and Ice Co. contained 1,825 parts per million of chloride. A sample from wells at the American Ice Co., 64 to 125 feet deep, contained 1,177 parts per million of chloride.

In view of these facts there is little doubt that salt water exists in the seaward extensions of the 100 and 200-foot horizons at least within five or six miles of the Absecon pumping station. It probably is present even nearer to the water-works well field, for the water in Absecon Bay is salty and at times of unusually high tide this water covers the meadow to within half or three-quarters of a mile of the well field. Samples of water from Absecon Creek, near the Pennsylvania Railroad station in Absecon, showed a range from 5,200 parts per million of chloride when collected shortly after low tide to 15,000 parts per million two hours after high tide. A sample collected at low tide at the bridge over the creek on the so-called "new road" half a mile farther upstream contained 4,900 parts per million of chloride. A sample collected at low tide from the creek just below the dam of Absecon pond contained 725 parts per million of chloride. At the time of collection some water was discharging from the pond, and this undoubtedly reduced the salt content of the creek below the dam. Doubtless, under ordinary conditions at high tide, the water in the creek as far up as the dam is nearly as salty as the water in the bay. Therefore, at such times salt water is present within three-fourths of a mile northeasterly from the well field. There is no reliable informa-

[52]Annual report of the State Geologist for 1892, p. 277.

tion to show whether the salt water has penetrated the water-bearing sands to any depth beneath the bay, the meadows, or Absecon Creek, or whether in these areas local clay beds may shut it out. A well drilled recently to a depth of 100 feet or more on the Fox development on the south side of the Pleasantville Boulevard about half a mile out in the meadows and only a few feet from the bay found only salt water. A sample from this contained 8.075 parts per million of chloride.

Analyses of the water from the 100 and 200-foot horizons, given on page 15, do not show any indications of salt water entering the formation. However, as shown in the discussion of the possibility of salt water invading the 800-foot horizon (pages 112 and 119), this cannot be considered as conclusive evidence that salt water may not be drawn in with even a comparatively small increase in pumpage. As has been pointed out above, the radius of the area of influence of the 200-foot horizon when pumping three million gallons a day is probably not more than three-fourths of a mile to a mile, and of the 100-foot horizon it is probably considerably less. The areas of influence thus barely extend out to the limits of nearest approach of salt water on the surface to the wells. However, if the pumpage in the present waterworks well field were greatly increased, for example, doubled or tripled, the areas of influence would be greatly widened, and the consequent greater lowering of the head beneath the meadows, bay or creek would tend to cause a greater flow of water from the immediate vicinity toward the wells. Whether or not salt water would move toward the wells would obviously depend upon whether the nearest salt water in the formation was within the circle of influence of the well field. The only way in which this can be determined is by drilling test borings.

It has been suggested that additional supplies of ground water can be developed from wells to be drilled on property now owned by the city along the pipe line between the pumping station and Absecon Pond; likewise, one or two wells might be placed along the pipeline from the station across the meadows to the city. Presumably, the wells would be of large diameter and placed several hundred feet apart, in accord with modern practice. Each well would be equipped with a deep-well turbine pump—the wells along the line to the city to the pump directly into the distribution system, and the others to pump into the conduit from Absecon Pond. In view of the presence of salt water in the shallow horizons at Atlantic City and its possible existence even much nearer to the mainland it is surely not wise to locate wells nearer the meadows without drilling test wells and making exhaustive pumping tests to prove whether or not salt water is likely to be drawn in. The wells to be drilled along the right of way between the pumping station and Absecon Pond would be dangerously near Absecon Creek if the salt water from it has access to the water-bearing horizons. Therefore, similar test wells should be drilled near the creek to determine the conditions there.

Even though pumping tests failed to draw in salt water, it could not be assumed with assurance that salt water would not be drawn in with increasing draft upon the water-bearing horizons. The most exhaustive tests would doubtless place a far less draft on the beds than would result from continuous pumping. The quantity of water to be drawn in before salt water reached a well, even if it lay only a comparatively short distance away, would require a considerable period under ordinary testing conditions. This can be shown by the following assumed example. Suppose a well be drilled approximately 1,000 feet from a possible source of salt water, that it drew from a 50-foot bed of sand overlain by clay so that the water could move only laterally, that the water moved with equal velocity from all directions, and that the effective porosity of the sand was 33.3 per cent. The volume of water stored in the sand within a radius of 1,000 feet of the well would be about 390 million gallons. Pumping at the rate of a million gallons a day, it would take 390 days for water 1,000 feet from the well to reach it. Obviously, it would have to be a very severe test that would show the presence of salt water under the conditions cited, especially in view of the fact that the transition zone between fresh and salt water may be only 60 to 100 feet wide (see page 118), and the further fact that fresh water coming from the landward direction would greatly dilute the salt water. But under actual operating conditions, even if the rate of pumping were no greater, the salt water would be drawn in a little more than a year.

