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State Water Policy Commission

Howard T. Critchlow, Engineer in Charge

Supplementary Report on the Ground-Water Supplies of the Atlantic City Region

By Henry C. Barksdale, Raymond W. Sundstrom, and Maurice S. Brunstein

Prepared in cooperation with the United States Geological Survey

New Jersey State Water Policy Commission

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SUPPLEMENTARY REPORT ON THE GROUND-WATER SUPPLIES OF THE ATLANTIC CITY REGION, NEW JERSEY

By Henry C. Barksdale, Raymond W. Sundstrom, and Maurice S. Brunstein

ABSTRACT

This report is the second progress report on the ground-water investigations in the Atlantic City region. Many important problems still remain to be solved, however, and it is in no sense a final report.

The report covers the area immediately surrounding Atlantic City, extending from Brigantine to Sea Isle City along the coast and from Absecon to Somers Point on the mainland. In addition to this, a few data are presented bearing on the area along the coast as far south as Wildwood. The area lies in the southern part of the New Jersey Coastal Plain, and the water-bearing formations considered are all unconsolidated and of Miocene or more recent age. The major formations in the region dip gently toward the ocean and possibly extend out under the ocean to the edge of the Continental Shelf, about 100 miles from Atlantic City. The principal ground-water supplies in the area are derived from the so-called "800-foot sand," a member of the Kirkwood formation, and from the overlying Cohansey sands. The 800-foot sand is of wide extent and apparently fairly uniform. The Cohansey sands, on the other hand, cover a wide area but are by no means uniform. At the Atlantic City Water Works two Cohansey sands are recognized—the so-called "100-foot" and "200-foot" sands. Neither of these sands can be differentiated from the other sands of the Cohansey formation over a distance greater than 4 or 5 miles in any direction.

In addition to the supplies derived from ground water, some surface water is used at present by two of the public water supplies. The quality of the water from all the sources of supply now used is satisfactory. The total consumption of water in the region has increased gradually over the entire period of record, except for a moderate decline from 1929 to 1934. Additional water supplies can be obtained from either of two fairly large streams near the region, and possibly also from a more widespread development of the Cohansey sands. The 800-foot sand should not be counted upon as a source of additional water supply, in view of its liability to salt-water contamination. The same danger also exists in the Cohansey sands on the mainland near the shore, but farther inland it is not a serious menace to the supply from these sands.

The 100-foot sand at the Atlantic City Water Works has been overdeveloped since 1930, with the result that the head of the water in it has been lowered materially and salt water has been drawn into it through holes in the overlying clay beneath the nearby salt marshes. Three of the five new large-capacity wells drilled to this sand in 1930 have been temporarily or permanently abandoned on account of salt-water intrusion, and the two others will probably have to be abandoned also, unless suitable remedial measures are promptly adopted. It is recommended that the wells to the 100-foot sand be used only when needed to supply the seasonal peak demand and that consideration be given to a project to transform the tidal marshes into a fresh-water pond by means of a suitable dam in order to protect the formation from further contamination. If detailed study proves that the dam and fresh-water pond would not be economically justified, a smaller pond and an embankment and tide gates on the main stream to keep the salt water from flooding the marshes are recommended as less effective but less expensive remedial measures. In view of the experience with the 100-foot sand at the Atlantic City Water Works, it is further recommended that any additional development of the Cohansey sands be preceded by a comprehensive test-well program that will indicate not only the capacity of the sands, but the location of salt water in them and the possibility of its being drawn into existing wells or the proposed new wells.

The salt-water intrusion into the 100-foot sand was effectively studied by means of driven-well points, which, it was found, could easily be driven to a depth of about 100 feet. The fact that the screen of these wells was driven with the casing and that no water was used in the drilling process made it possible to collect true samples of water from every sand encountered in them. This, in turn, made it possible to study the vertical distribution of salt water in each well. The interpretation of the vertical distribution of salt water in these wells was very helpful in arriving at a final decision as to the source of the salt water.

The 200-foot sand at the Atlantic City Water Works has also been subjected to a considerably increased draft since 1930. Although there is no evidence at present that this sand has been overdeveloped, a study of its characteristics suggests that it may not be capable of yielding permanently the capacity of the present wells that tap it. Three test wells have been installed between the well field and the source from which this sand might derive salt water, and they should be sampled regularly to determine the danger of salt-water intrusion into the sand. In a landward direction this sand merges into the other Cohansey sands. It is therefore advisable that any additional development of the Cohansey sands should be undertaken so far inland that the pumping from it will not affect the present wells to the 200-foot sand and thereby increase the danger of salt-water contamination in them.

At present more potable water is taken from the Atlantic City 800-foot sand than from any other source of supply for the region. This sand is the sole source for some of the smaller communities on the barrier beaches. The original static head of the water in it at Atlantic City was between 20 and 25 feet above sea level. The head has been lowered more than 50 feet over much of the region, and in parts of Atlantic City it has been lowered considerably more than 100 feet. A consideration of the principles governing the relation between salt water and fresh water in water-bearing sands indicates that the 800-foot sand probably con-

tained salt water at a distance of 5 or 10 miles out from Atlantic City before any water was pumped from it. The evidence collected in this investigation indicates that the cone of depression created by the pumping from this sand in the Atlantic City region has probably extended inland to the intake area of the sand, the nearest part of which is probably about 40 miles from Atlantic City. If this is so, the conclusion is almost inescapable that it has also extended oceanward for a distance considerably greater than the 5 or 10 miles to the original zone of contact between the fresh and salt waters, and that salt water is probably being drawn toward the Atlantic City region through this sand. The time of its arrival will depend primarily upon the rate of pumping in the region and upon how much of the fresh water that originally lay between the region and the zone of contact must be removed before the salt water can reach the region. It may arrive in the near future if it advances in the form of a narrow tongue. On the other hand, if it advances along a broader front, so that more of the intervening fresh water must be pumped out of the formation, its arrival may be delayed for some time.

INTRODUCTION

HISTORY AND SCOPE OF THE INVESTIGATION

The investigation of the ground-water resources of the Atlantic City region was begun in 1923 by the United States Geological Survey and the New Jersey Department of Conservation and Development as a cooperative project. The work in the Atlantic City region is a part of a general study of the ground-water resources of New Jersey. In order to derive the greatest benefit from this study, most of the work has been concentrated in a few regions where ground-water conditions are critical or are typical of those in other parts of the State. The location of the principal regions under study is shown in figure 1. Reports have already been published on the Atlantic City,(1)* Asbury Park,(2) Camden,(3) and Canoe Brook(4) regions, and the data collected in the two remaining regions are being assembled for reports. In addition to a study of certain permanent features of a region, such as its geology and geography, the quantitative investigation of its ground-water resources involves a study of factors, such as precipitation and pumpage, that vary not only from season to season but from year to year and over longer periods of time. The work in each of the regions selected for study is therefore being continued and intensified so far as practicable, and this report and those which have preceded it are essentially progress reports.

O. E. Meinzer, geologist in charge of the division of ground water of the United States Geological Survey, and H. T. Critchlow, engineer in charge of the New Jersey State Water Policy Commission and formerly chief of the division of waters of the New Jersey Department of Conservation and Development, have exercised general supervision over the work since its beginning. David G. Thompson, of the United States Geological Survey, was in charge of this work from its beginning through June, 1927. Mr. Thompson was assisted at different times by Ernest W. Downs and Henry C. Barksdale. In July, 1927, Mr. Thompson was assigned by the United States Geological Survey to ground-water work outside of New Jersey, and from that time until June 30, 1931, the

* Numbers in parentheses refer to list of references, page 133.

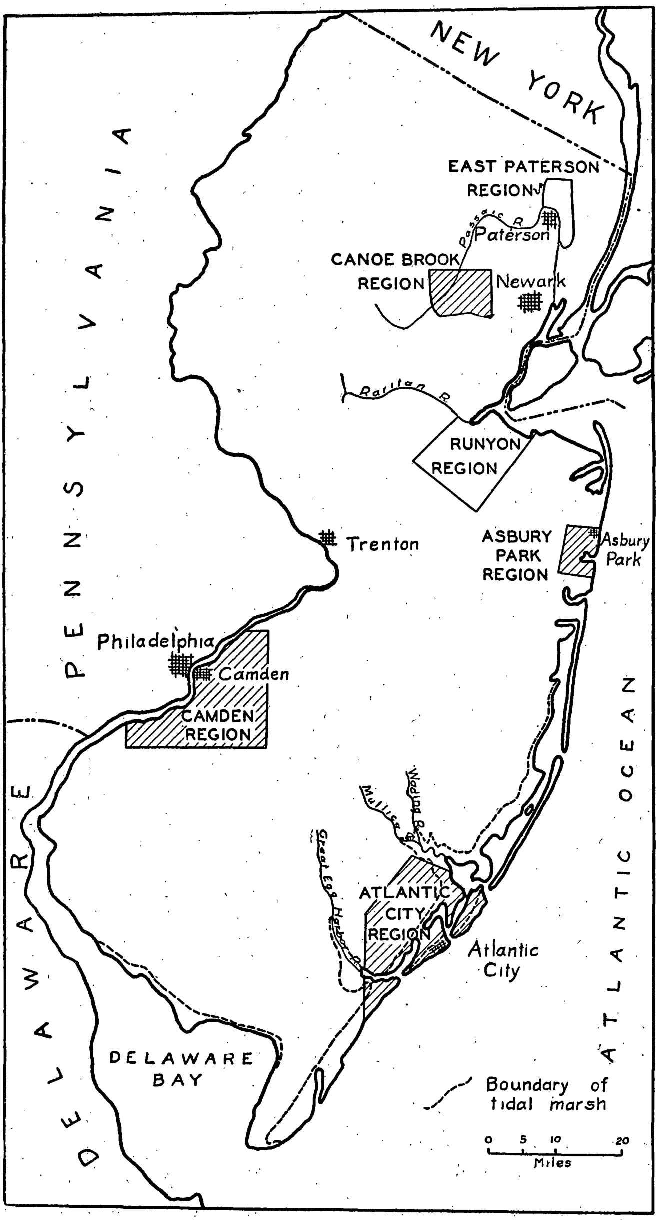

FIGURE 1.—Map of New Jersey, showing the principal regions in which ground-water studies are being made and indicating by shading those regions on which reports have been published.

investigation was carried on independently by the State Department of Conservation and Development and its successor in water-supply matters, the State Water Policy Commission, with Mr. Barksdale in charge of the work. On July 1, 1931, formal cooperation with the United States Geological Survey was resumed by the State Water Policy Commission. At that time Mr. Thompson renewed his connection with the work in an advisory capacity, although the active work has been carried on by Mr. Barksdale with the assistance of Raymond W. Sundstrom.

In the course of the investigation more than 2,000 samples of water have been collected for laboratory examination. Most of them were analyzed only for their chloride content, but a few more or less complete analyses were made. These samples were analyzed in the water-resources laboratory of the United States Geological Survey by C. S. Howard, K. T. Williams, E. W. Lohr, and W. L. Lamar, chemists, and in the Atlantic City Water Laboratory by Maurice S. Brunstein, chemical engineer and assistant superintendent of the Atlantic City Water Works.

The authors of this report are especially indebted to Mr. Thompson; to Mr. Meredith E. Johnson, assistant State geologist of New Jersey; and to Mr. John N. Brooks, assistant division engineer of the New Jersey State Water Policy Commission, for advice and criticism on various phases of this report and of the investigation that preceded it.

All the officials of public water supplies in the region have cooperated generously in the investigation, furnishing records of pumpage, water levels, and other information and providing observers for water-stage recorders where needed. The writers wish to express their appreciation to the many individuals who have assisted them by furnishing freely information of various kinds. They are especially indebted to the late Commodore Louis Kuehnle, formerly commissioner in charge, Mr. Lincoln Van Gilder, superintendent, and Mr. Frank J. Tumbore, chief engineer, of the Atlantic City Water Department; Mr. Harry Singley, chief engineer of the Ventnor Water Works; Mr. James Boice, chief engineer of the Margate Water Department; Mr. Jacob E. Frye, superintendent of the Longport Water Department; Mr. E. S. Steelman, superintendent of the Ocean City Water Service Co.; Mr. T. E. DeBow, superintendent of the Sea Isle City Water Department; Mr. Howard C. Banks, formerly superintendent, and Mr. William Niell, superintendent, of the Wildwood Water Department; to the owners and operators of private wells in the region; and to the officials and drillers of the Layne-New York Co. and the Artesian Well Drilling Co.

The area considered in this report includes the region along the Atlantic coast from Brigantine to Sea Isle City and on the mainland from Absecon to Somers Point, an area of about 180 square miles. Some information has also been collected from points as far north as Tuckerton and as far south as Wildwood. The general location of the Atlantic City region is shown in figure 1.

The results of the investigation in this region from the time of its beginning through April, 1928, were published in 1928 (1). The present report reviews some of the data presented in the earlier report and gives the results of the investigation from that time to December 31, 1934, and some data collected as late as September 30, 1935. It presents briefly the general situation with respect to water supply in the region and deals in greatest detail with the conditions affecting the 100-foot sand at the Atlantic City Water Works and the Atlantic City 800-foot sand. The general principles worked out by Mr. Thompson have been the basis of the work done since the publication of his report, but certain conditions have arisen which have called for special treatment. In particular, it is believed that the study of the encroachment of salt water into the 100-foot sand at the Atlantic City Water Works and the further study of the relation between pumpage and draw-down in the Atlantic City 800-foot sand will be of general interest wherever similar problems are encountered. The test-well driving procedure and the development of vertical profiles of salinity should be applicable to other localities along the coast where existing water supplies are threatened with the intrusion of salt water, or new supplies are contemplated in positions that might be exposed to such intrusion. It is hoped that some of the other results presented herein, especially the idea of regional specific capacity, may also be found applicable in other localities.

Though many of the problems relating to the ground-water supplies of the Atlantic City region are now fairly well understood, there is still much to be learned about some of them. The problems of determining the safe yield of the 800-foot sand and the relation between pumpage and head in this sand seem to be approaching a solution. It is believed that much information that will be valuable both locally and in the general study of ground-water hydrology can be obtained by continuing the observations of the pumpage from this sand and the water levels in wells ending in it. The danger of salt-water contamination of this sand is believed to be very real. The regular collection of water samples from representative wells and the semiannual collection of samples from every possible well to this sand should be continued. By these means it may be possible to predict more definitely the time when the salt water will reach the region. If this can be done, the necessary adjustments of sources of supply can be made with the least inconvenience.

The study of the safe yield of the Cohansey sands on the mainland is still in a preliminary stage. Much valuable information can probably be procured by continuing the observations on these sands, and especially by studying the progress of the salt-water contamination of the 100-foot sand, whether or not the remedial measures suggested in this report are carried out. The test wells located between the ocean and the active 200-foot wells should be sampled regularly in order to ascertain whether the salt water is advancing into this sand. In general it is recommended that most of the regular observations that have been made in this region be continued, and some more detailed observations might be justifiable.

Most of this report has been written by Mr. Barksdale. The establishment of a water laboratory by the city of Atlantic City, which uses water from each of the principal sources of supply in the region, has permitted a more detailed study of some problems relating to the quality of the waters of the region than has been possible heretofore. The results of this study have been incorporated in the section on the quality of the waters of the region, which Mr. Brunstein has written. Mr. Brunstein has also assisted in the preparation of the section on the possible sources of future water supplies for the region insofar as the quality and treatment of the surface waters is considered. The section on test-well drilling methods has been written by Mr. Sundstrom, who has also assisted in preparing the section on the recovery and drawdown tests on the 100-foot sand and in drawing the accompanying diagrams. Mr. Anthony L. Marolda drew most of the illustrations for this report.

GEOLOGY OF THE REGION

The Atlantic City region is in the Coastal Plain of New Jersey, which is underlain by beds of sand, gravel, and clay, that range in age from Cretaceous to Recent and are almost entirely unconsolidated. The water-bearing sands and the accompanying beds of clay with which this report deals are all of Tertiary age and are members of the Kirkwood and Cohansey formations. The shallow deposits of sand and gravel of Pleistocene and Recent age, which overlie the Cohansey formation in much of the region, are of little importance as sources of ground water, but they have a capacity to admit water to the Cohansey sands.

The major formations of the Coastal Plain in New Jersey have the general form of broad flat sheets, which slope gently to the southeast. They extend out under the ocean and presumably crop out on its bottom at the edge of the Continental Shelf, about 100 miles from Atlantic City, where the gentle slope of the ocean bottom near the shore ends and the depth of the ocean increases very rapidly. In a landward direction they rise gradually until they reach the surface in bands that extend across or partly across the State, in a general northeast-southwest direction. The higher and younger formations crop out near the ocean; the older and deeper formations outcrop farther inland. A generalized cross section of the Coastal Plain from Philadelphia to Atlantic City is shown in figure 2. The line of this section lies approximately in the direction of the greatest slope of the formations.

Although the major formations extend over wide areas and have a fairly uniform slope, it is not necessarily true that the individual beds of sand and clay of which they are composed extend over any great distance or even slope in the same direction as the formations. This is particularly true of the Cohansey formation, which is essentially a sand body containing irregular beds and lenses of clay dispersed throughout its extent. Some of these beds of clay are 50 or 60 feet thick and extend for several miles, but most of them are much smaller. This condition has an important bearing upon the salt-water problem in the Atlantic City Water Works 100-foot sand, which is not a water-bearing sand overlain by a continuous sheet of protecting clay but which lies between and around irregular lenses of clay, which do not extend for any very great distance.

The Cohansey sands are also irregular in character, ranging from coarse, clean, excellent water-bearing sands to fine clayey sand that is practically worthless as a water-bearing material. Particularly in the upper sands of the formation this change is likely to take place in a relatively short distance either horizontally or vertically.

Beneath the island beaches, where the principal resort cities are situated, the Cohansey sands contain brackish water that is not used except for cooling, for which it is better suited than the warmer water from the deeper sands. On the mainland, however, the Cohansey sands yield water of good quality. At the Atlantic City Water Works, where the largest development of ground water from these sands has been made, water-bearing sands are found between 30 and 100 feet and between 138 and 230 feet below the surface. Beds of clay overlie each

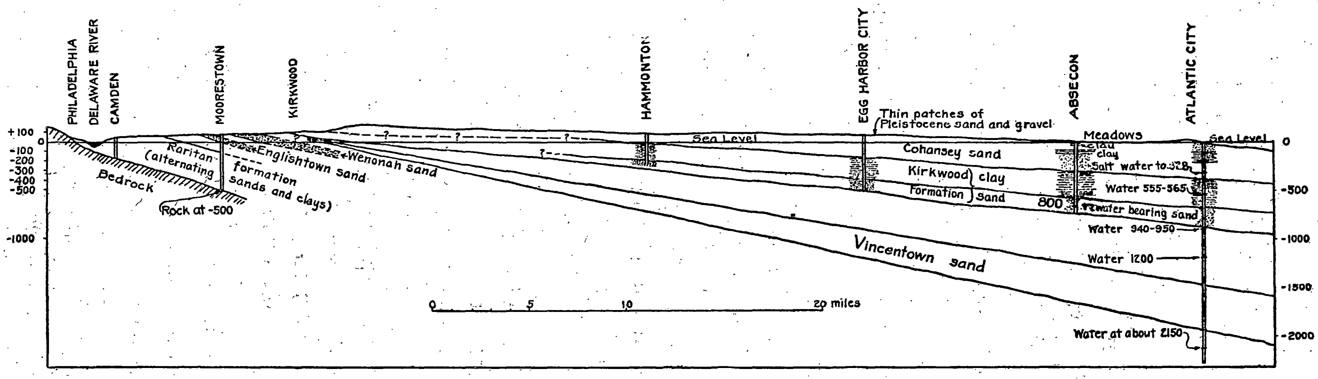

FIGURE 2.—Generalized cross section from Philadelphia to Atlantic City, showing principal water-bearing beds.

of these sand beds, although the one overlying the shallower sand has been found to be of very small extent. Neither of these sands can be distinguished from other sands of the Cohansey formation over any great area. Wells deep enough to encounter the lower sand are not very numerous except at the Atlantic City Water Works. However, the logs of wells at the Sea View Country Club, about 3 miles northeast of the water works, and of several test wells drilled in the progress of this investigation indicate a possibility that this sand and its overlying bed of clay may extend for several miles toward the northeast. Northwest of Doughty Pond the clay pinches out and toward the southeast, near the edge of the salt marshes bordering Absecon Bay, it apparently grades into a clayey sand. Because wells penetrating the two sands at the Atlantic City Water Works are about 100 and 200 feet deep these sands are referred to in this report as "Atlantic City Water Works 100-foot and 200-foot sands" or simply as the "100-foot and 200-foot sands."

The Kirkwood formation underlies the Cohansey. In the Atlantic City region this formation is composed chiefly of a bed of clay 300 to 400 feet thick underlain by a bed of good water-bearing sand about 80 feet thick. Both beds are of wide areal extent, having been encountered in wells from Brigantine to Wildwood and possibly as far south as Lewes, Del., and as far north as Tuckerton, N. J. Inland they have been encountered at Pleasantville and Egg Harbor City, and probably at Hammonton. The sand is the chief source of ground water in the region and is encountered at Atlantic City at an approximate depth of 760 to 840 feet. Because of this fact, it has come to be known as the "Atlantic City 800-foot sand." In this report it will be referred to by this name, or simply as the "800-foot sand."

As indicated in figure 2, a well drilled at Atlantic City in 1901 extended to a depth of more than 2,300 feet (5, pp. 110-117). Below the 800-foot sand "scant" supplies of water were reported in this well at depths of 941 to 950 feet, 1,200 to 1,205 feet, and about 2,150 feet. No wells are now known in the Atlantic City region that draw from a bed deeper than the 800-foot sand. Some of the earliest deep wells on the island, drilled in 1888 or 1889 (6, p. 73) by the Consumers Water Co., obtained water from a depth of about 1,100 feet, but the deeper sand has not been used for many years. An analysis (6, p. 75) of the water from this depth shows that it contained 1,100 parts per million of total solids and 330 parts per million of chloride. This rather high mineralization probably accounts for the abandonment of the sand as a source of supply. No information is available about the quality of the water encountered below the 800-foot sand in the deep well, but if the record is to be relied upon the supply of water at these depths was not large.

In the left-hand part of figure 2 are shown the Vincentown, Wenonah, and Englishtown sands and the Raritan formation. The Raritan is one of the best water-bearing formations in the State, and the Wenonah and Englishtown sands also yield considerable quantities of good water in some parts of the Coastal Plain. Presumably these formations extend down the dip and occur beneath the Atlantic City region, but there is little definite information to prove it or to indicate whether or not they are water-bearing in the Atlantic City region if they extend that far. The Vincentown sand was identified in the deep well at Atlantic City, but it yielded no water. This well probably did not extend to the Wenonah sand. Even if the deeper sands extend beneath the Atlantic City region and are water-bearing there, it is probable that they would yield salt water in this region, because the head of the water in these formations farther west is not great enough to hold the salt water back at the great depths at which the sands would occur here. In view of the facts recited above, it is considered improbable that any satisfactory supply of fresh water can be obtained from wells extending below the 800-foot sand in the Atlantic City region.

All the sands from which water supplies are now developed in the Atlantic City region were laid down under salt water and therefore were originally filled with salt water. That they now contain fresh water is apparently due to the fact that the land surface has been above the surface of the sea for a long time, and the fresh water from rainfall has replaced the salt water and forced it back toward the ocean as the fresh-water head has increased. The fact that it was possible for the fresh-water head to force the salt water out of the water-bearing formations of the region to depths far below sea level implies that there is or has been a connection between these sands and the ocean. This has an important bearing on the problem of salt-water encroachment into the water-bearing formations in the region, for if the connection still exists the salt water can be drawn back into the sands by heavy pumping. This problem is discussed in another part of this report.

SOURCES AND CONSUMPTION OF WATER IN THE REGION

PRESENT SOURCES OF SUPPLY

Except for springs and shallow dug or driven wells on the mainland, the potable water supply of the Atlantic City region is drawn from three sources—streams on the mainland, wells to the Cohansey sands on the mainland, and wells to the Atlantic City 800-foot sand, which underlies the entire region. The location of the surface-water supplies and of the principal well supplies is shown in figure 3.

Water from streams on the mainland is now used only by the city of Atlantic City and by the Atlantic County Water Co. The Atlantic City Water Department takes its surface water from Absecon Creek at Doughty Pond, which provides a considerable amount of storage. Additional storage will be provided in the Kuehnle Reservoir, now under construction. The Atlantic County Water Co. takes its surface water from Patcong Creek at Bargaintown Pond. Both of these supplies are now mixed with well water and used without any treatment except sterilization.

Wells to the Cohansey sands on the mainland are used by the city of Atlantic City, by the Atlantic County Water Co., and for a few private supplies. The Atlantic City Water Works has a total of twelve large wells to these sands—five to the 100-foot sand and seven to the 200-foot sand. The total capacity of these wells is about 16.5 million gallons a day. The Atlantic County Water Co. has five wells to the Cohansey sands. Two of these are in Pleasantville and probably draw their water from the Atlantic City 100-foot sand or from some sand closely connected with it. The remaining three wells, at Bargaintown and Somers Point, are too far from the Atlantic City Water Works to attempt any correlation. The largest of the private supplies drawn from the Cohansey sands on the mainland is that of the Sea View Country Club, which has two wells that probably tap the 200-foot sand, and several shallower wells. The remaining private supplies drawn from these sands are small and of little importance in the general water-supply situation in the region. Most of these are in Pleasantville.

The Atlantic City 800-foot sand is the source of water for all public supply systems along the shore between Brigantine and Stone Harbor except Atlantic City. It also supplies about 30 hotels and industries in Atlantic City and four in Ocean City through private wells (see fig. 3). One well at the Atlantic City Water Works, on the mainland,

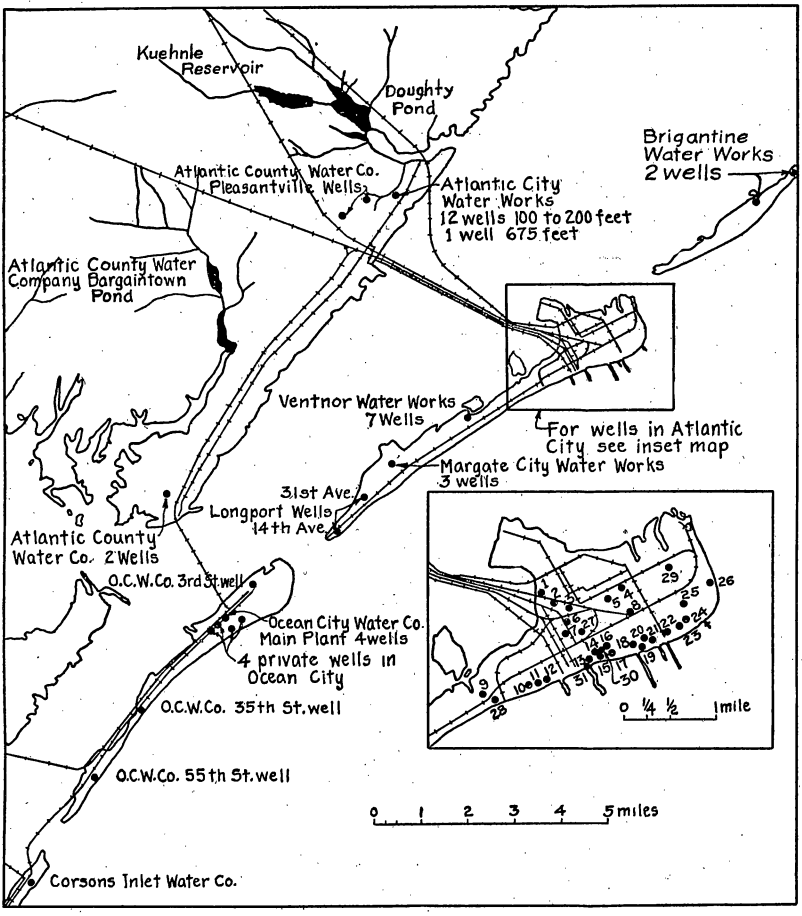

FIGURE 3.—Map of the Atlantic City region, showing the location of the present surface-water supplies and the principal well supplies. Numbers on inset map of Atlantic City refer to privately owned wells as follows:

1. Atlantic City Electric Co. (2 wells)
2. Pennsylvania Railroad (abandoned)
3. Atlantic City Gas Co.
4. Supplee-Wills-Jones Dairy Co.
5. Abbott Dairy Co.
6. Reading Railroad (abandoned)
7. Atlantic City Brewing & Ice Co. (abandoned)
8. Guarantee Trust Building
9. Atlantic City High School
10. Chelsea Hotel
11. Ambassador Hotel
12. Ritz-Carlton Hotel
13. Shelbourne Hotel (2 wells)
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)
21. Strand Hotel
22. Blackstone Hotel (abandoned)
23. St. Charles Hotel
24. The Breakers Hotel (2 wells)
25. Galen Hall
26. Royal Palace Hotel (abandoned)
27. American Ice Co.
28. President Hotel
29. Citizens Ice Co. (abandoned)
30. Claridge Hotel
31. Warner Theater

draws from this sand at a depth of about 675 feet and furnishes part of the water for that system. Wells drawing water from what is believed to be the same sand are utilized for the public supplies of Egg Harbor City and Hammonton and for a part of the public supply of Wildwood.

CONSUMPTION OF WATER IN THE REGION

Table 1 presents a summary of the consumption of water in the Atlantic City region from each of the principal sources of supply from 1917 to 1934. It is compiled from the reports of water consumption made by the public water supplies to the New Jersey State Water Policy Commission and its predecessors and from records of private pumpage from the Atlantic City 800-foot sand collected during this investigation. There are in the region no private supplies that use surface water, and the data at hand do not justify an estimate of the amount of water consumed from private wells to the shallow or Cohansey sands on the mainland. However, the total amount of consumption from private shallow wells probably does not exceed an average annual rate of 750,000 gallons a day. Complete records of pumpage from all the public water supplies in the region prior to 1917 are not available, and there are practically no records of the consumption of water from private supplies before 1924.

The table shows an irregular increase in the total consumption of water from 1917 to 1929 and a decrease from 1929 to 1933. The consumption in 1934 was considerably more than in 1933. In general, the consumption of water from the individual supplies has followed the same general trend, although the greatest percentage increases were shown in the supplies for Margate, Ventnor, and Atlantic City, in the order named. In 1929 the consumption of water from public supplies was 204 percent of that in 1917; in 1933, 177 percent; and in 1934, 186 percent. From these figures it is apparent that while there has been a definite decrease since 1929, most of the gain in consumption from 1917 to 1929 has been maintained and the increase in 1934 was noteworthy. The consumption in 1932 and 1933 was greater than that in 1925 or in any preceding year. The average annual rate of increase from 1917 to 1934 was 460,000 gallons a day.

In addition to the public supplies, a large amount of water is taken from private wells. The water from these private wells must be considered in any comprehensive study of the consumption of water in the region.

TABLE 1.—AVERAGE DAILY CONSUMPTION OF WATER FROM EACH SOURCE IN THE ATLANTIC CITY REGION IN THOUSANDS OF GALLONS, 1917-34*

	1917	1918	1919	1920	1921	1922	1923	1924	1925	1926	1927	1928	1929	1930	1931	1932	1933	1934
Surface water																		
Atlantic City Water Department	3,544	3,057	2,848	5,534	5,902	6,944	6,265	6,474	6,973	7,371	6,188	7,272	8,255	9,486	4,657	5,514	5,909	6,600
Atlantic County Water Co.	419	370	257	236	351	360	432	494	556	606	585	453	474	281	259	52	3	280
Total surface water	3,963	3,427	3,105	5,770	6,253	7,304	6,697	6,968	7,529	7,977	6,773	7,725	8,729	9,767	4,916	5,566	5,912	6,880
Cohansey sands																		
Atlantic City Water Department **	4,083	5,000	5,533	4,051	4,610	4,175	4,597	4,765	5,016	5,663	5,630	5,425	5,194	2,987	7,482	5,582	5,265	5,586
Atlantic County Water Co.	0	0	0	0	0	0	0	23	16	1	28	82	121	324	420	608	632	560
Total from Cohansey sands *	4,083	5,000	5,533	4,051	4.610	4,175	4,597	4,788	5,032	5,664	5.658	5.507	5,315	3,311	7,902	6,190	5,897	6,146
Atlantic City 800-foot sand																		
Atlantic City Water Department **	0	0	0	0	0	0	0	0	†850	1,000	1,350	1,320	1,270	1,240	1,240	1,240	1,240	895
Brigantine	0	0	0	0	0	0	0	0	‡31	§40	136	142	128	115	144	146	118	132
Ventnor	411	516	561	581	636	828	989	937	979	1,100	1,153	1,154	1,231	1,305	1,224	1,172	1,151	1,165
Margate	79	95	112	§90	94	§95	155	189	281	382	497	560	564	570	585	609	679	755
Longport	62	79	88	79	71	49	33	55	88	91	96	84	81	103	111	119	111	0
Ocean City Water Service Co.	397	422	445	513	530	648	750	653	793	824	882	1,050	1,070	943	858	770	764	765
Total public supplies from 800-foot sand	949	1,112	1,206	¶1,263	1,331	¶1,620	1,927	1,834	3,022	¶3,437	4,114	4,310	4,344	4,276	4,162	4,056	4,063	3,712
Private supplies from 800-foot sand ¶								4,362	4,489	4,680	5,410	5,313	5,206	4,633	4,142	3,625	3,415	3,661
Total from 800-foot sand ¶								6,196	7,511	8,117	9.524	9.623	9,550	8,909	8,304	7,681	7,478	7,373
Total public supplies from all sources	8,995	9.539	9,844	¶11,084	12.194	¶13,099	13,221	13,590	15,583	¶17,078	16.545	17,542	18,388	17,354	16,980	15,812	15,872	16,738
Grand total from public and private supplies *¶								17,952	20,072	21,758	21,955	22,855	23,594	21,987	21,122	19,437	19,287	20,399

* Does not include consumption of water from private wells to the Cohansey sands on the mainland. This probably does not exceed 750,000 gallons daily in any year.
** From May, 1925, to July, 1930, the consumption from the deep well at the Atlantic City Water Works was not metered separately. During this period the figures in this table are based on estimated yield of the deep well and total consumption of ground water at this plant.
† Well put in operation about May 20, 1925.
‡ Well put in operation about July 1, 1925.
§ Estimated.
¶ Partly estimated.

Almost all the water for private supplies is taken from wells to the Atlantic City 800-foot sand. Since Mr. Thompson began the investigation of the ground-water supplies in this region in 1923, most of the owners of private wells to the 800-foot sand have furnished records of the amount of water pumped from their wells, but a few have had no means of measuring their consumption and have been unable to furnish this information. Some of the records furnished are computed from meter readings, some from records of the time of pumping combined with the estimated rate of yield of the well, and some from records of pump strokes and capacity. Obviously the estimates of pumpage derived by the last two methods are not as accurate as the metered records, but they have been valuable in preparing an estimate of the total pumpage from the 800-foot sand by private wells. From the records furnished by the well owners and such information as could be obtained for those wells where no regular records have been furnished, it has been possible to compute a fairly accurate average rate of consumption from private wells to the 800-foot sand. The public and private consumption of water from the principal sources of supply in the region is shown graphically in figure 4. In this figure, as in table 1, a small amount of pumpage from private wells drawing from the shallow sands has been omitted. The upper line in the diagram represents the total pumpage in the region from public and private supplies from 1924 to 1934, the period in which records of private pumpage are available. The next line shows the total consumption from public supplies from 1917 to 1934. In the lower part of the diagram are lines indicating the amount of the consumption from public supplies derived from surface water, the shallow sands, and the Atlantic City 800-foot sand from 1917 to 1934, and the amount of consumption from private wells from 1924 to 1934. All the lines on the diagram turn up from 1933 to 1934, except that for public supplies from the 800-foot sand, which turns down because of a decrease in consumption from this sand at the Atlantic City Water Works—a decrease counterbalanced by a larger consumption of surface water at that plant.

The rate of consumption of water in the Atlantic City region is by no means uniform throughout the year. It is comparatively low in winter and high in summer, reaching a maximum in August or early in September and then decreasing very rapidly until January or February. During the 18 years of record, the August rate of pumpage from the public water supplies has ranged from 162 percent of the

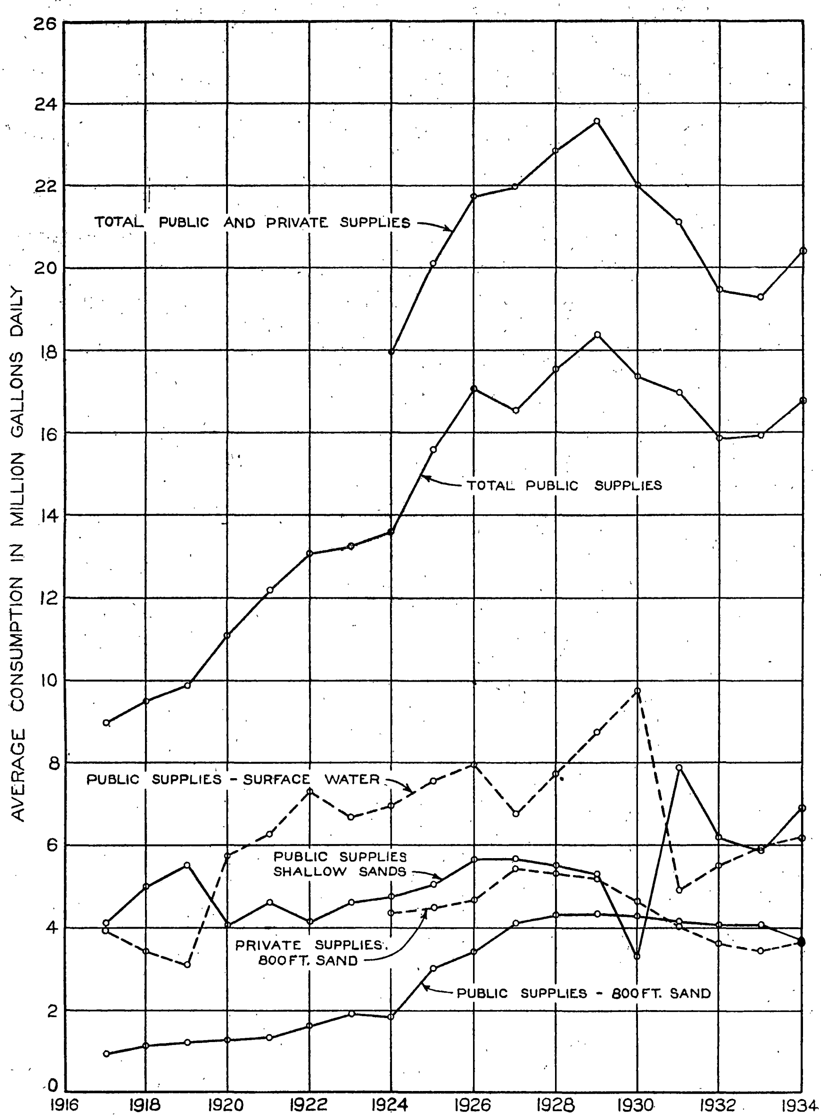

FIGURE 4.—Annual rate of consumption of potable water in the Atlantic City region from public and private supplies according to sources, 1917-34, exclusive of a small amount of consumption from private wells to the shallow sands and all private consumption prior to 1924.

annual rate in 1917 to 129 percent in 1927 and has averaged 146 percent. The variation in the private water supplies from 1924 to 1934 has not been as great as in the public supplies, the range being from 143 percent of the annual rate in 1933 to 122 percent in 1927 and the average 130 percent. As the February rate of pumpage ranges from 80 to 85 percent of the average annual rate, the maximum monthly rate, which usually occurs in August, is from one and a half to two times as great as the minimum monthly rate. No complete records of the maximum daily rate are available, but it is probably two or three times the average annual rate. The importance of the maximum daily rate of consumption is emphasized by the fact that none of the beachfront municipalities have enough storage capacity within their corporate limits to take care of their demands for water for a single day at the peak of the season.