Conclusions regarding shallow horizons.—It is believed that the wisest policy will be not to attempt to greatly increase the supply from the present field of the Atlantic City Water Works or to develop new supplies near likely sources of salt water contamination, but to get as far away from them as can be done. A region that seems to offer favorable conditions is the watershed of Absecon Creek, already owned largely by the city. This area presents a possible important advantage over others in that, unless there is a very extensive bed of impervious clay beneath the Absecon and Doughty ponds and around their borders, these bodies of water will serve as excellent storage reservoirs from which the ground-water supply may be replenished, and some of the flow of Absecon Creek that now is wasted could be saved. A series of wells drilled around these ponds would essentially constitute a natural filter system. If such conditions do exist, the yield of the well system would probably be greater than if an overlying impervious bed necessitated slower recharge by essentially horizontal movement of the water. Furthermore, the elevation of the water level in the reservoirs, being above the natural level if there were no storage, provides a greater head to hold back salt water and therefore a greater factor of safety than in the area below the dam. It is not certain that the conditions around the ponds are favorable for recharge from them, but this could be readily ascertained by a few test holes.

An obvious feature revealed by the above discussion is the lack of data in regard to critical conditions. It is not known definitely, for example, just how far-reaching is the area of influence of wells now in operation in the 100 and 200-foot horizons at the Absecon water works, nor how near to the well field salt water may be except that it exists beneath Atlantic City and probably is even nearer. No information is available as to the extent of the water-bearing beds—whether beds with water-bearing capacities similar to those in the water works well field exist beneath the watershed of Absecon Creek and elsewhere. These and other questions can be answered only by drilling wells and making extensive tests.

To obtain the most prudent development of the shallow horizons no large project should be undertaken without first making these necessary tests, for, if started in ignorance, after considerable expenditure of money conditions may be found that will necessitate the abandonment of the project, resulting not only in the financial loss but also loss of valuable time when water may be needed. A few thousand dollars and a few months' time spent in obtaining the necessary information will, in the long run, be found to pay for itself on a project that must eventually cost at least several hundred thousand dollars. Plans must be made not only for its immediate needs but for those of two or three decades hence. If it is found that conditions elsewhere in the region are not as favorable as in the water works well field, it may be wiser and more economical to undertake one of the projects considered in the past to obtain surface water from one of the more distant watersheds. The problem requires a careful analysis of ultimate cost as well as a study of the hydrologic conditions.

RECOMMENDATIONS FOR FURTHER WORK.

Observations should be continued on the fluctuations of the head on the water in the 800-foot sand. The Citizens Ice Co. well in Atlantic City, and the Longport well, present opportunities to obtain valuable records and every effort should be made to continue the operation of automatic recorders on these wells. Continuous observations should also be made at other localities between Brigantine and Wildwood and on the mainland at the Atlantic City Water Works.

Recent developments emphasize the need of more accurate data on the head on the Atlantic City 800-foot sand between the coast and the outcrop area. If possible, observations should be made on fluctuations of the head at Egg Harbor City and Hammonton. Periodic measurements should be made on a number of wells in or near the outcrop area to determine the extent of the fluctuation of the water level as a result of seasonal changes in precipitation.

In order to interpret accurately fluctuations of head in the western part of the area underlain by the Kirkwood formation more information is desired as to the geologic conditions to determine just where is the intake area of the Atlantic City 800-foot sand. Data are needed as to the thickness and permeability of the sand. Well drillers should be asked to report data on wells in this area.

In order to determine more accurately the relation between changes in pumpage and fluctuations of the head it is necessary to have more accurate data as to the pumpage from private wells. An effort, therefore, should be made to enlist the interest of every private well owner in the Atlantic City region in keeping daily records of pumpage. An important problem is that of keeping track of new wells, or of wells that are abandoned, to determine marked changes in draft from year to year. More information is needed in changes in the yield of wells as the head on the water changes.

The possibility of salt-water contamination, although now seemingly remote, is so important that a careful watch should be kept for the slightest indication of its encroachment. Samples from several wells should be analyzed periodically to determine whether the chloride content increases in summer when the pumpage is heavy. Since the key to the situation may be found in conditions in the vicinity of Wildwood, the developments there should be watched as well as those in Atlantic City.

Since accurate data are lacking on the distribution of the shallow water-bearing horizons on the mainland, it is important to obtain logs of any wells that may be drilled. All possible data in regard to yield of wells and fluctuations of the head in the formation should be obtained. Where wells are near to salt water observations should be made to determine the possible danger of contamination of the wells.

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