ESTIMATES OF FUTURE CONSUMPTION IN THE REGION

Before 1928 no estimates of the probable future consumption of water from the Atlantic City region as a whole had been made. At that time Thompson (1, pp. 22-24) estimated that if the rate of increase in consumption between 1917 and 1928 were maintained, the probable daily consumption of water from the public supplies in the region would be at least 24 million gallons in 1938, 32 million gallons in 1948, and 39 million gallons in 1958. Because of the business depression of 1929 to 1934, which could not be foreseen at the time that this estimate was made, the anticipated rate of increase has not been maintained, and it may be that the consumption of water from public supplies in the region will not reach the figures indicated. It is noteworthy, however, that the consumption in 1928 and 1929 closely followed the trend line used by Thompson.

The estimate by Thompson and the one presented below are both based on the assumption that the rate of growth that has occurred in the past will be maintained in the future. Obviously it is unsafe to apply this assumption for any great stretch of future time, for the population of an area tends to reach a maximum and stop growing. Furthermore, the rate of increase of population in the country as a whole has been declining, owing to the progressive restriction of immigration and to a declining birth rate in American families. In a well-established resort center, such as the Atlantic City region, two other factors that tend to decrease the rate of growth must be considered. The rapid development of highways and the automobile has made it possible for many people who might otherwise have established residence at a seashore resort to enjoy most of its benefits without doing so. Furthermore, the older resort communities are being subjected to more and more competition from newer communities along the seashore.

In 1928 the record of consumption of water from private supplies in the region was only 4 years long. The data were therefore inadequate for any estimate of the total consumption of water in the region from all sources. The record of private consumption is now 10 years long, and an attempt may be made to estimate the total consumption of water from all sources in the region, as that would be the most satisfactory estimate for general use. The trend line used by Thompson for the public water supplies was established during the period from 1917 to 1927. There is no record of private pumpage from 1917 to 1923, but as four new private supplies were put in service during this period, there is no doubt that the consumption of water from private supplies was increasing as well as the consumption from public supplies. If a record of total consumption of water in the region had been available, it would therefore have shown a greater rate of increase than that shown by the public supplies alone. The record of the total consumption of water from public supplies and from private supplies to the Atlantic City 800-foot sand from 1924 to 1929 shows that during this period the combined rate of increase was greater than that for the public supplies alone. On the basis of these facts a trend line has been established which is somewhat steeper than that used by Thompson for the public supplies, and it is estimated that the total average daily consumption of water in the region from Brigantine to Ocean City and from Absecon to Somers Point will be about 23 million gallons in 1938, 25 million gallons in 1940, and 34 million gallons in 1950. The data at hand do not justify any estimate of the future consumption beyond 1950. The estimate just given takes into consideration the consumption of potable water from all sources except that from private wells drawing from the Cohansey sands, which is a very small part of the total consumption in the region.

During the 10 years from 1924 to 1933 the rate of consumption of water from all sources in the maximum month was 142 percent of the average annual rate. On this basis it is estimated that the average daily rate of consumption in the maximum month will be about 33 million gallons in 1938, 36 million gallons in 1940, and 48 million gallons in 1950.

POSSIBLE SOURCES OF FUTURE SUPPLY

With the normal growth and expansion of the region it will be necessary to consider an expansion of its present facilities for water supply. Heretofore it has been possible to develop all the water needed from wells and streams within the region itself. As the limit of capacity of these nearby sources of supply is approached it will be necessary to seek a supply from some more remote source. When this occurs it will be desirable for the various municipalities in the region to consider some form of cooperative action, in order to finance such an undertaking more easily and more equitably. It is the purpose of this section to point out the sources of additional supply that seem to be most readily available, without any attempt to estimate the cost of their development.

The Atlantic City 800-foot sand now furnishes a larger part of the water used in the region than any other source. It is the sole source of supply of the smaller municipalities on the island beaches and furnishes a considerable part of the water used in Atlantic City, mainly through private wells but also through one well at the Atlantic City Water Works. As pointed out on pages 103-110, there are some indications that the amount of water now being drawn from this sand may be in excess of its capacity to yield water continuously for all time. Furthermore, it is probable that salt water is being drawn into this sand from the direction of the ocean. It will be impossible to tell definitely whether or not salt water is approaching until it reaches the principal water supplies drawn from this sand, as they are situated on the very edge of the ocean. In view of these facts, the 800-foot sand should not be considered as a source of additional water supply for the region. The very real danger of salt-water intrusion into this sand makes it more imperative that the plans for an additional supply be prepared in definite form and that a reserve supply be made available, if possible. For example, if the water in the Atlantic City 800-foot sand had become salty during the peak season in 1929, the Atlantic City Water Works might have been called upon to supply about 8 million gallons daily in addition to its normal peak load of about 24 million gallons daily. This increased demand would have come from hotels and industries in the city of Atlantic City alone, and still more might have been required to supply the needs of the adjoining municipalities. It is probable that the wells to this sand would not all become salty so quickly that an emergency supply would have to be used in the first summer that the salt water appeared, but additional reserve supplies might be needed before the next summer.

An additional supply of water can be developed from wells to the Cohansey sands on the mainland. However, as has been forcibly brought out by the recent experience with the 100-foot sand at the Atlantic City Water Works, great care must be exercised in the location of wells to these sands to avoid contamination with salt water. A comprehensive program of test-well drilling to determine the proximity of salt water, as well as the quantity and quality of the water available, should precede any further development of these sands. A program should then be worked out that will provide for their development in reasonable steps, with sufficient time between each step to observe its effect and modify the program, if necessary.

The investigations of the extent of the cone of influence of the present wells at the Atlantic City Water Works and of the size of their intake area indicate that any additional development of the Cohansey sands should be undertaken more than 6 miles from the center of the present well field if the existing 200-foot wells are to be used to their full capacity. If these wells should have to be abandoned on account of salt-water intrusion, it would probably be safe to replace at least some of them with new wells in the upper drainage basin of Absecon Creek. Too great a concentration of wells in that area, however, would not increase the total amount of water available, for they would merely take water that would otherwise be stored in surface reservoirs and used by Atlantic City. Any major additional development of water from the Cohansey sands would therefore have to be made a considerable distance inland. This would necessitate the construction of long pipe lines to deliver the water to the points of consumption. It is also probable that the water from such a supply, or at least a part of it, would require treatment for the removal of iron or the reduction of corrosiveness. The cost of constructing and operating a water supply from this source should be carefully compared with the cost of a major surface-water supply for the region before either is undertaken.

Either of two fairly large streams, the Mullica River and the Great Egg Harbor River (see fig. 1), could be developed as a major surface-water supply for the region. The Mullica River is the larger of the two, and an intake could probably be constructed on it at a point about 15 miles north of the Atlantic City Water Works. It has a drainage area of about 222 square miles above a point just below the mouth of the Batsto River, one of its tributaries. Another tributary, the Wading River, which enters the Mullica in its tidal reaches some distance below the mouth of the Batsto, has a drainage area of about 170 square miles. The Great Egg Harbor River has a drainage area of about 216 square miles at Mays Landing, about 12 miles west of the Atlantic City Water Works, and has no important tributaries below this point. Neither of these drainage areas is thickly populated, but the density of population is somewhat less in the Mullica River basin than in that of the Great Egg Harbor River.

In common with many of the streams on the Coastal Plain of southern New Jersey, the water of these two streams is low in turbidity, but at some seasons of the year it is rather highly colored and may have disagreeable tastes and odors caused by the minute aquatic plants technically known as "algae." The elimination of the tastes and odors might be accomplished by aeration but might also require superchlorination, treatment with activated carbon, or other special treatment. The removal of the color would probably require coagulation followed by sedimentation and filtration through rapid sand filters. The regulation of the hydrogen ion concentration, pH, which is necessary for proper coagulation, could be accomplished by the use of chemicals such as aluminum sulphate or lime, the choice depending on the character of the water at the time of treatment. The final addition of chlorine or chloramine for sterilization would produce a very satisfactory water. The cost of treatment would probably represent a considerable part of the operating costs of a surface-water development.

QUALITY OF THE WATERS IN THE REGION

In general, the quality of the water from each of the four principal sources in the Atlantic City region is excellent for both domestic and industrial purposes. The water from each source has certain characteristic qualities, which are discussed below. Analyses of representative samples of water from each of the four sources are given in table 2.

TABLE 2.—TYPICAL ANALYSES OF WATERS FROM THE PRINCIPAL SOURCES IN THE ATLANTIC CITY REGION

MINERAL ANALYSES

[Analyzed by W. L. Lamar, U. S. Geological Survey. Parts per million]

	1 (Doughty Pond)	2 (100-foot sand)	3 (200-foot sand)	4 (800-foot sand) [a]
Silica	4.5	6.9	22	28
Iron	[b] .02	.21	1.20	.07
Calcium	1.0	3.5	1.6	9.0
Magnesium	.9	2.7	.9	2.6
Sodium	3.3	9.2	4.4	24
Potassium	.4	1.1	1.4	3.3
Carbonate	0	0	0	0
Bicarbonate	1.0	2.0	3.0	77
Sulphate	3.1	10	11	16
Chloride	6.0	14	4.5	6.6
Nitrate	.08	9.1	.0	.05
Total dissolved solids	39	64	50	126
Total hardness (calculated)	6.2	20	7.7	33

1. Doughty Pond, Atlantic City surface supply, collected Sept. 7, 1933.
2. Well 2, Atlantic City pumping station, collected Sept. 6, 1933.
3. Well 12, Atlantic City pumping station, collected Sept. 5, 1933.
4. Chalfonte Hotel, 1913 well, collected Feb. 5, 1935.

a. This sample contained 0.1 part per million of fluoride. Fluoride determinations were not made on samples 1, 2, and 3.

b. Determinations of iron in samples collected regularly eleven times monthly for the years 1933 and 1934 indicate that the average iron content of the water from Doughty Pond is about 0.18 part per million. The maximum iron content found in these samples was 0.70, and the minimum 0.10.

TABLE 2.—(Continued)

SANITARY ANALYSES

[Analyzed by M. S. Brunstein, Atlantic City Water Laboratory]

	5 (Doughty Pond)	6 (100-foot sand)	7 (200-foot sand)	8 (800-foot sand)
Color	35	0	0	0
Odor (cold)	2e	2m	1m	0
Odor (hot)	2e	2m	0	1m
Turbidity	2	0	0	0
Temperature °C.	3	13	13.5	21
Hydrogen ion concentration.......pH	4.5	4.9	4.7	7.5
Free carbon dioxide...parts per million	6.4	16	26	3.1
N as free ammonia..........do......	.015	.014	.009	.035
N as albuminoid ammonia...do......	.037	.012	.007	.002
N as nitrites...............do......	.003	.002	.002	.018
N as nitrates...............do......	.04	.10	.04	.50
Chloride ....do......	6.0	15	5.0	9.8
Alkalinity ....do......	0	3.0	1.8	63
Total hardness (soap).......do......	10	20	25	36
Iron ....do......	.10	.22	.60	.08
Total solids at 103° C.......do......	44	94	66	136
Residue on ignition..........do......	23	62	42	106
Loss on ignition............do......	21	32	24	30
Bacteria per cc at 37° C.	55	3	2	c23
Bacillus coli in 50 cc	0	0	0	0

5. Doughty Pond, Atlantic City surface supply, collected and analyzed Dec. 10, 1934.
6. Well 2, Atlantic City pumping station, collected and analyzed Nov. 19, 1934.
7. Well 12, Atlantic City pumping station, collected and analyzed Dec. 5, 1934.
8. Mixed water from wells at Chalfonte and Haddon Hall Hotels, Atlantic City, collected and analyzed Dec. 17, 1934.
c. This determination was made on a sample from a single well pumped by air lift. The normal water in the 800-foot sand is believed to be sterile.

Two types of analyses, mineral and sanitary, are presented for each source. The mineral analyses furnish definite information about those constituents of the waters that are most important to industry. The sanitary analyses include a determination of some of the major mineral constituents of the water and also of other characteristics that are of primary interest from esthetic and sanitary considerations. They also include those constituents of the water that are transitory and should be determined soon after the collection of the sample. The mineral analyses were made in the water resources laboratory of the United States Geological Survey. The sanitary analyses were made in the Atlantic City Water Laboratory in accordance with the standard methods of the American Public Health Association.

The surface waters vary considerably at different seasons of the year, chiefly in color and turbidity, which are affected by varying conditions of precipitation. These waters are very palatable and of excellent quality, although at times they may have a light-amber or brownish color. The color is due to the extraction of coloring material from the vegetable humus and the solution of iron in the form of tannates and gallates from the swamps and bogs of the area over which the water flows and stands. When mixed with a sufficient quantity of well water this color can be so much reduced as to be entirely unobjectionable. Occasionally tastes and odors are produced by minute aquatic plants (algae). In the Atlantic City water supply these growths are minimized by lowering the level of Doughty Pond to expose the littoral growths to the effect of sunlight. Further treatment if necessary is effected with copper sulphate used as an algacide and by superchlorination to destroy the tastes and odors. The surface waters are sterilized with chlorine gas before being delivered to the consumers. At the Atlantic City Water Works the entire supply, composed of a mixture of surface and ground waters, is sterilized by means of an automatic chlorinator, which is actuated by a venturi tube so as to feed the chlorine proportionally to the rate of flow.

As may be seen from table 2, the water from the 100-foot sand is soft and very low in mineral content. It is fairly high in free carbon dioxide, with very little alkalinity and a low hydrogen ion concentration. Wells drawing from this sand yield a very clear, colorless, and cool water, with sufficient carbon dioxide to make it very palatable.

The danger of salt-water intrusion is ever present in all water-bearing sands along the seacoast. Such intrusion has already occurred in the 100-foot sand at the Atlantic City Water Works, where the water from three of the five 100-foot wells has increased materially in salt content. Besides sodium chloride, or common salt, sea water contains large quantities of other mineral salts. To be perceptible to the normal taste the chloride content of a water must be at least 300 to 400 parts per million. However, before this point is reached the water becomes flat and tasteless, and its hardness is materially increased, resulting in greater soap consumption and an increased deposit of scale when used in boilers. A larger proportion of sea water renders the water unfit for use in boilers, because of foaming and priming, and increases its corrosiveness.

At present it is possible to dilute the more mineralized water from the 100-foot sand at the Atlantic City Water Works with water from other sources, so that the salt content is not perceptible to the taste. However, if this plant were operated at maximum capacity, with all the 100-foot wells in service, the mixed water delivered to Atlantic City would contain about 100 parts per million of chloride even if the chloride content of the water from the 100-foot wells did not increase. The hardness and soap-consuming capacity of the water would also be increased materially. Unless remedial measures are taken the amount of salt water entering these wells will almost certainly increase with continued pumpage.

In general, the water from the 200-foot sand is similar to that from the 100-foot sand. However, it is higher in silica and iron content and contains a trace of hydrogen sulphide. If used without dilution with water from other sources, the water from this sand would require treatment for removal of iron. In fact, if the Atlantic City Water Works were operated at its full capacity with all the 200-foot wells in service, some trouble might be experienced from the high iron content of the combined supply. There has been no difficulty up to the present time with salt-water intrusion into this sand, although it is probably connected with sands that contain salt water. (See pp. 85-86.)

Like the 100-foot sand, the Atlantic City 800-foot sand yields a satisfactory water for almost any purpose. It is considerably higher in mineral content, but may be classed as a soft water. It is comparatively high in bicarbonate and has a greater tendency to produce scale in boilers than the softer waters from the other sources. The hydrogen ion concentration is higher, along with a greater alkalinity which makes it less corrosive. This water contains hydrogen sulphide and should be aerated to render it more palatable.

Some mention should be made of the sanitary aspects of the wells driven by individuals to depths of less than 50 feet. Far too many of these wells are adjacent to cesspools and are otherwise poorly located and constructed with respect to possible pollution. Many of these shallow wells are potentially dangerous.

It is apparent from the preceding discussion that all the sources of the major water supplies in the Atlantic City region produce water of good quality from both sanitary and industrial considerations. Furthermore, by proper and judicious mixing of the four types, whatever disadvantages may exist in the water from the individual sources can be minimized to make a final product superior to that from any one of the original sources. It is believed that this mixed water—or, in fact, the water from any of the individual sources of supply when properly treated—will compare favorably with that from most other public supplies in the country.

RELATION BETWEEN SALT WATER AND FRESH WATER IN WATER-BEARING SANDS

NATURAL RELATIONS WHEN NOT DISTURBED BY PUMPING

The problem of obtaining fresh water from sands that are exposed for a part of their extent to the waters of the ocean has been studied in many parts of the world. The earliest scientific work on this problem was done in Europe, where the basic principles were first pointed out in 1887 by Badon Ghyben (7, p. 21), a Dutch captain of engineers, and in 1900 by Herzberg (8), who appears to have had no knowledge of the earlier work. The basic principles that govern the relation of salt water to fresh water in a water-bearing sand have now been fairly well established. They are discussed by Brown (9, pp. 274-294) (10, p. 16) in papers published in 1922 and 1925.

At the contact between the fresh and salt waters the zone of diffusion is surprisingly narrow. In Holland, Pennink (11, pp. 183-238) found a range of salinity from 100 to 15,000 parts per million of chloride in distances varying from 60 to 100 feet. In the present investigation ranges from 800 to 8,000 parts per million and from 1,900 to 7,300 parts per million were observed in 4 feet of depth.

Salt water is heavier than fresh water and tends to fill the lower parts of a formation. The fresh water in the sand floats on the salt water much as ice floats on water, with most of its volume submerged. The position of the contact is determined by the head of the fresh water above mean sea level and by the relative specific gravities of the two waters. This is the principle developed by Badon Ghyben and Herzberg.

This theory is illustrated in figure 5, A and B. Figure 5, A, shows a simple U-tube with both ends open to the air. The two legs of the tube are filled with two liquids of different specific gravities. The liquids in the tube will come to rest in such a way that the pressure at the bottom of one leg is exactly equal to and balanced by that at the bottom of the other leg. The surface of the lighter liquid will, therefore, necessarily stand higher than that of the heavier liquid. Furthermore, as the heavier liquid fills the lower part of the tube in both legs up to the level of the contact between the liquids, the pressure at this level is equal in both legs, and the heights of the two columns of liquid above the level of the contact are inversely proportional to the specific gravities of the liquids.

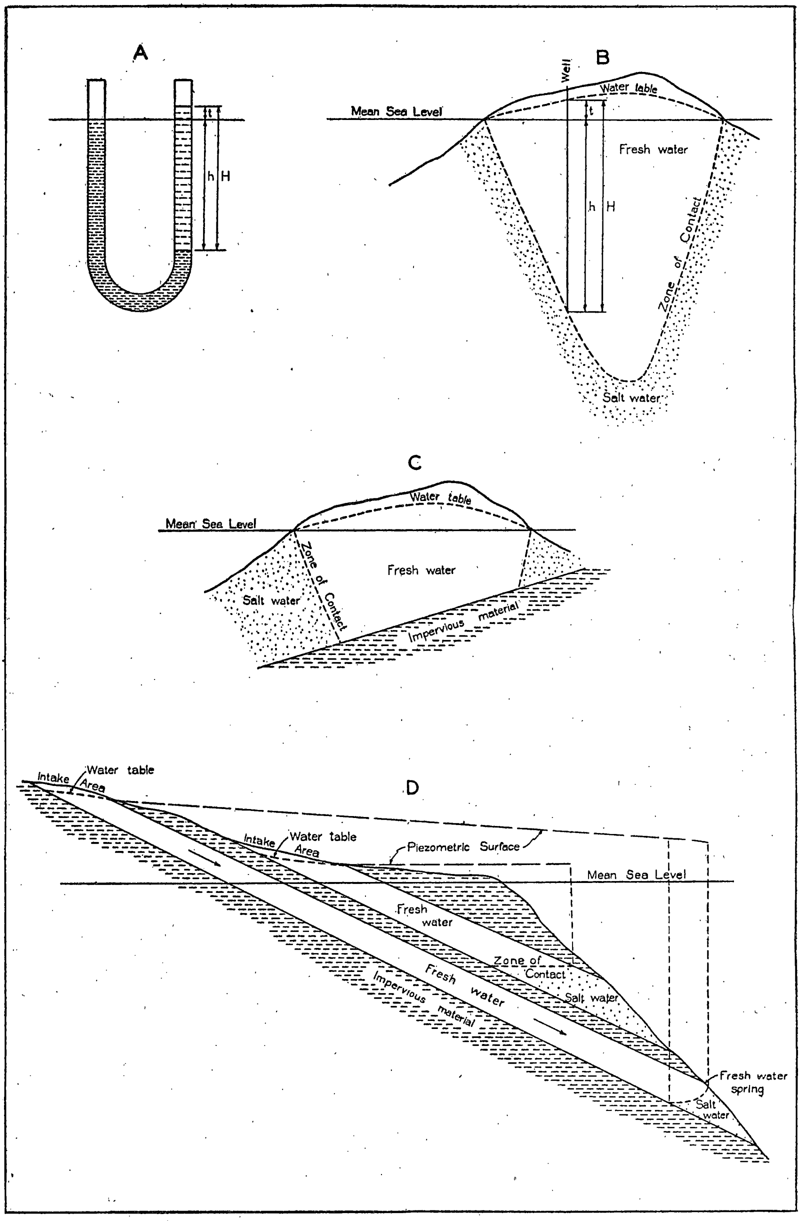

FIGURE 5.—Relation between fresh water and salt water in water-bearing sands when not disturbed by pumping. A, U-tube showing balance between two liquids of different specific gravities. B, Section through an island composed entirely of sand and surrounded by salt water. C, Section through a sand island underlain by impervious material. D, Section through a coastal plain composed of alternate layers of pervious and impervious materials.

In a small island or narrow peninsula composed entirely of permeable sand and surrounded by sea water, this same balance of pressure occurs between sea water and the lighter fresh water. Figure 5, B, represents a cross section of such an island and shows that the salt water not only fills the sand around the island but also extends entirely under it below the lens-shaped body of fresh water. In such an island the resistance of the sand to the flow of water causes the fresh water from rainfall to build up a head above sea level sufficient to cause it to flow out into the ocean at the shores of the island. It also prevents the mixing of the salt and fresh waters in the sand below sea level by wave action. As the sand is permeable in all directions, the fresh-water head will cause a downward flow of fresh water until it fills the sand to a depth at which its head is balanced by the head of the salt water. When equilibrium has thus been reached, the depth of the fresh water below sea level at any point on the island will be proportional to the fresh-water head above sea level at that point and the ratio between the depth and head of the fresh water will depend upon the relation between the specific gravities of the fresh and salt waters.

The following explanation, given by Brown (10, p. 16), of the relation between salt water and fresh water under a small sand island is applicable both to figure 5, A, and figure 5, B:

Let H = total thickness of fresh water.
h = depth of fresh water below sea level.
t = height of fresh water above mean sea level.

Then $H = h + t$

But the column of fresh water H must be balanced by a column of salt water h in order to maintain equilibrium. Wherefore, if g is the specific gravity of sea water and the specific gravity of fresh ground water is assumed to be 1,

$$H = h + t = hg$$

whence $$h = \frac{t}{g - 1}$$

In any case $g - 1$ will be the difference in specific gravity between fresh water and the salt water.

If it is assumed that the specific gravity of sea water is 1.025, which is about an average figure, then $h = 40\ t$. In other words, for every foot that the fresh water stands above sea level, it extends 40 feet below sea level. This ratio is so extreme that it is not practicable to show it in the various parts of figure 5. For convenience, therefore, the first three parts of this figure have been drawn with a ratio of 1 to 10 between the head and depth of the fresh water. This would be the true condition if the specific gravity of the sea water were 1.100 instead of about 1.025. The fourth part of this figure is drawn with a ratio of 1 to 5 between the head and depth of the fresh water and represents an imaginary specific gravity of sea water of 1.200. The general relation between fresh and salt water shown by these diagrams is not affected in the least by this assumption of a specific gravity of sea water greater than the range that occurs in nature. The specific gravity of sea water varies from place to place, so that the figure of 1.025 used in the example above is only an approximate average.

In nature a body of land composed entirely of permeable material to any great depth is rare. The occurrence of beds or layers of impermeable material does not change the basic principles just discussed, but it does modify their application. If the island shown in figure 5, B, were underlain by clay or bedrock that reached a level above the bottom of the fresh-water body, conditions such as those shown in figure 5, C, would occur. Along the coast the position of the contact would be determined by the head of the fresh water, just as in an island composed entirely of sand, but under the center of the island fresh water would extend all the way down to the impermeable layer and would not be in direct contact with salt water.

The modification of conditions by impermeable formations is even more marked on the coasts of larger bodies of land, where water-bearing sands may lie under and between as well as above layers of impermeable material and may slope upward to remote intake areas well above sea level. Along such a coast the conditions in a permeable sand underlain by impermeable material would be similar to those in the sand island underlain by impermeable material, except that the fresh water would be in contact with salt water only on the side exposed to the ocean.

Figure 5, D, shows two conditions which occur in water-bearing sands confined between layers of impermeable material. This diagram differs essentially from the others in that it shows the conditions that occur when the fresh water in the sand is under artesian head rather than under water-table conditions. In the upper sand in this diagram the salt water and fresh water are in balance, just as in the preceding examples. Salt water fills the lower part of this sand, and fresh water fills the upper part of it. The position of the contact is determined by the head of the fresh water, which in turn is determined by the elevation of the intake area. The similarity between the conditions in this sand and those in the U-tube in figure 5, A, is easily apparent.

In an artesian sand the water is prevented from rising to the surface by the overlying impermeable bed. It is under a head that would cause it to rise in a well to a level above the bottom of the confining bed. The imaginary surface that would pass through the surface of the water in a well drilled to the sand at any point throughout its extent is called the "piezometric surface." The piezometric surface is therefore a pressure-indicating surface, and its elevation at any point indicates the head on the water in the sand at that point. At the intake area of the sand it merges into the water table which, though not imaginary, might be considered a part of the piezometric surface. In a section such as figure 5, D, the line representing the piezometric surface is the hydraulic gradient of the water in the sand along the section. As there is no flow in the upper sand in this figure, the line representing the piezometric surface is level and extends from the intake area toward the ocean as far as the fresh water extends in the sand.

In the lower sand in figure 5, D, the head of the fresh water is sufficient to cause a flow of fresh water into the ocean below sea level, forming a suboceanic fresh-water spring. The fresh water fills the water-bearing formation down to the bottom edge of the overlying impermeable layer and far enough below this level to permit the water to flow out into the ocean. Here again the salt water fills the lowest part of the formation, but as the pressure in the main body of fresh water is greater than that in the salt water at the outlet, the salt water fills only that part of the formation in which the head of the fresh water has been reduced below the pressure of the salt water by the resistance of the sand to its movement. The line representing the piezometric surface for this sand slopes gently downward from the intake area to the point where the thickness of the sand carrying fresh water is reduced by the intrusion of salt water. From that point to the point of discharge the slope increases.

EFFECT OF PUMPING

If the basic principles that govern the relation between fresh and salt waters in water-bearing sands are kept in mind, it is usually possible to develop a continuous supply of fresh water from sands that are exposed for a part of their extent to salt water. The amount of water that can be taken from such a supply without drawing in salt water will, however, depend on the methods used to develop the supply, on local conditions, and especially on the amount of fresh water available for recharging the sand.

Any general lowering of the head of the fresh water in a sand exposed for a part of its extent to the waters of the ocean will permit the salt water to advance farther inland and occupy more of the sand. The lowering may be caused by natural conditions, such as a dry year or a series of dry years, but lowering due to such causes is not likely to have any serious consequences, unless it occurs in conjunction with artificial withdrawal of water from the sand. This is usually accomplished through wells, either by pumping or by the natural flow from artesian sands. Pumping water from a water-bearing sand lowers the head of the water in it materially in the immediate vicinity of the point of pumping and, to a decreasing extent, for a considerable distance away. If this lowering of head or "cone of depression" occurs above or extends beyond the zone of contact, it will disturb the balance between fresh and salt water and permit the salt water to move up through the formation toward the well. The radius and depth of the cone of influence increase as the rate of pumping from the well is increased. It might, therefore, be possible to take a small amount of fresh water from a well in a water-bearing sand exposed to salt-water contamination without drawing in salt water, whereas if the same well were pumped at a higher rate the salt water would enter it.

The specific gravity of sea water varies slightly from place to place and sometimes at different depths at the same place, but it is never much greater than that of fresh water. For the purpose of this report the specific gravity of fresh water may be considered to be 1.000. In the summer of 1913 Bigelow(12) found that the specific gravity of the water off the Atlantic coast of the northern United States at different places and at different depths ranged from 1.019 to 1.028.

Owing to the very small difference between the specific gravity of fresh water and that of salt water, a slight change in the head of the fresh water produces a very considerable change in the position of the zone of contact. If a water-bearing sand is exposed to sea water having a specific gravity of 1.025, the level of the fresh water in it must be maintained at 2.5 feet above mean sea level if the zone of contact is to be held at a depth of 100 feet below sea level. A fresh-water head of 5 feet above mean sea level would be sufficient to hold back the sea water to a depth of 200 feet below sea level. Similarly, if the fresh-water head in such a sand were lowered only 2.5 feet, it would permit the salt water to rise 100 feet. If the fresh-water head in the sand were lowered to sea level, the salt water would rise to sea level. In a gently sloping confined sand, such as the upper sand in figure 6, C, a

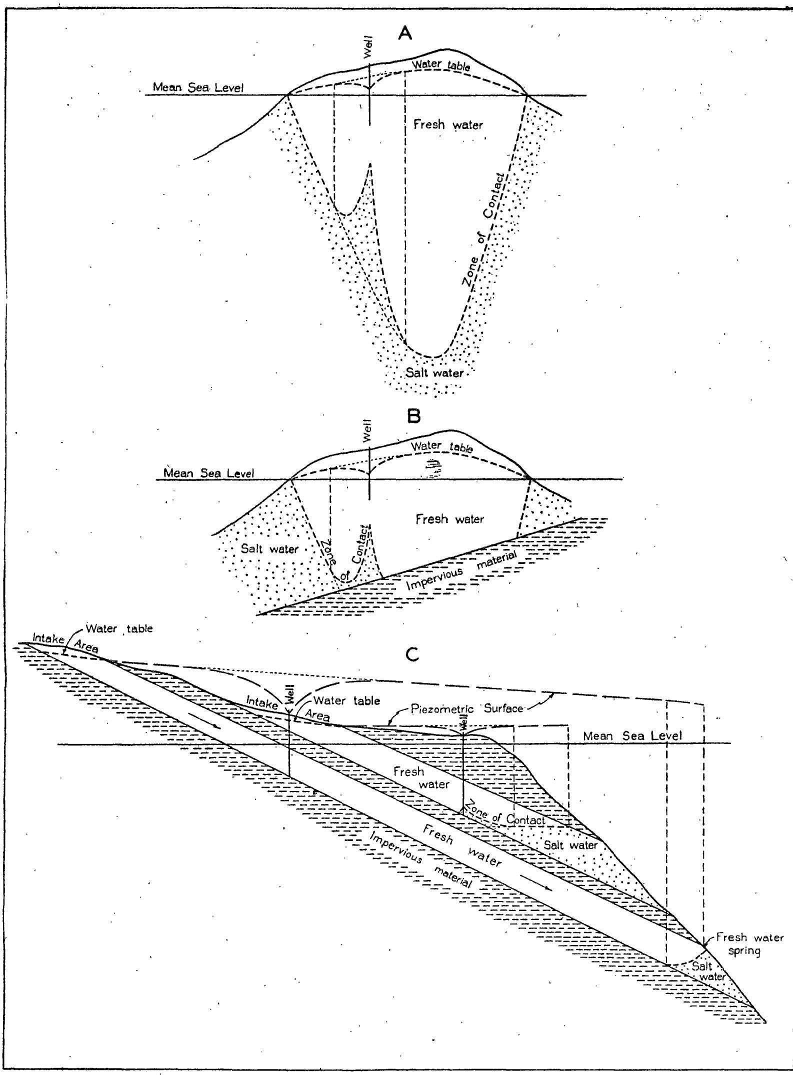

FIGURE 6.—Effect of pumping water from wells in sands exposed to salt-water contamination: A, in an island composed of sand; B, in a sand island underlain by impervious material; C, on the coast of a large body of land where the water is confined between impermeable layers.

vertical rise of 100 feet might represent a movement of the salt water several miles inland.

The mere fact that a well or well field in a sand containing both salt water and fresh water yields fresh water when it is first pumped is no assurance that it will not eventually yield salt water. The adjustment of the position of the zone of contact to the lowering of the fresh-water head caused by pumping would not be instantaneous, but the upward movement of the salt water would begin as soon as the fresh-water head above the zone of contact was lowered. The salt water would continue to move upward until equilibrium was again established or until it entered the well. The rate of movement of the salt water would be governed by the rate of pumpage from the well, because it would be necessary to remove, by pumping, the fresh water between the original position of the zone of contact and the position that it would occupy when equilibrium had again been established. If the well were situated in a uniform sand and if the lowering of head were enough to draw salt water into it eventually, a considerable part of the fresh water between the well and the zone of contact would have to be pumped out before salt water could enter the well. Usually this would require a considerable period of time. However, in irregular sands such as the Cohansey sands at the Atlantic City Water Works, a well draws water from the more permeable layers of sand at a much greater rate than it does from the less permeable layers. Therefore, once the salt water begins moving toward a well in such sands, it will advance rather quickly along the line of least resistance and may reach the well in a comparatively short time, before any appreciable part of the water lying between the well and the zone of contact has been removed.

It has already been pointed out that salt water fills the sand around and beneath the lens of fresh water under a small island composed entirely of sand. The effect of pumping a well in such a sand island is shown in figure 6, A. As the depth of the zone of contact at any point on this island is determined by the head of the fresh water at that point, any lowering of the water table on the island would cause a rise of the salt water beneath the point where the lowering of head occurred. The section in figure 6, A, is shown passing through a shallow well that is being pumped at a rate sufficient to draw the level of the fresh water down to a point somewhat above sea level. The cone of depression caused by pumping this well causes the salt water to rise from beneath the island in a shape similar to the cone of depression but inverted and proportionally much greater in its vertical dimension. This rise in the zone of contact might well be called a salt-water cone of elevation. The distance which the salt water rises is proportional to the amount of lowering of the water table, and the ratio between the lowering of the water table and the rise of the salt water is determined by the relation between the specific gravities of the fresh water and the salt water. The position of the zone of contact beneath the island is not affected outside of the area of the cone of depression produced by pumping the well.

A lowering of the water table on the island by the pumping of a well will, of course, produce the same effect whether the well is shallow or deep. As long as the water table is not lowered to sea level, there will be a space filled with fresh water between the bottom of the cone of depression and the peak of the salt-water cone of elevation. It is evident, therefore, that a shallow well on such an island might yield fresh water, whereas a deeper well at the same point and pumped at the same rate would penetrate the salt-water cone of elevation and yield salt water. The most practicable method of obtaining a continuous supply of fresh water on an island of this character is by the use of collecting galleries or very shallow wells, which skim off the top of the fresh water and do not draw the water table down to sea level. These collecting works should be located where the water table is highest and as far as possible from the shore. The quantity of water that could be taken from such a supply would depend primarily upon the amount of precipitation falling on the island.

Figure 6, B, shows the result of pumping water from a well on a sand island underlain by impervious material. A well very near the coast of such an island would, of course, encounter conditions similar to those in an island composed entirely of sand. Obviously the safest location for a well on such an island would be near its center. In this location a well might be pumped at a rate that would draw the water table down even below sea level without drawing in salt water, provided the cone of influence did not extend to any point at which it would be lowering the fresh-water head above the zone of contact. Under such conditions a "fresh-water barrier" is said to be maintained between the well and the salt water. If the location of the well or the rate of pumping from it is such that the cone of influence extends beyond the zone of contact, the fresh-water barrier will be broken down, and salt water will be drawn into the well. The diagram shows the conditions that will occur when a well on the island is pumped at a rate which would cause its cone of influence to extend beyond the nearest part of the zone of contact. The salt water would move in under the island and form a cone of elevation beneath the well, similar to the one that would be formed on the sand island shown in figure 6, A, except that it would be cut off at the bottom by the impervious layer. Here again a shallow well might yield fresh water, whereas a deeper well at the same place pumped at the same rate would yield salt water, and here again the safest way to develop a continuous supply of fresh water is by the use of shallow wells or collecting galleries, situated where the water table is high and as far as possible from the shore.

In an artesian sand the pumping of a well may not draw the head down to such a depth that the sand around the well is drained, as under water-table conditions. Usually pumping a well that taps an artesian supply merely lowers the head at and around the well and creates a cone of depression in the piezometric surface without unwatering any of the sand. Figure 6, C, illustrates conditions under which salt water might be drawn into such a sand. In the upper sand in the figure a well in the part of the formation that contains salt water would, of course, yield salt water from the beginning. Salt water would be drawn into a well farther inland if the cone of influence of the well extended beyond the edge of the zone of contact. If the well were near the zone of contact, as shown in the diagram, this might occur with only a very slight lowering of the fresh-water head in the formation as a whole. On the other hand, if the well were near the intake area, it would probably be possible to lower the fresh-water head in the formation around the well materially before the cone of influence would extend to the zone of contact and salt water be drawn into the well.

The head of the water in the lower sand in figure 6, C, is much higher than that in the upper sand. It would therefore be possible to pump a well to this sand at a rate that would lower the head in it much more than would be safe in the upper sand before salt water would be drawn in. In practically any part of this sand it would be possible to pump out the quantity of water naturally flowing past that area without drawing in salt water. If a well could be drilled to this sand very near the outlet into the ocean, salt water might be drawn into it without entirely stopping the fresh-water discharge into the ocean. Otherwise, it would be impossible to draw salt water into a well in this sand until the head had been reduced enough to stop the flow of fresh water past the well into the ocean. When the flow of fresh water into the ocean was stopped, conditions in this sand, so far as the relation between salt water and fresh water is concerned, would become similar to those in the upper sand.

In an artesian sand it may be difficult to predict whether or not a given rate of pumping will draw in salt water, particularly if the pumping wells are near the edge of the ocean, as in Atlantic City, where it is impossible to drill test wells farther out toward the salt water in the formation. The original position of the salt water can be determined approximately if the original head of the water in the sand and the general slope, thickness, and extent of the formation are known. The ultimate extent of the cone of depression for any given rate of pumpage is not so easily ascertained. The effect of pumping wells near the seashore cannot usually be measured far in the direction of the ocean, but it is usually possible to measure the lowering of head in a landward direction, and if it is assumed that the cone of depression is symmetrical, it is possible to arrive at some idea of the extent of the lowering of head in the direction of the salt water and the probability that salt water may be drawn in toward the wells. Theoretically the cone of depression of a well pumping continuously from an artesian sand will continue to expand until it extends to the intake area of the sand, even though that area may be at a great distance from the well. In some sands this would require a period of many years. The basis of this theory is that the storage capacity of an artesian sand is definitely limited, and any sustained withdrawal of water from it must be supplied from its intake area. One application of this theory to the salt-water problem is that, in the course of time, pumping from an artesian sand may draw in salt water from a surprisingly great distance. The facts that a well field is yielding fresh water even after prolonged pumping, and that the head appears to be such as to prevent the advance of salt water toward the wells, provide no definite assurance in themselves that the salt water may not eventually be drawn into the wells without increased pumping.

Another application of this theory can be made to an artesian sand in which fresh water is not flowing out into the ocean, as in the upper sand in figure 6, C. As the cone of depression of a well to such a sand must eventually extend to the intake area, it would seem that a well situated nearer to the zone of contact than to the intake area must eventually draw in some salt water, no matter what the rate of pumping is, provided the sand is uniform throughout its extent, so that the cone of depression expands equally in all directions, because its cone of depression would pass the edge of the zone of contact before it reached the intake area. As soon as the fresh-water head at the zone of contact was lowered, the salt water would begin to move toward the well. If the well is so situated that before its cone of depression reaches the zone of contact it extends far enough to encompass a part of the intake area sufficient to produce recharge equal to the discharge of the well, the cone of depression will not extend any farther in the direction of the ocean, and salt water will never be drawn into the well as long as the rate of pumping is not increased.

As indicated in figure 6, C, if salt water is drawn into a well in an artesian sand, it will form a cone of elevation around the well somewhat similar to the cones of elevation formed in the sand islands. However, if the salt water is being drawn into the well and carried away, it must be moving constantly toward the well and will lose some of its head by friction with the sand, so that the salt-water cone of elevation would not rise around the well as high as it would if it were possible to lower the fresh-water head the same amount without removing salt water from the sand. As a practical matter, the water from a well is usually rendered unfit for use by the addition of 3 or 4 percent of sea water. It is interesting to note, however, that under artesian conditions, if only a single well situated inland from the zone of contact is being pumped, it would be impossible to draw into the well 100 percent of sea water, no matter how much the head might be lowered in the well. This is true because so long as there is any fresh water in the formation it will be drawn into the well and dilute the sea water. If the flow of fresh water into the well were stopped, the fresh-water head in the sand would build up and force the salt water back from the well.

Although it is theoretically impossible to draw 100 percent sea water from a single well situated inland from the zone of contact in an artesian sand, it would be possible to draw practically 100 percent sea water from the most exposed wells in a large group. In such a group the wells nearest to the source of salt water will draw in most of the salt water that approaches the well field and so tend to protect the remaining wells from contamination. It is conceivable that under some conditions it might be possible to pump a line of wells between the source of salt water and a well field yielding fresh water and thereby protect the fresh-water wells from contamination with salt water. The advisability of such a program of protective pumping should be considered in areas where the salt-water contamination has already begun. Usually, under such circumstances, if the outlying wells are abandoned, the wells farther from the source of salt water will soon be contaminated also and have to be abandoned. The money spent to continue pumping the outlying wells, thereby protecting the remaining fresh-water wells, might be a profitable investment. In considering such a step it should not be forgotten that the pumping of this line of protective wells would further lower the head of the water in the formation and thus tend to increase the amount of salt water being drawn toward the well field. Protective pumping may, however, be used to postpone the time when it will be necessary to seek a new supply. Under the most favorable conditions it might make possible the continued pumping of fresh water from a well field that would otherwise have to be abandoned entirely, although of course the cost of pumping would be greatly increased. An example of the protective effect of pumping from wells near the source of salt water is afforded by wells in the 100-foot sand at the Atlantic City Water Works. (See pp. 60-61 and 75.)

Certain practical conclusions may be drawn from the preceding discussion of the theory of salt-water intrusion into artesian sands. One is that in establishing a water supply from an artesian sand that is exposed to salt-water contamination, it is advisable to locate the wells as far as possible from the source of the salt water. Such a precaution would decrease the probability that the cone of influence might extend beyond the zone of contact and draw salt water into the wells. It would also have the advantage that test wells could be driven between the well field and the source of salt water, so that the extent of the cone of influence in the direction of the ocean could be determined and any advance of the salt water could be discovered before it reached the active wells. The second conclusion is that in the management of water supplies that draw from an artesian sand, where the conditions are such that salt water will probably be drawn in eventually, it is highly important that all waste of water be eliminated, in order to keep the rate of pumping as low as possible and thus postpone the arrival of the salt water.

THE 100-FOOT SAND AT THE ATLANTIC CITY WATER WORKS

INCREASED DEVELOPMENT SINCE 1930

Since 1930 the relative importance of the shallow sands on the mainland as sources of water supply for the Atlantic City region has been increased by the drilling of several large wells to these formations by the Atlantic City Water Department and the Atlantic County Water Co. At the Atlantic City Water Works the daily capacity of the wells drawing from the 100-foot sand has been increased from about 3 million gallons to over 8 million gallons. The Atlantic County Water Co. has drilled two wells to this formation with a combined daily capacity of about 3 million gallons. Thus the capacity of wells to this sand has been increased almost four times.

WATER-LEVEL FLUCTUATIONS UNDER OLD AND NEW SYSTEMS

It is interesting to compare the water level and range of fluctuations at the Atlantic City Water Works under the old suction system with those under the new system of large-capacity deep-well pumps. A water-stage recorder was maintained on well A-27 for a few months in 1924 and from February, 1930, to the present time. The daily and long-time fluctuations of water level observed in this well are shown in figure 7. Under the old system of operation the water surface in this well ranged from 1 to 4 feet below sea level when the active wells were being pumped and promptly rose to 4 to 6 feet above sea level when they were shut down. When pumping was discontinued for 3 days in May, 1924, the water surface in this well rose to more than 5 feet above mean sea level. In the spring of 1930 work was begun on the construction of new wells to this sand. This necessitated shutting down some of the wells that had been pumping, and during May and June of that year the water surface in well A-27 stood about 2 feet above sea level most of the time. During July, 1930, a gradual transition was made from the old system to the new one. Regular operation of the first two new wells was begun in August, 1930. From that time until December, 1931, the water surface in the observation well was never above sea level, although it approached sea level two or three times when the wells were shut down for 2 or 3 weeks. In July, 1931, the average rate of pumpage from the 100-foot wells at the Atlantic City Water Works was 6.9 million gallons daily. During this month the water surface in well A-27 reached a

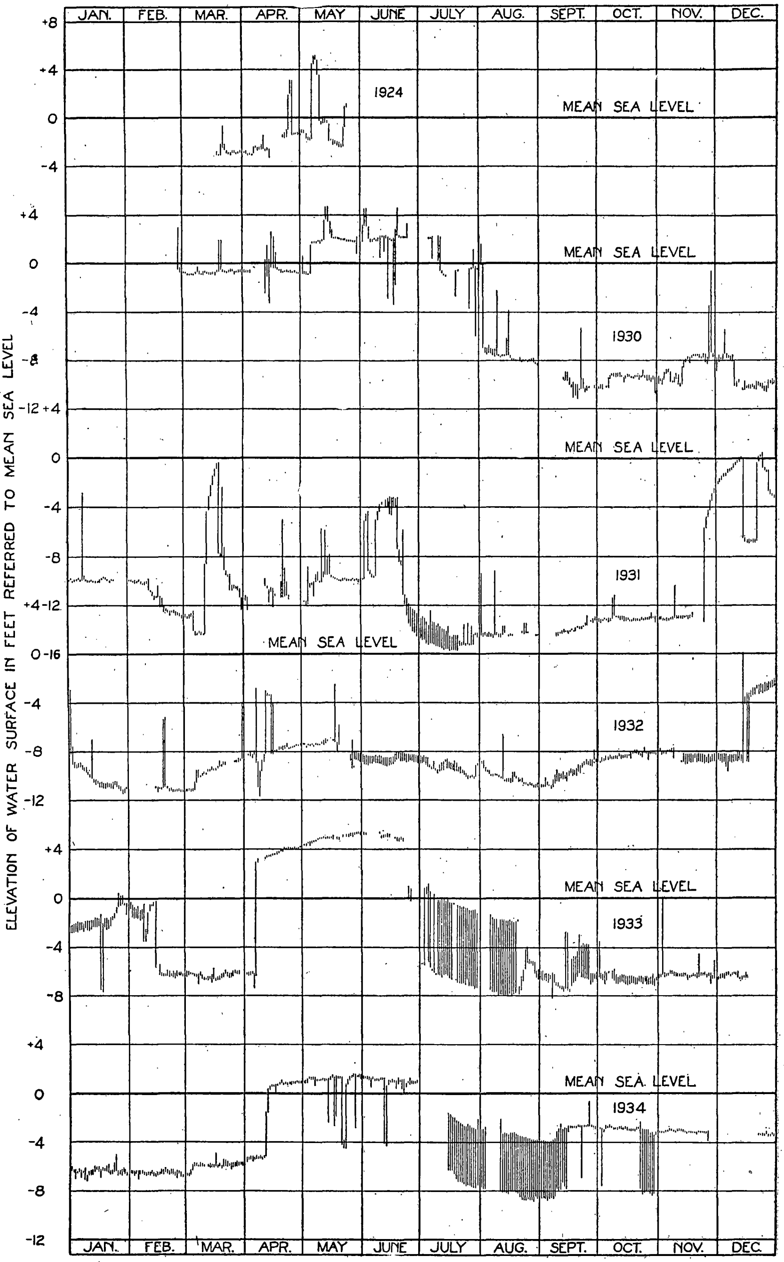

FIGURE 7.—Daily fluctuations of water level observed in well A-27 to the 100-foot sand at the Atlantic City Water Works, 1924 and 1930-34. The daily range in altitude of the water surface is indicated by vertical bars.

record low position of almost 16 feet below mean sea level. Heavy pumpage from this sand was continued until late in November, 1931, and the water surface in well A-27 averaged about 14 feet below sea level during all of this period. From November 20, 1931, to January 10, 1932, a test was conducted to determine some of the hydraulic characteristics of this sand including the shape and extent of the cone of depression in it and the recovery of the head after about 1½ years of pumping under the new system. This test is discussed in detail on pages 43-52. After a shut-down of 3 weeks the water surface in well A-27 rose to a point just above mean sea level. During almost the entire year of 1932, when the pumpage from the sand averaged about 3.5 million gallons daily, the water surface in well A-27 ranged from 7 to 12 feet below mean sea level, except during brief shut-downs. A daily rate of 3.5 million gallons is not much in excess of the rate at which water was pumped from the sand under the old system of operation. However, under the old system the water was drawn from many wells scattered over a fairly wide area, whereas under the new system it was drawn chiefly from three wells of large diameter. The draw-down in these large wells was necessarily much greater than that in any of the smaller old wells and the shape of the cone of depression around the pumping wells was materially changed by this method of operation. It is probable that the effect outside of the immediate well field of pumping the new wells at a daily rate of 3.5 million gallons was not much greater than the effect of pumping 3 million gallons under the old system. The change in the distribution of pumpage in the well field doubtless accounts for the much lower water levels observed in well A-27 during 1932 than during 1924 and early 1930. The significance of this change lies in the fact that the center of pumpage in the well field was moved northward, nearer to the salt marshes along Absecon Creek and Conovers Run. As the salt-water intrusion into the 100-foot sand comes from this direction (see p. 73), the redistribution of pumpage probably had an important effect upon the movement of salt water in this sand.

Under the new system the water levels in well A-27 are most affected by changes in the rate of pumpage from well 4, which is nearest to the observation well. In late January and early February, 1933, wells 4 and 13 were shut down but well 2 was pumped steadily at a rate of almost 2 million gallons daily. During this period the water surface in well A-27 stood at or just below sea level. From April 6 to June 24, 1933, all the wells to the 100-foot sand at the Atlantic City Water Works were shut down completely, to study the effect of the shut-down on the salinity of the water yielded by the new wells. The water surface in well A-27 promptly rose to about 3 feet above sea level and continued to rise for about 8 weeks, when it stood about 5½ feet above sea level. From July, 1933, to March, 1934, the rate of pumpage from the 100-foot sand again averaged almost 3.5 million gallons daily, and the water surface in well A-27 fluctuated around 6 or 7 feet below sea level. During most of April, May, and June, 1934, well 4 was shut down and the average daily rate of pumpage from wells 2 and 13 was slightly over 2 million gallons. During most of this period the water surface in well A-27 stood from 1 to 2 feet above sea level.

In general, the water level in wells to the 100-foot sand at the Atlantic City Water Works has been maintained at a considerably lower elevation under the new system than under the old one. The range of fluctuation has also been much wider since the installation of the new wells. Comparisons of the static water levels during periods of shut-down under the old and new systems are believed to be especially significant, because the water levels are then affected very little by the changed distribution of pumpage. When the wells operating under the old system were shut down, in May, 1924, the water rose to more than 5 feet above sea level within 3 days. Again in May and June, 1930, when all or most of the pumping from the sand was discontinued for periods of 2 or 3 days, the water in well A-27 promptly rose to about 5 feet above sea level. When the new wells were shut down, in November and December, 1931, the water level immediately rose several feet and then continued to rise gradually until the end of the 3-week shut-down, when it had risen to an elevation only slightly above sea level. During a similar shut-down of the new wells in April, May, and June, 1933, the water promptly rose to about 3 feet above sea level and then gradually worked its way up to more than 5 feet above sea level in a period of 8 weeks. It should be noted that the two periods when shut-downs were observed under the old system were both in the spring, when the ground-water supply had been replenished by the rains of the preceding winter. The shut-down in December, 1931, occurred after an unusually dry summer, which may have had some effect in lowering the water table. However, it is hardly conceivable that any drought of a few months' duration would lower the water table in this sand practically to sea level. This shut-down also occurred after a 5-month period of exceptionally high pumpage, and it seems probable that the pumping was at least as effective in lowering the water level as the drought. Whatever the cause, the static water level in this sand was about 5 feet lower in December, 1931, than in May, 1924, or in May and June, 1930.

The shut-down in April, May, and June, 1933, occurred at about the same time of the year as the shut-down in 1924 and might therefore be considered more significant than that of December, 1931. During this shut-down the water level in the sand rose to about the same elevation which it had reached during the shut-down in May, 1924. However, it required 8 weeks for the water level to reach this elevation in 1933, as compared to 3 days in 1924. The precipitation in the months preceding the shut-down was about the same and slightly above normal both in 1924 and in 1933. As the two periods of shut-down were so widely different in duration, it may be more significant to compare the first part of the shut-down in 1933 with that in 1924. In 1933 the water table recovered in 3 days to a level about 2 feet lower than that to which it recovered in the same time in 1924. After almost 2 months of gradual recovery in 1933 the water level was about as high as it was at the end of less than 1 week of recovery in 1924. This comparison again suggests that the pumpage under the new system may have somewhat depleted the supply of water in this sand. The average daily rate of pumping from this sand during the period immediately preceding the shut-down in 1933 was only about 3.25 million gallons. It is estimated that the daily rate of pumping before the shut-down in 1924 was about 2.5 million gallons.

The 100-foot sand in the Atlantic City Water Works well field is overlain by a bed of clay, but this bed is not of wide extent—in fact, it probably does not extend very much beyond the well field. It therefore seems reasonable to believe that a lowering of the static level in wells in the well field represents not merely a decrease in pressure, due to frictional losses of head in the transmission of the water from the intake area to the well field, but also a lowering of the water level in the intake area and a withdrawal of water from storage in the sand. This belief is supported by the fact that old residents of the vicinity report that swampy land near the water works was dried up when the pumping of the 100-foot wells was begun. The fact that in June, 1933, while the 100-foot wells at the water works were still shut down, the static water level in wells to the sand began to decline also suggests a close connection between the 100-foot sand and its intake area. This decline was probably due to transpiration by plants on the intake area.

TEST OF NOVEMBER, 1931, TO JANUARY, 1932

PURPOSE OF TEST

The drilling of the large new wells to the 100-foot sand and the abandonment of eighteen smaller old wells furnished an excellent opportunity to study this sand with reference to ground-water hydraulics. A test was undertaken in November, 1931, to determine, if possible, the shape of the cone of depression around wells to this sand at the Atlantic City Water Works, the extent of the cone when pumping was being done at different rates, and the elevation of the static head of the water in the formation. An attempt was also made to determine the permeability of the sand by applying the Thiem method developed by G. Thiem in Germany (13). At the time of the test this method was in its experimental stages in this country, and one reason for applying it to the results of this test was to determine its applicability to conditions such as those existing at the Atlantic City Water Works. The test extended into the early part of January, 1932, before it was completed.

OBSERVATIONS MADE

In addition to the water-stage recorder on well A-27, similar recorders were installed on wells A-33 and A-22. These recorders were operated throughout the test. Toward the end of the test recorders were installed on wells 6 and 8. Recorders were considered desirable on these two wells from the start, but the wells were equipped with individual deep-well pumps, which could not be removed without great expense. The space between the pump column and the casing was large enough to accommodate a small float, but it was sealed over except for a 1¼-inch hole in the pump base for the breather pipe. The difficulties were at first considered insurmountable, but as the need for recorders on these wells became increasingly apparent, several attempts were made to operate a recorder on one of them, using floats of various kinds that could be inserted through the 1¼-inch hole. Finally an ordinary hot-water bottle was adapted for this purpose by attaching an automobile tube valve to the plug and adding enough weight to the lower end of the bag to cause it when inflated to float in water with its point of maximum diameter at the water surface. The bag was deflated and inserted, with its weights, through the hole in the pump base, then inflated and lowered to the water surface. As the daily fluctuation of the static water level in these two wells was never more than 2 or 3 feet, the counterweight could be kept above the floor of the well house by adjusting the length of the counterweight tape when necessary. This installation proved very satisfactory and gave an excellent record of the fluctuation of water levels in these wells during the later part of the test. The recorder on well 8 is believed to be the first recorder installed on a well equipped with a deep-well pump, and the method used may be serviceable in other localities where similar difficulties are encountered. By suitable adjustment an installation of this type can probably be made to record a much wider range of fluctuations than was necessary in wells 6 and 8.

When the test was begun, on November 23, 1931, wells 2, 4, and 13 had been pumped continuously for several weeks at a rate of 4.25 million gallons daily. Before making any change in the operation of these wells, a series of observations were made to determine the elevation of the water surface and the shape of the cone of depression under these conditions. Throughout the test frequent observations of water level were made on every available well to the 100-foot sand, a total of 23 wells. The fluctuations of the tide in Absecon Creek were also observed, at first by means of frequent readings of a staff gage and later by means of a water-stage recorder. Each of the new wells was equipped with a meter that recorded the rate at which it was being pumped whenever it was in operation. The fluctuations of the water level in some of the wells that are considered typical or especially significant are shown in figure 8, together with the rates of pumping the different wells and the fluctuations of the tide in Absecon Creek. Owing to the method of operation of the plant, the rate of pumping varied slightly from time to time. This caused small fluctuations over periods of a few hours in the water level in the pumped wells but did not have any appreciable effect on the water level in the other wells observed. The rates of pumping shown in figure 8 and used in the text are the average rates. In the study of Thiem's method both the average rate of pumping and water level and figures obtained by observations made as nearly simultaneously as possible were used.

After the measurements of water level had been made, with wells 2, 4, and 13 being pumped, these wells were all shut down, and the water level in the sand was allowed to recover, in order to determine, if possible, the static level in the formation and the slope of the piezometric surface, which would indicate the direction from which the water was moving into the well field. The water level did not rise within 5 feet of the elevation to which it had risen in 1924, but during the entire test it showed a tendency to rise very gradually. However, at the end of 3 weeks the water level was rising so slowly that it was decided to continue

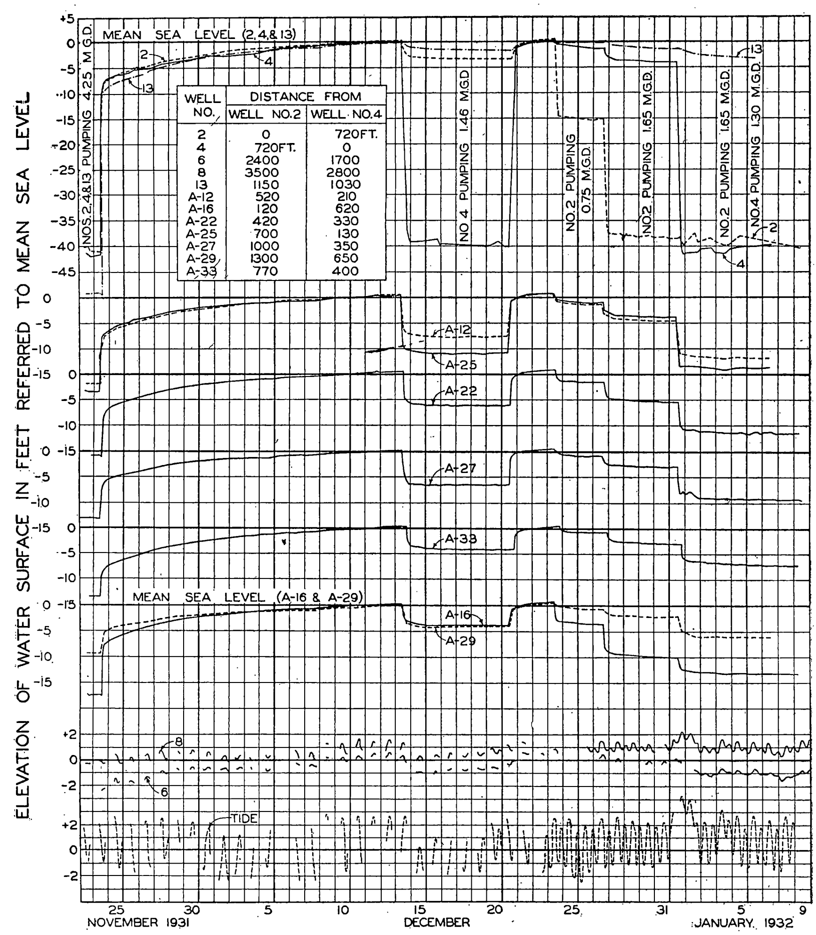

FIGURE 8.—Fluctuations of water level in significant or typical wells to the Atlantic City Water Works 100-foot sand, the rates of pumping from the sand, and the tidal fluctuations in Absecon Creek from November 23, 1931, to January 9, 1932.

with the remainder of the test, assuming that the water levels then established represented static conditions. Well 4 was then pumped continuously at an average rate of 1.46 million gallons daily from 9:55 a. m. December 14 to 11:30 a. m. December 21, when the water levels had again become nearly constant. The observations of water level made at that time were used to determine the shape of the cone of depression in the sand when a single well was being pumped and also to determine the permeability of the sand by the Thiem method. After the measurements were made well 4 was again shut down, and no water was pumped from the sand until uniform conditions had once more been established. Well 2 was then started and operated at a rate of 0.75 million gallons daily from 10:26 a. m. December 24 to 2:46 p. m. December 27, when the rate was increased to 1.65 million gallons daily. Each rate of pumping was maintained until the fluctuations of water level in the observation wells had become very small. At each rate of pumping observations of water level were made to determine the shape and extent of the cone of depression and for study by the Thiem method. Well 4 was started again at 11:28 a. m. January 1, 1932, and operated along with well 2 at a combined rate of 2.95 million gallons daily, in order to determine the extent of the cone of depression at this rate of pumpage. When these observations had been made the test was concluded, on January 9, 1932.

SHAPE AND EXTENT OF CONE OF DEPRESSION

With two and three wells being pumped in the well field, the cone of depression extended far beyond the limits of the old well field, where practically all the observation wells were situated. It was therefore impossible to obtain a very definite idea of the shape and extent of the cone. Of the two wells that were pumped alone, well 4 is more nearly in the middle of the group of observation wells, and the best idea of the shape of the cone of depression was therefore obtained from the test of this well. The shape of the piezometric surface at the end of the shutdown just before well 4 was pumped and after this well had been pumped for 7 days and the elevation of the ground surface are shown in figure 9.

Several facts are brought out by these maps. The water levels in the sand had not completely recovered when the pumping of well 4 was begun. This accounts for the very irregular shape of the piezometric surface at that time. As indicated by the dashed lines on map A, the pressure was low in the vicinity of well A-29 and high in the vicinity of wells 2 and 8. A trough of lower pressure extends from old well A-29 toward well 13. Northwest of this trough the piezometric surface

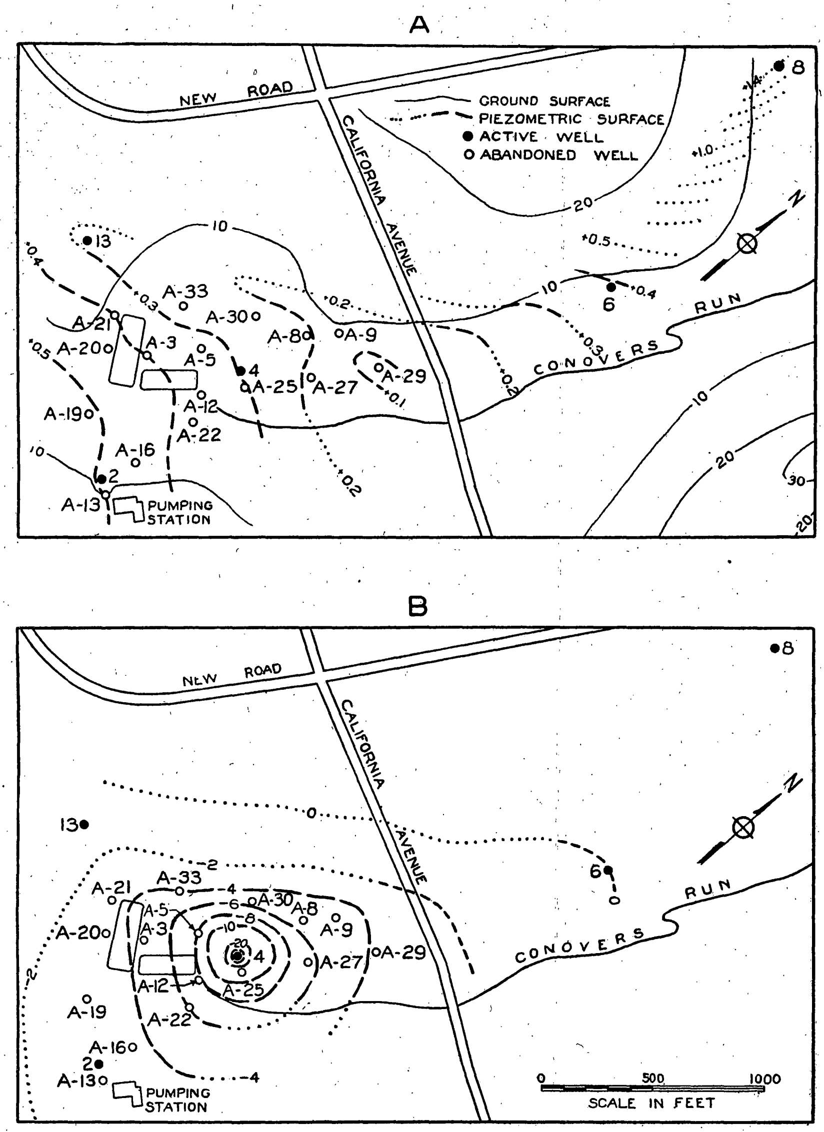

Figure 9.—Maps of well field at Atlantic City Water Works, showing the location of wells to the 100-foot sand and indicating by contours the elevation of the ground surface and of the piezometric surface. A, Ground surface and piezometric surface before well 4 was pumped. B, Piezometric surface after well 4 had been pumped 7 days at 1.46 million gallons daily.

probably rises toward the higher ground beyond New Road. Apparently another ridge of higher pressure extends southwestward from well 2. The trough between wells A-29 and 13 is perhaps a remnant of the depression that existed in the well field when all the wells were pumped. The lower water level in well A-29 might also be caused to some extent by the fact that this well contained water of considerably higher salt content than any of the other wells. This salt water had a somewhat higher specific gravity than the fresh water in the other wells and therefore stood at a somewhat lower elevation than it would have if it had been fresh. This would not, however, account for the low water levels in such wells as A-8, A-9, and A-30, all of which contained fresh water. The shape of the piezometric surface shown in figure 9, A, seems to indicate that the water supply for the well field comes principally from the north-northwest and from the southwest, rather than from the northwest, which is the direction of the general slope of the major formation.

The shape of the cone of depression when well 4 was being pumped, shown in figure 9, B, is even more significant than the shape of the piezometric surface before the pumping was started. On this map the steepest slope of the piezometric surface was in a southeasterly direction from the vicinity of well A-30 toward well 4. There was a much more gradual slope from wells A-29, 2, and 13 toward well 4. Southeast of well 4 there were no observation wells far enough away to define the shape of the cone of depression very definitely, but it seems probable that in this direction also the cone had a more gradual slope. The steeper slope from well A-30 to well 4 seems to indicate that the resistance of the formation to the movement of water is greatest in that direction—or, in other words, that its permeability is lowest—and that possibly a smaller proportion of the water supplied to the well may come from that direction than from other directions. This interpretation of the steep slope in this direction conforms to the conclusion drawn from the shape of the piezometric surface before well 4 was pumped—that less water enters the well field from the northwest than from the north-northwest and the southwest. The results of the determinations of the permeability of the formation made by the Thiem method (p. 51) also seem to confirm this conclusion.

The information yielded by this test as to the extent of the cone of depression of a well being pumped from the 100-foot sand was not as definite as had been hoped. Unfortunately the water level in the observation wells most remote from the pumped wells—wells 6 and 8—was affected by the tide, so that it was difficult to tell exactly how much the pumping influenced the water level in them. The bed of clay overlying the 100-foot sand is so local in extent that when pumping begins the cone of depression unquestionably reaches the intake area fairly promptly. Thereafter the cone presumably continues to expand until it includes an area in which the recharge is great enough to yield continuously the amount of water being pumped from the sand. Short periods of pumping such as those observed during this test, of course do not indicate the ultimate extent of the cone of depression under prolonged pumping. They are useful in that they may give some idea of its magnitude, and the following facts observed during the test, and shown on figures 8 and 9, are therefore significant: When well 4 was pumped at an average rate of 1.46 million gallons daily for 7 days its cone of depression very definitely extended to well 6, more than 1,700 feet away, where the water level was lowered about 0.4 foot. It also appeared to extend to well 8, at a distance of about 2,800 feet, lowering the water level there about 0.2 foot. When wells 2, 4, and 13 were being pumped together at the beginning of the test, they were withdrawing water from the sand at a rate of 4.25 million gallons daily. After these wells were shut down, the water level in well 8 recovered about 1 foot in 3 weeks.

The effect of pumping well 2 was not so evident in well 8 but was apparent in well 6, and the effect of pumping wells 2 and 4 together was evident in both wells 6 and 8. It is believed that the cone of depression caused by pumping one or more wells to the 100-foot sand at the Atlantic City Water Works at a rate of 1.5 million gallons daily extends at least half a mile from the well field and that the effect of pumping 4.25 million gallons daily will be measurable considerably more than a mile from the pumped wells.

APPLICATION OF THIEM METHOD

The coefficient of permeability is a measure of the water-carrying capacity of a sand. It has been expressed in different units by different workers in hydrology. As used by the United States Geological Survey, it is defined as the rate of flow, in gallons a day, through a square foot of area of the sand under a hydraulic gradient of 100 percent at 60° F. (14, p. 148.) The Thiem method of determining the coefficient of permeability is based on the mathematical theory of the flow of water into wells. Its advantage over most of the other methods heretofore in use is that the field observations needed are comparatively simple, comprising measurements of the rate of pumping from one well and of the lowering of the water level in two other wells in a straight line with it, both on the same side of it, and preferably at right angles to the original hydraulic gradient. Thiem's formula for the coefficient of permeability is

$$P = \frac{q\,(\log_e a_1 - \log_e a)}{2\,\pi\,m\,(S - S_1)}$$

in which P = coefficient of permeability

q = rate of pumping, in gallons a day.

a and a_1 = distances to the nearer and farther observation wells, respectively from the pumped well, in feet.

π = 3.1416

m (for artesian conditions) = thickness of water-bearing bed, in feet.

m (for water-table conditions) = average thickness (at a and a_1) of the saturated part of the water-bearing bed, in feet.

S and S_1 = lowering of the water level at the nearer and farther observation wells, respectively, in feet.

The conditions for determining the permeability of the 100-foot sand at the Atlantic City Water Works by the Thiem method were not ideal during this test, for four reasons. First, the true static conditions were not reached in the formation before well 4 was started. Probably this was not a serious obstacle, however, because both observation wells were probably affected similarly. Second, very few pairs of wells were in direct line with the pumped well, and the direction of the original flow of the ground water, if any, was not determined. Third, the thickness of the water-bearing sand was not uniform, and an average had to be assumed from a few well logs, which were not necessarily representative of the whole sand. Fourth, the water levels in some of the wells adjacent to Conovers Run were affected in varying degrees by the tide, which made exact interpretations of the water level in them impossible.

In spite of these difficulties, coefficients of permeability were computed for twelve pairs of observation wells, all of which were within 1,000 feet of the pumped well and approximately in line with it. These computations showed a range in the coefficient of permeability from 502 to 1,440 and an average of 1,040. In comparison with these figures, the coefficients of permeability determined in the laboratory on samples of sand from the Atlantic County Water Co.'s well at New Road and Delilah Avenue, about 2,000 feet southwest of the Atlantic City well field, range from 190 to 880. Laboratory coefficients of permeability on samples from a test well west of New Road near well 8 ranged from

390 to 1,500 and averaged 722. In view of the fact that the 100-foot sand varies widely in character from one place to another, it is reasonable to assume that the results obtained by the Thiem method may be as reliable for estimating the permeability of the sand as a whole as those obtained in the laboratory on samples from a few scattered spots. It is interesting to note that the highest coefficients of permeability in this well field were found by using lines of wells that extended north and south from well 4, along the major axis of the cone of depression, as shown in figure 9. The lowest coefficients were found on lines approximately at right angles to this axis.

TIDAL FLUCTUATIONS IN 100-FOOT WELLS

Several of the wells observed during this test were subject to tidal influence, and the water level in them fluctuated in essential agreement with the fluctuations of the tide. This influence was greatest in the wells nearest Absecon Creek, especially in wells 6 and 8. It occurred to a lesser extent in wells A-9 and A-29 and possibly in wells A-8, A-27, and A-25.

This phenomenon is not unusual in wells near the ocean. Under strictly artesian conditions it is believed to be purely a pressure effect, due to the varying load on the overlying formations as the tide rises and falls. It has been found that under such conditions the fluctuations in the wells coincide almost exactly in time with the movements of the tide and that the ratio of the fluctuations in the well to those of the tide depends upon the distance from the well to the tidal body of water. Fluctuations of this type are considered on pages 93-96, in the discussion of the Atlantic City 800-foot sand. Under strictly water-table conditions some fluctuation of the water table occurs near the ocean with the rise and fall of the tide. However, such a fluctuation depends upon the movement of water through the formation and is therefore dampened and retarded by the resistance of the sand to the motion of water. The conditions in the 100-foot sand at the Atlantic City Water Works might be called semiartesian. Throughout the well field the 100-foot sand is overlain by a confining bed of clay and the water in it is under slight artesian pressure. However, it has been found that at comparatively short distances from the well field this overlying clay bed disappears or at least thins out in spots, leaving openings through which water is free to move.

A comparison of the tidal fluctuation in wells 6 and 8 with the fluctuation of the tide in Absecon Creek is shown in figure 8 and in greater detail in figure 10. The effect of the tide on the water level in the wells is essentially the same as under artesian conditions, except that the peaks and valleys in the wells usually occur from 1 to 2 hours later than the peaks and valleys of the tide. This time lag is significant, because it indicates that the tidal fluctuation in these wells is not due entirely to the pressure on the sand caused by the tidal loading of the nearby marshes, but is due in some measure to conditions that cause changes in the rate of movement of the water in the sand. There are probably holes in the confining clay bed which, permit the fresh water in the formation to flow out into the tide channels of Absecon Creek or Conovers Run or permit salt water to flow into the sand, the direction of flow depending upon the head of the fresh water in the sand. Rising tides would decrease the outflow of fresh water or increase the flow of salt water into the sand, and falling tides would have the opposite effect. Each rising tide would create a back pressure against the water in the sand. Each falling tide would tend to lower the pressure of the ground water. These changes in pressure would attain their maximum intensity some time after high or low water in the adjacent bodies of salt water, because they involve changes in the rate of flow in the sand, which would continue in effect for some time after the turn of the tide.

INTRUSION OF SALT WATER INTO THE 100-FOOT SAND

HISTORY OF THE INTRUSION

In 1930 the Atlantic City Water Department abandoned its old system composed of thirty-two 10-inch wells 100 and 200 feet deep, all pumped by direct suction, and installed a system of large wells each pumped by a deep-well pump. The first of the new 100-foot wells was completed in June, 1930, and was put into service very soon thereafter. By the end of 1930 practically the entire new system, consisting of five 100-foot wells and seven 200-foot wells, was in service. The daily capacity of the five new 100-foot wells is about 8 million gallons. A new well with a daily capacity of about 1 million gallons was completed nearby for the Atlantic County Water Co. in May, 1932. This well is about 2,000 feet southwest of the Atlantic City Water Works.

It was not possible to measure separately the amount of water furnished by the 100-foot and 200-foot sands under the old system, but it

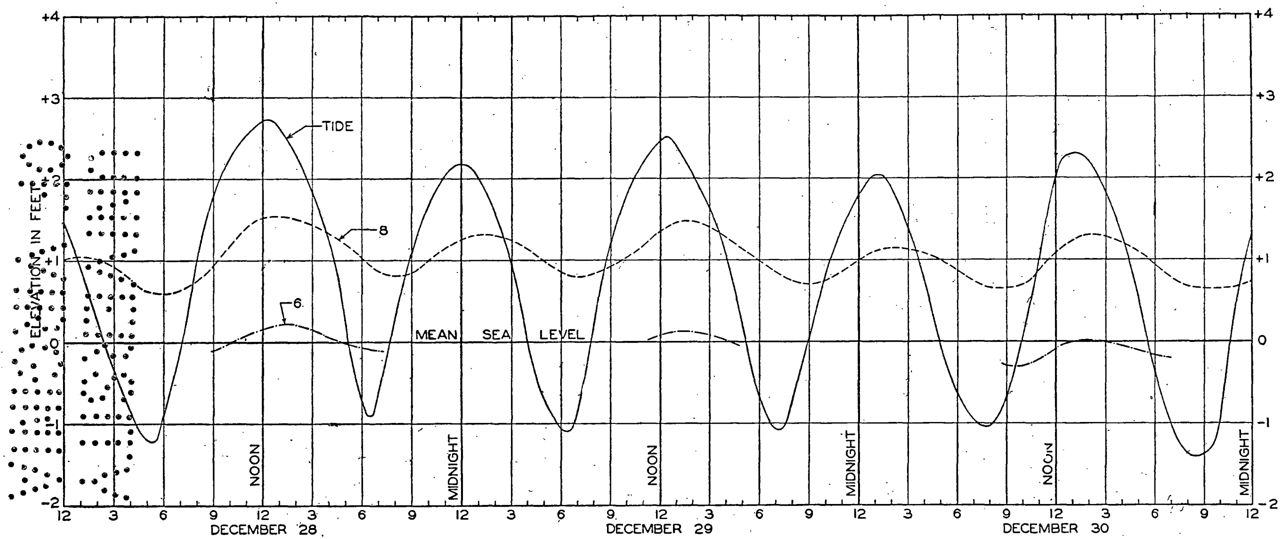

FIGURE 10.—Fluctuations of the tide in Absecon Creek at New Road and of the water levels in wells 6 and 8, December 28-30, 1931.

was estimated that each sand yielded about 3 million gallons daily. If so, the present capacity of wells to the 100-foot sand in this vicinity is about three times the capacity of the old wells used before 1930. However, the new wells have never been pumped at their full capacity for any great length of time. The three highest monthly averages at the Atlantic City Water Works were, in February, 1931, 6.2 million gallons daily; July, 1931, 7.0 million gallons daily; and August, 1931, 5.8 million gallons daily. Since that time the pumpage from the formation for any month has not exceeded 5 million gallons daily and has been less than 4 million gallons daily most of the time.

During the first summer no increase in the salt content of the water from the 100-foot sand was observed, although the total pumpage from the sand was increased somewhat. The periodic analysis of the water from these wells was begun in March, 1931, and at that time the water from three of the five 100-foot wells was found to contain considerably more than its original chloride content. Water from well 4 (see fig. 11) contained 25 parts per million; from well 6, 48 parts per million; and from well 8, 95 parts per million. In contrast samples of water collected from each of these wells soon after their completion contained from 14 to 16 parts per million of chloride. As the pumpage increased with the approach of summer, the salinity of the water from these wells also increased. By the fall of 1931 the chloride content of water from well 4 had risen to about 30 parts per million, that from well 6 to over 600 parts per million, and that from well 8 to almost 500 parts per million. Well 6 was shut down in July, 1931, and well 8 in September, 1931, and neither well was pumped again, except for the purpose of collecting samples until August, 1935.

Well 4 was shut down in September, 1934, after the chloride content had risen to 310 parts per million and was pumped only a few days until January and February, 1935, when it was again in operation. From February 27, to August 12, 1935, well 4 was operated only a few hours a week for the collection of samples of water. The chloride content of water from well 2 rose to about 20 parts per million for several months in the summer of 1933 while well 4 was shut down, but declined to its original content of about 14 parts per million after well 4 had been in operation again for a few months. Again after the shut-down of well 4 in September, 1934, the chloride content of the water from well 2 rose and on March 19, 1935, it was 41 parts per million. On March 20, 1935, this well was shut down and it was not pumped again except for the collection of samples of water until August 14, 1935. The chloride

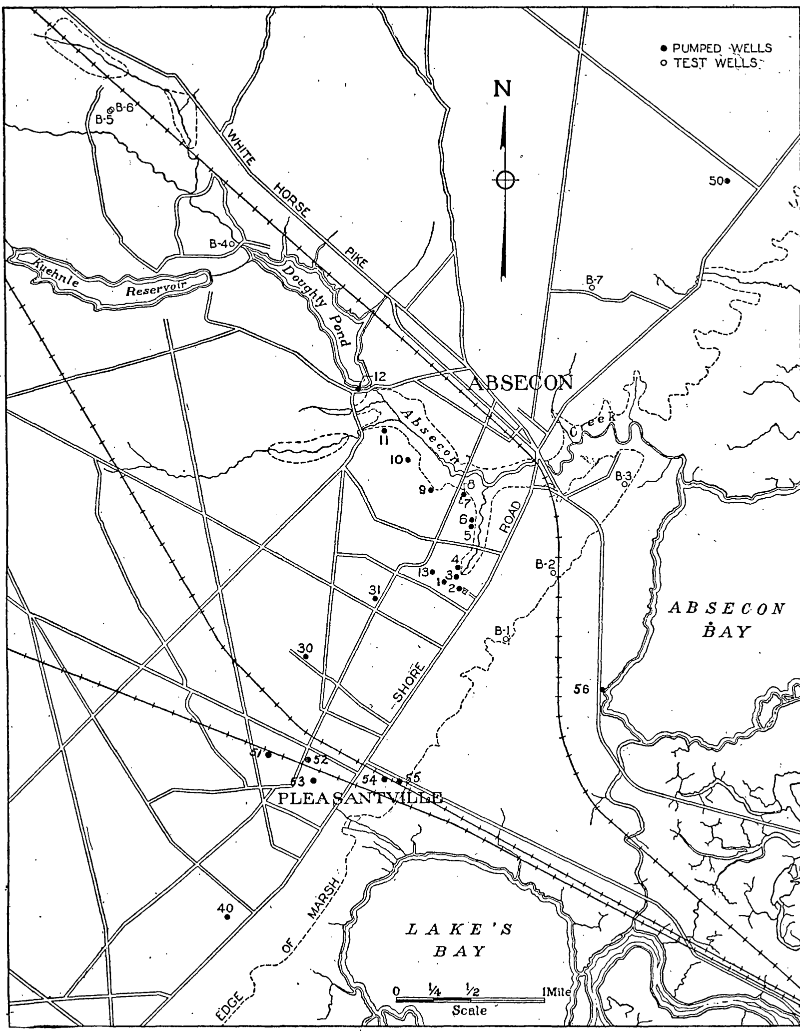

FIGURE 11.—Map of the area surrounding the Atlantic City Water Works, showing the location of the principal active wells and of the outlying test wells drilled in the course of this investigation. 1-13, Atlantic City Water Works wells: 1, 675-foot well (to Atlantic City 800-foot sand); 2, 4, 6, 8, 13, 100-foot wells; 3, 5, 7, 9-12, 200-foot wells. 30, 31, Atlantic County Water Co.'s wells (30 probably to 100-foot sand, 31 to 100-foot sand). 40, Atlantic County Hospital well (to a part of the Cohansey sand not correlated with those at the Atlantic City Water Works). 50, Sea View Golf Club (7 wells—2 to 200-foot sand, 5 to a shallow sand). 51, O. J. Hammel Co. 52, Peerless Dye Co. 53, Risley Laundry Co. 54, Taylor Packing Co. 55, Hygienic Ice Co. 56, Paxton's service station (probably to 200-foot sand). B-1, B-2, B-3, B-5, B-7, test wells to 200-foot sands. B-4, B-6, test wells to shallow sands.

content of the water from well 2 had declined to 16 parts per million on August 3, 1935. Well 13 has remained comparatively fresh up to August 3, 1935, when the chloride content of the water from it contained only 10.4 parts per million. This is the only 100-foot well which was in practically continuous operation from March to August, 1935.

INVESTIGATIONAL WORK

SCOPE OF THE INVESTIGATION

When the salinity of the water from the 100-foot wells at the Atlantic City Water Works began to increase, an attempt to determine the mode and cause of the salt-water intrusion was made a part of the ground-water investigation in this region. Both the new and the old wells to the 100-foot sand were tested to make sure that they were not admitting salt water to the formation. The effect of changing rates of pumping on the salinity of the water from the wells was studied, and the 100-foot sand around the water works was explored by means of a system of test wells. A survey was also made of the bottoms of the nearby tidal streams to locate possible points of entrance for salt water. The intrusion of salt water progressed steadily while it was being studied, and the approach to the problem had to be changed on more than one occasion to fit the developments. The principal steps in the investigation are described below in the order in which they were taken, although by far the most conclusive results were obtained from the last three steps.

TEST OF THE NEW WELLS

The first step in this work was to determine whether or not the casings of the contaminated new wells were leaking. The tests were made by the method suggested by Thompson (1, pp. 100-104) and used by him in connection with his studies of contaminated wells to the 800-foot sand in Atlantic City. It is based on the principle that salt water, being heavier than fresh water, will settle toward the bottom of a well if it enters through a leak. In doing so, it mixes with the water in the casing below the leak and increases its salinity. The well is pumped steadily until it is fairly certain that the water being discharged is truly representative of water in the formation. During this time samples are taken periodically to determine whether or not the chloride content is increasing, and one or more samples are taken just before the well is shut down. The well is then allowed to stand idle at least overnight, and if possible for several days. When pumping is resumed, a sample is collected of the very first water from the well, and other samples are collected at intervals of a few seconds until all the water standing in the casing at the start has been pumped out. If there is a leak in the casing above the static water level, all the samples will have a higher chloride content than the last water pumped from the well, except where the well is pumped through a drop pipe, when the water in the drop pipe should be the same as the last water pumped. If there is a leak in the casing below the water level, the first samples, which represent the water standing in the upper part of the casing, will have a chloride content about the same as the last samples taken before the well was shut down, and later samples representing water from depths equal to or greater than that of the leak in the casing will have a higher chloride content. If the leak is a serious one, there will be a very marked and usually sudden increase in the chloride content of the water. If the samples are well timed and taken frequently, and if the rate of pumpage and the diameter of the casing are known, it is usually possible to determine approximately the depth of the leak. If the water standing in the casing shows no increase in chloride content, there is no appreciable leak in the casing. Under such conditions an appreciable amount of chloride, which remains about the same throughout the test, indicates general contamination of the formation through some natural channel, or through a leak in some other well nearby.

Where the well is equipped with a drop pipe through which the water is withdrawn, much of the first water coming from the well may be derived from the annular space between the drop pipe and the casing. This introduces a degree of uncertainty into the problem, and it may be necessary to take frequent measurements of the draw-down in the annular space in order to estimate the amount of water derived from this source. Also under these conditions it would be very difficult to determine the approximate position of a leak in the casing above the bottom of the drop pipe. As was anticipated, no leaks were found in the casings of the new wells at the Atlantic City Water Works.

TESTS OF THE OLD WELLS

When the old wells were abandoned they were left open, at Mr. Barksdale's request, for the purpose of making a series of water-level observations. The tops of some of these old wells were near the surface of the ground and possibly subject to inundation by extremely high tides. The second step in this investigation was to collect samples from all the old 100-foot wells, in order to determine, if possible, whether or not the salt water was entering the formation through them. The chloride content of the water from wells A-27 and A-29 was found to be much higher than in any of the other wells. These two wells could still be pumped with a portable pump. Probably no more than two or three tides had been high enough to overtop them since they had been open, and this overtopping, if it occurred, was of such short duration that only a small quantity of water could have entered the wells. Therefore these two wells were pumped for a considerable time to see if the chloride content of the water from them would decrease. Much more water was pumped than could possibly have entered the wells by tidal overtopping, but instead of decreasing, the chloride content increased. The maximum chloride content found in the water from each well was 2,600 parts per million, but the average chloride content in well A-29 was much higher than that in well A-27. From these and the preceding tests it was concluded that the salt water must be entering the 100-foot sand somewhere other than through the casings of the new wells or over the tops of the old wells.

RELATION OF SALINITY TO PUMPAGE

Another step in the investigation was to study the relation between the rate of pumpage and the salinity of the water from the wells. If the salt water were moving into the well field from any part of the formation that contained salt water, or through openings in the overlying clay, its rate of movement should correspond, to some extent at least, with the rate of pumping, and the salinity of the water from the wells should increase most rapidly when the pumpage rate was highest. In figure 12 the pumpage is plotted on an ordinary arithmetic scale, but the chloride content is plotted on a logarithmic scale. This method of plotting serves two purposes: it permits the plotting of low chlorides in considerable detail on the same sheet with the much higher chlorides found in the water from some of the wells; and it brings out the relative importance of changes in chloride content more clearly than an arithmetic scale would. For example, an increase of 10 parts per million in the chloride content of water from a well that has a normal chloride content of 10 parts per million amounts to a doubling of the chloride content and is therefore much more significant than an increase of 10 parts per million in the chloride content of a well that normally delivers water containing 500 parts per million.

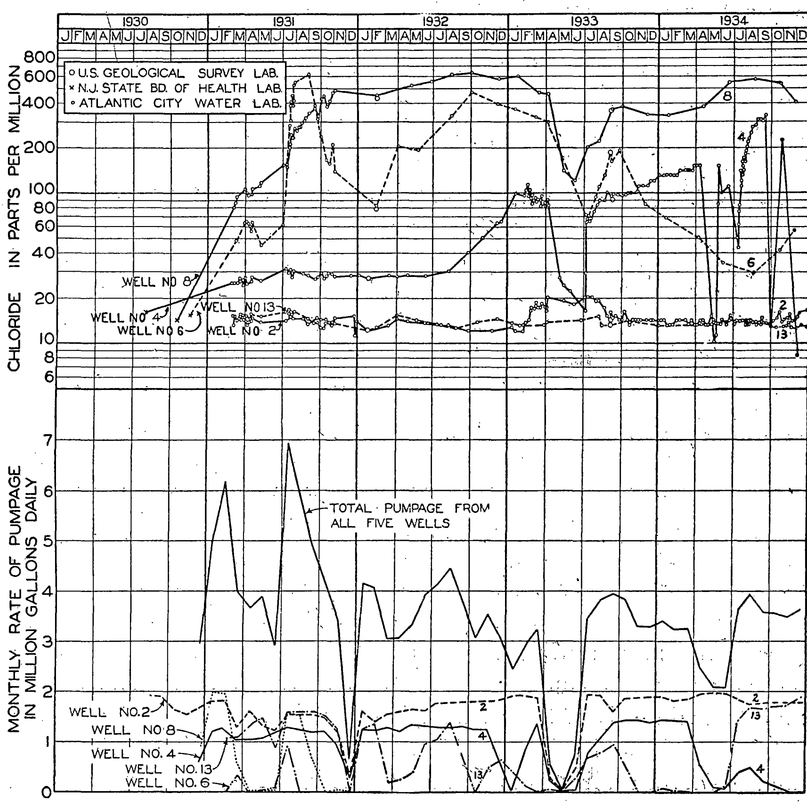

FIGURE 12.—Average monthly rate of pumpage from each of the five new 100-foot wells at the Atlantic City Water Works, total average monthly rate of pumpage from all five wells, and chloride content of samples collected from each well from July, 1930, to December, 1934.

A general similarity in trend between the line representing the total pumpage from the sand and the lines representing the chloride content of the water from wells 6 and 8 is apparent. The fact that the salinity of the water from these two wells has tended to vary with changes in the rate of pumpage from the other 100-foot wells, even though both of these wells have been shut down since the later part of 1931, indicates rather clearly a relation between the rate of pumping from the sand as a whole and the salinity of the water in it in the vicinity of the Atlantic City Water Works. When either of these wells is pumped for sampling, the salinity of its water increases rather rapidly, so that there is a considerable difference in the salinity of samples taken after 1 hour of pumping and after 2 hours of pumping. It is therefore probable that the similarity just noted would be even more apparent if each well had been pumped the same length of time before collecting every sample throughout the period while they were shut down.

Except for a gradual upward trend, the line representing the salinity of water from well 4 conforms more closely with the line representing the pumpage from that well than with the line representing the total pumpage from the sand. This probably results from the distribution of the wells with respect to the source of the salt water; for well 4 did not become very salt until rather recently and with a few interruptions has been pumped almost continuously from the time of its completion until the autumn of 1934, whereas wells 6 and 8 became very salt a short time after they were first used and have since been shut down. As shown by the results of the test-well program (p. 63), the salt-water body, or at least the most advanced part of it, lies under the marshes along Absecon Creek and Conovers Run. Wells 2, 4, and 13 are much farther from the main body of the salt marshes than wells 6 and 8. Of the three wells in the old well field, well 4 is the nearest to the salt marshes. Wells 6 and 8, situated fairly close to the salt water, were quickly contaminated, but it has taken fairly steady pumping of wells 2, 4, and 13 at an average rate in excess of 3 million gallons a day for almost 4 years to draw in enough salt water to bring the chloride content of water from well 4 up to about 300 parts per million. As the more concentrated salt water was drawn nearer to the well field, the chloride content from well 4 increased more rapidly.

The water from wells 2 and 13 has remained comparatively low and fairly uniform in chloride content throughout almost the entire period, except that from February to September, 1933, the chloride content of water from well 2 increased from 12 to 20 parts per million. It is significant that this increase occurred almost immediately after well 4 had been shut down for about 2 months, while well 2 was pumped continuously, and that the salinity in well 2 did not return to its original range until after well 4 had been back in service for a considerable time. This is further evidence that the salt water is moving into the well field along the general course of Conovers Run. While well 4 was shut down and well 2 was in operation, salt water was drawn past well 4 into well 2. When the pumping of well 4 was resumed, the tongue of salt water that had been moving toward well 2 was diverted again into well 4, and as soon as the salt water that had already passed well 4 was pumped out of the formation, the salinity of the water from well 2 dropped to its original range. It is therefore highly probable that if wells 2 and 13 are pumped continuously while well 4 is shut down, the water from both of them will increase materially in salinity within a comparatively short time.

This prediction, originally made in 1934, was confirmed in the winter of 1934-35, when with well 2 pumped almost continuously and well 4 shut down practically all the time, the chloride in water from well 2 rose to 41 parts per million, a record high point. If wells 2 and 13 are pumped alone, it is probable that within a year or two they will yield water at least as salt as that which was pumped from well 4 in the summer of 1934. The fact that the salinity of water from well 4 has steadily increased except when the well was shut down seems to indicate that the salt-water body has been drawn closer and closer to the well field by the pumping of wells 2, 4, and 13. Therefore, the salinity of the water from wells 2 and 13 probably would increase more rapidly now than the salinity of the water from well 2 increased in 1933.

TEST WELL PROGRAM

It seemed highly desirable to ascertain, if possible, the location and nature of the salt-water body nearest to the well field and the direction of its movement. A program of test-well drilling was therefore undertaken with this end in view. At first it was planned to drive 4½-inch test wells with churn tools, but experiments with 1¼-inch driven-well points showed that this was a more satisfactory and cheaper method of sinking the test wells needed for this study. A total of 23 test wells were driven, of which 3 were shallow and 20 extended about to the bottom of the 100-foot sand. In general, the location of each test well or group of wells was determined by the results obtained from the preceding tests. The location of the test wells is shown in figure 13.

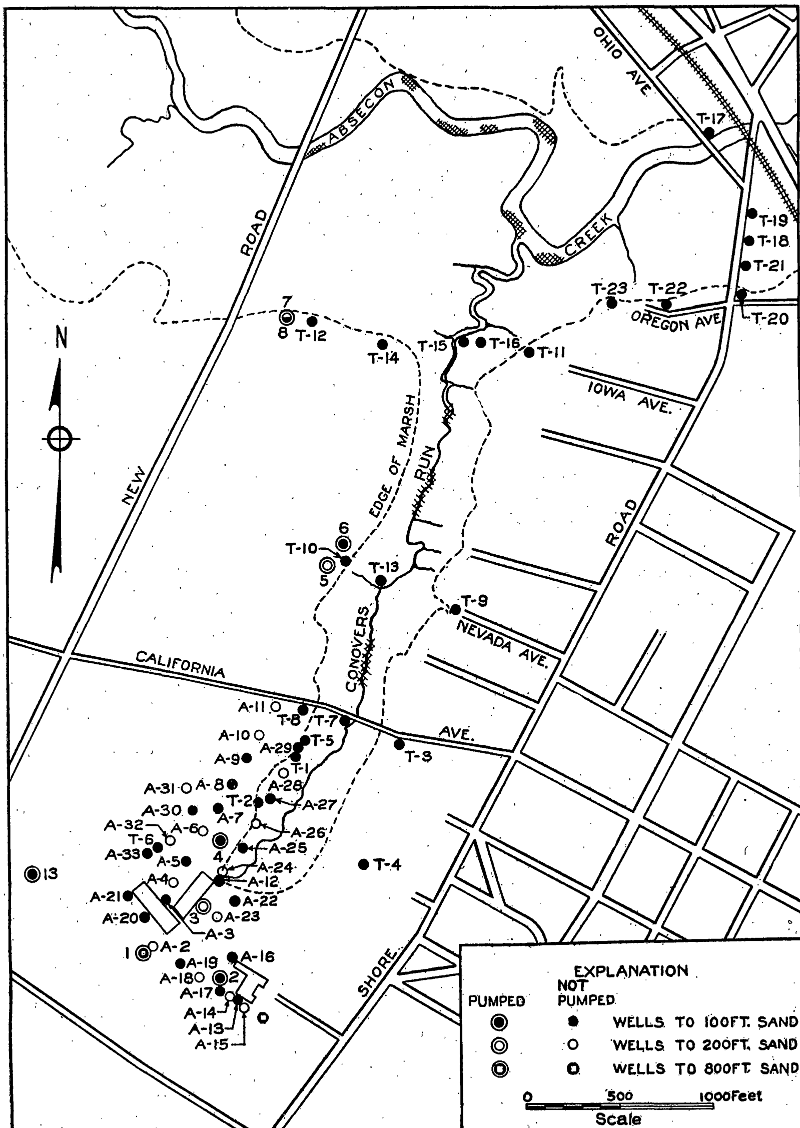

FIGURE 13.—Map showing wells in the immediate vicinity of the Atlantic City Water Works, including the abandoned wells and the test wells to the 100-foot sand drilled in the course of this investigation, and indicating by cross-hatching possible salt-water intakes in the stream beds. Abandoned wells are indicated by the letter A and test wells by the letter T.

In the old well field of the Atlantic City Water Works the 100-foot sand is overlain by a bed of clay, which in turn is overlain by sand that extends to the surface. The first two test wells driven (T-5 and T-6, fig. 13), were shallow wells, driven to determine the salinity of the water in the sand above the clay in the vicinity of well A-29 and farther south, near the center of the old well field. No water as salt as that from wells A-27 and A-29 was found in these test wells. The first deep test well, T-1, was driven near well A-29 to determine, if possible, from what part of the formation the salt water was coming. The water near the bottom of this test well had a higher salt content than any water ever pumped from the old well. This bottom water also contained much more salt than any water found in the surface sands at well A-29. The results from these test wells confirmed the conclusion which had already been reached by pumping well A-29—that a leak in its casing was not the cause of the high salt content of its water.

After the completion of test well T-1 and of a shallower well, T-2, near well A-27, it was decided to drive groups of test wells in widening circles around the salt-water body that evidently existed around wells A-27 and A-29, in an attempt to define its limits. The first group of four wells, T-3, T-4, T-7, and T-8, indicated rather definitely that the salt water extended to the north of the well field along the course of Conovers Run, and not to the east or southeast. The second and third groups of test wells, T-9 to T-16, were driven in lines extending across the meadows along Conovers Run from wells 6 and 8 respectively. (See fig. 13.) They indicated that the salt-water body extended in the form of a narrow tongue beneath the salt marsh bordering Conovers Run. The wells on the edges of the marsh on each line yielded water of comparatively low chloride content, but in the center the maximum chloride ran as high as 8,000 parts per million. The fourth group of wells, T-17 to T-23, were situated across the meadows of Absecon Creek below the mouth of Conovers Run, along the line of Ohio Avenue and Shore Road, and extended around the eastern edge of the marsh toward the end of the third line. None of the wells in this group yielded water containing as high chloride as the saltiest wells in each of the three preceding groups. Except for well T-22, none of them yielded water containing more than 2,000 parts per million of chloride, and the chloride content of nearly all the samples from this group of wells was very low. Unless there is a very narrow tongue of salt water extending across this line or around its ends, the results from this line of wells seem to indicate that the salt water is entering the 100-foot sand upstream from it.

The screen of each 1¼-inch test well was driven with the casing, so that the driving could be stopped at any depth where the screen was in sand, and a sample of water from the sand at that depth could be collected. It was therefore possible to obtain a vertical profile of the salinity of the water in all the sands encountered in each of the test wells. These profiles showed two surprising features—first, in many of the wells there was a wide range of salinity, in some within a very few feet; second, there appears to be very little uniformity in the vertical distribution of high chlorides from one well to another. (See table 3.) These irregularities in salinity are probably due to the irregularities in porosity and permeability of the sands and to the fact that water, either salt or fresh, moves most readily through the parts of the sands that are most permeable. The position of a well with reference to the source of salt water might also affect the concentration and distribution of the salt water found in it. It was impossible to collect representative samples of the materials encountered in driving these test wells, but it was possible to tell whether or not the material through which the drive point was passing was permeable enough to yield water, and those formations that would not yield water were called "clay." The logs of the wells obtained in this way furnish evidence of the lack of uniformity in the shallow formations. Beds of clay several feet thick appear in one well and not at all in another well only 200 or 300 feet away. The chloride content of the water found at different depths in the test wells is given in table 3. A well point having a 2-foot screen was used in driving the wells and the depth given for the samples is the depth of the middle of the screen. Gaps of over 4 feet between samples generally represent impermeable material from which samples could not be obtained.

Graphic logs of six representative test wells with the chloride content of each sample taken from them are shown in figure 14. In this diagram the impermeable materials from which no water samples could be collected are represented as clay, and the permeable materials as sand. The chloride content of each sample collected is represented by a bar, whose position indicates the depth at which the sample was taken.

The first well shown on the diagram, test well T-13, is near well 6. It yielded water with a higher average concentration of salt than any of the other test wells, although the maximum concentration was not as great as that observed in well T-15. The second test well shown on the diagram, well T-12, is near well 8. The average concentration of salt water in this well is obviously much less than that in well T-13, although one sample collected at a depth of 20 to 22 feet contained over

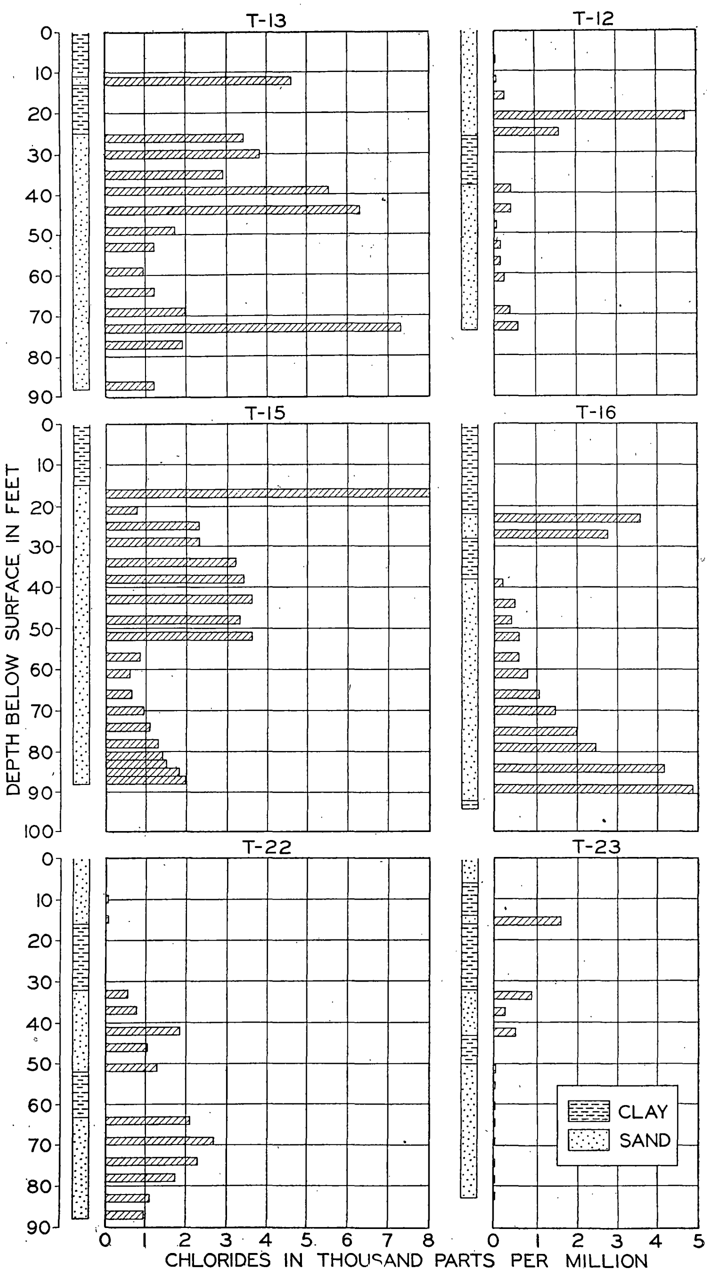

FIGURE 14.—Materials encountered and chloride content of the water at different depths in six representative test wells to the 100-foot sand at the Atlantic City Water Works.

TABLE 3.—CHLORIDE CONTENT OF SAMPLES OBTAINED IN DRIVING TEST WELLS TO THE ATLANTIC CITY WATER WORKS 100-FOOT SAND

[Analyzed by M. S. Brunstein, Atlantic City Laboratory]

Depth below surface (feet)	Chloride (parts per million)																						
	T-1	T-2	T-3	T-4	T-5	T-6	T-7	T-8	T-9	T-10	T-11	T-12	T-13	T-14	T-15	T-16	T-17	T-18	T-19	T-20	T-21	T-22	T-23
4	....	270	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
5	380	....	7.1	11	950	22	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
6	....	....	....	....	†††	†††	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
7	530	230	....	....	....	....	....	....	25	....	12	9.3	....	20	....	....	....	....	....	....	....	....	....
8	....	....	10	16	....	....	....	....	....	12	....	....	....	....	....	....	....	....	....	....	....	....	....
9	640	....	....	....	....	....	....	250	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
10	....	280	21	18	....	....	3,900	....	....	....	....	....	....	....	....	....	....	....	....	....	....	33	....
11	650	....	....	....	....	....	....	....	....	....	890	....	....	....	....	....	....	....	....	....	....	....	....
12	....	....	....	....	....	....	....	....	130	34	....	53	4,600	480	....	....	....	....	....	....	....	....	....
13	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	150	....	....	....
14	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	290	....	....
15	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	61	1,700
16	....	....	....	....	....	....	....	....	....	....	....	270	....	....	....	....	....	....	....	280	....	....	....
17	....	....	....	....	....	....	....	....	....	....	1,800	....	....	3,500	8,000	....	....	....	51	....	....	....	....
19	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	120	....	....	....	....
20	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	770	....	....	....	....	....
21	....	....	....	....	....	....	....	....	59	....	....	4,700	....	....	790	....	....	....	....	....	....	....	....
23	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	3,600	....	....	....	....	....	....	....
24	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	590	....	....	....	....	....
25	....	....	....	....	....	....	....	....	....	....	....	1,600	....	130	2,300	....	....	....	....	....	....	....	....
26	....	....	....	....	....	....	....	....	....	....	....	....	3,400	....	....	....	....	....	....	2,000	....	....	....
27	....	....	....	....	....	....	....	....	27	....	....	....	....	....	....	28	....	....	....	....	....	....	....
28	63	59	....	....	....	....	....	62	....	....	....	....	....	....	....	....	....	....	460	....	....	....	....
29	....	†††	....	....	....	....	....	....	....	49	....	....	....	....	2,300	....	....	....	....	160	....	....	....
30	61	....	....	17	....	....	....	....	....	....	360	....	3,800	250	....	....	....	....	....	....	....	....	....
32	....	....	31	....	....	....	900	....	....	....	....	....	....	....	....	....	....	....	....	....	100	....	....
33	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	440	820	120	....	570	950
34	....	....	30	....	....	....	....	....	....	120	360	....	....	....	3,200	....	....	....	....	....	....	....	....
35	....	....	....	....	....	....	....	....	28	....	....	....	2,900	470	....	....	....	....	....	....	....	....	....
36	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	9.8	....	....	....	....	....	....
37	....	....	30	17	....	....	970	....	....	....	....	....	....	....	....	....	....	110	....	270	12	780	280
38	....	....	....	....	....	....	....	....	....	....	....	....	....	....	3,400	....	....	....	....	....	....	....	....
39	330	....	....	....	....	....	....	....	....	120	130	420	5,500	390	....	150	....	....	....	....	....	....	....
40	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	130	....	....	....	....	....
41	....	....	....	....	....	....	670	....	....	....	....	....	....	....	....	....	9.3	....	....	....	11	....	....

42	....	....	....	16	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	32	....	1,800	540
43	46	....	....	....	....	....	....	....	30	....	27	....	....	180	3,600	540	....	....	....	....	....	....	....
44	....	....	....	....	....	....	....	....	....	210	....	410	6,300	....	....	....	....	....	....	....	....	....	....
45	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	11	160	....	....	....	....	....
46	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	19	8.1	1,100	....
48	73	....	....	....	....	....	....	....	37	....	....	62	....	170	3,300	410	....	....	....	....	....	....	....
49	....	....	....	....	....	....	....	....	....	270	....	....	1,700	....	....	....	....	90	170	....	....	....	....
50	....	....	....	....	....	....	200	....	....	....	....	....	....	....	....	....	13	....	....	15	....	....	....
51	....	....	....	13	....	....	....	....	....	....	....	....	....	....	....	....	....	....	9.3	....	....	1,300	20
52	....	....	....	....	....	....	....	290	....	....	....	....	....	....	3,600	600	....	....	....	....	....	....	....
53	86	....	....	....	....	....	....	....	30	260	27	170	1,200	....	....	....	....	....	....	....	....	....	....
54	....	....	....	....	....	....	190	....	....	....	....	....	....	....	....	....	....	230	....	....	....	....	....
55	....	....	....	16	....	....	....	....	....	....	....	....	....	....	....	....	....	....	11	22	....	....	10
56	....	....	....	....	....	....	....	720	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
57	....	....	....	....	....	....	32	....	....	....	8.7	170	....	....	830	630	....	....	....	....	....	....	....
58	380	....	30	....	....	....	....	....	25	280	....	....	....	....	....	....	....	590	....	....	....	....	....
59	....	....	....	....	....	....	....	....	....	....	....	....	960	....	....	....	10	....	8.4	....	....	....	....
60	....	....	30	19	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	15	8.4	....	10
61	1,100	....	....	....	....	....	....	....	....	....	10	250	....	....	590	800	....	....	....	....	....	....	....
63	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	8.1	370	....	....	....	....	....
64	....	....	25	18	....	....	....	....	....	100	....	....	1,200	....	....	....	....	....	7.4	13	7.9	2,100	8.3
65	....	....	....	†††	....	....	....	....	21	....	6.5	....	....	....	....	....	....	....	....	....	....	....	....
66	1,600	....	....	....	....	....	....	1,200	....	....	....	....	....	600	640	1,100	....	....	....	....	....	....	....
67	....	....	24	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
68	....	....	....	....	....	....	....	....	....	58	....	....	....	....	....	....	8.1	850	....	19	9.6	....	....
69	....	....	24	....	....	....	3,200	....	....	....	....	400	2,000	....	....	....	....	....	8.2	....	....	2,700	8.9
70	2,400	....	....	....	....	....	....	....	....	....	....	....	....	500	950	1,500	....	....	....	....	....	....	....
71	....	....	....	....	....	....	....	....	30	13	8.8	....	....	....	....	....	....	....	....	....	....	....	....
72	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	190	....	....	....	....	....
73	....	....	24	....	....	....	....	2,300	....	....	....	600	7,300	590	....	....	7.2	....	8.3	8.1	10	....	....
74	....	....	....	....	....	....	....	....	....	....	....	†††	....	†††	1,100	....	....	....	....	....	....	2,300	7.8
75	3,100	....	25	....	....	....	....	....	....	....	7.5	....	....	....	....	2,000	....	....	....	....	....	....	....
76	....	....	....	....	....	....	....	1,900	23	16	....	....	....	....	....	....	....	....	....	....	....	....	....
77	....	....	22	....	....	....	5,000	....	....	....	....	....	1,900	....	....	....	7.2	120	8.3	....	49	....	....
78	2,700	....	....	....	....	....	....	....	....	19	....	....	....	....	1,300	....	....	....	....	7.2	....	1,800	7.6
79	†††	....	22	....	....	....	....	....	....	†††	....	....	....	....	....	2,500	....	....	....	†††	....	....	....
80	....	....	....	....	....	....	....	....	15	....	12	....	....	....	....	....	....	....	....	....	....	....	....
81	....	....	....	....	....	....	3,700	....	....	....	....	....	....	....	1,400	....	....	170	....	....	....	....	....
82	....	....	21	....	....	....	....	....	....	....	....	....	....	....	....	....	7.1	....	8.3	....	....	....	7.9
83	....	....	....	....	....	....	5,200	....	....	....	....	....	....	....	1,500	....	†††	100	†††	....	48	1,100	†††
84	....	....	....	....	....	....	†††	2,400	....	....	....	....	....	....	....	4,200	....	†††	....	....	†††	....	....
85	....	....	....	....	....	....	....	†††	26	....	550	....	....	....	1,800	....	....	....	....	....	....	....	....
87	....	....	....	....	....	....	....	....	23	....	720	....	1,200	....	2,000	....	....	....	....	....	....	1,000	....
88	....	....	....	....	....	....	....	....	†††	....	†††	....	†††	....	†††	....	....	....	....	....	....	†††	....
89	....	....	13	....	....	....	....	....	....	....	....	....	....	....	....	4,900	....	....	....	....	....	....	....
91	....	....	10	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
92	....	....	†††	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
94	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	†††	....	....	....	....	....	....	....

††† Indicates bottom of well.

4,500 parts per million of chloride. From these two wells it might be concluded that well 6 would ultimately yield much saltier water than well 8 if both were pumped continuously. However, well T-13 is out in the marshes, whereas well T-12 is merely on the edge of the marsh.

The next two wells shown on the diagram, wells T-15 and T-16, are both out in the marshes, and the average concentration of salt water in samples from them is fairly high. The top sample in well T-15 contained 8,000 parts per million of chloride, the highest concentration found in all the test wells. Perhaps the most interesting thing about these two wells is the fact that although they are only 125 feet apart, their logs and the vertical distribution of salt water in them are strikingly different. The chlorides at the top of well T-15 are higher than those found at the top of well T-16, and those at the bottom of well T-16 are higher than those at the bottom of well T-15.

The two remaining wells, at the bottom of the diagram, wells T-22 and T-23, also furnish very good examples of the irregularity of the shallow or Cohansey beds in the vicinity of the Atlantic City Water Works and of the distribution of salt water in those beds. These wells are both on the edge of the marsh and are only about 300 feet apart. Both the logs and the vertical distribution of chlorides in them differ considerably from each other. Fairly high chlorides were found in the two lower sands in well T-22 and very low chlorides in the upper sand. In well T-23, on the other hand, the only high chlorides encountered were found near the top, and the bottom sand contained water of very low chloride content. Except for the fact that the chlorides in several samples from well T-22 were higher than the maximum chloride observed in well T-23, it might be assumed that salt water was entering at the surface near well T-23 and working its way downward in the direction of well T-22. In view of the extremely lenticular nature of the formation, something of this sort may have occurred, although the salt water found in well T-22 obviously did not come from well T-23 or pass immediately by it.

Figure 14 emphasizes the fact, which has already been pointed out, that the shallow Cohansey sands are extremely irregular. It also serves to bring out another fact that had not been realized before the test wells were drilled—namely, that the distribution of salt water in the sands is also extremely irregular, both vertically and horizontally. All the wells shown, especially the first three, furnished excellent examples of the irregular distribution of salt water in a single bed of sand. The most striking of these examples was found in well T-15, where the chloride ranged from 8,000 to 800 parts per million within a depth of 4 feet, and the higher chloride was found in the upper sample. It is, of course, possible that a lens of clay about 2 feet thick occurred between the points at which these two samples were taken. However, in view of the fact that much thicker beds of clay in this formation disappear within a very short distance, it is probable that such a thin clay bed would not be very extensive.

Only one of the wells shown on figure 14, well T-16, had the type of vertical distribution of salt water that might normally be expected if salt water were advancing through a uniform sand. In the lower sand in this well the salinity increased gradually from top to bottom. In view of the irregularities in all the other wells, it is probable that this merely indicates that the most permeable sand in well T-16 is at the bottom. However, the same distribution would occur if the sand were uniform and salt water were advancing through the formation, because the salt water, being heavier than the fresh water, would advance first and farthest along the bottom of the formation, so that at any given point the highest concentration of salt water would be found at the bottom of the sand.

The casings and screens of all the test wells, except T-4, which was broken off in driving and abandoned, were left in place for further observations. Samples of water have been taken from most of the wells on several occasions since their completion. The chloride content of these samples shows some marked changes in the salinity of the water at the bottom of the test wells since they were first driven. In most of the wells the water in the sand at the bottom seems to have freshened, but in some it has increased in salinity. The distribution of the changes is somewhat irregular. It is difficult to say whether the changes have been brought about by the pumping of wells 2, 4, and 13, by the shutdown of wells 6 and 8, which has permitted the fresh-water head around them to be built up, or by some other factor not yet apparent. The principal conclusion that can be drawn from these changes is that the salt water in the formation is not static but is moving as a result of the forces acting upon it. The direction in which it is moving could not be determined, but the increasing salinity of the water from wells 2 and 4 indicates that at least some part of it is moving toward the old well field. The changes in salinity noted would probably be more significant if the later samples could have been collected from the point of maximum salinity in each well. This was generally impossible, however, because the maximum salinity rarely occurred at the bottom of the wells where the screen was left. It would be worth while to select two or three key test wells and drive beside them a few additional test wells to different depths, so that the changes in salinity throughout the vertical column could be studied over a period of time.

STREAM-BOTTOM SURVEY

When the results of the test-well program began to indicate the probability that salt water was entering the 100-foot sand upstream from Ohio Avenue a survey was made of the bottoms of Conovers Run and Absecon Creek between Ohio Avenue and New Road. The survey was made from a rowboat, and the bottoms of the streams were explored by means of a hand-driven metal sounding rod. The results of the survey indicate that it is entirely possible for salt water to enter the 100-foot sand through the beds or banks of these streams. In several places good, clean sand 2 or 3 feet or more thick was found on the stream beds. In some places it was impossible to determine the total thickness of the sand by driving in the sounding rod by hand, owing to the unsteadiness of the boat. However, in view of the fact that the Cohansey formation is composed largely of sand, it is probable that a bed of sand 3 feet or more thick would extend far enough to connect with other beds of sand and probably with the sand from which the 100-foot wells draw their water. In one place along the bank of Absecon Creek, a little above the level of low tide and approximately opposite well 8, a streak of highly permeable gravel and coarse sand only a few inches thick but persisting for over 300 feet was observed. In view of the fact that the bottom of Absecon Creek is from 10 to more than 15 feet below low tide throughout most of the section included in this survey, it seems entirely possible that similar beds of permeable material may be cut by the stream banks below the low-tide level.

The salinity of the water in Absecon Creek and Conovers Run varies widely, depending upon the amount of fresh water being discharged into their upper ends and upon the height of the tide. The water in Absecon Bay is almost as salt as sea water. Conceivably this water could be carried into the marshes along Absecon Creek and Conovers Run, under the most favorable conditions. The chloride content of the samples collected from Absecon Creek during this investigation ranged from 3,500 to 15,000 parts per million. If any of the beds of permeable material observed along the banks or in the beds of Absecon Creek or Conovers Run are connected with the main part of the 100-foot sand, salt water would enter this sand through them whenever the head of the fresh water was lowered enough to permit it. The principal exposures of the sand in Absecon Creek and Conovers Run are indicated by cross hatching on figure 13.

CONCLUSIONS

The intrusion of salt water into the 100-foot sand at the Atlantic City Water Works was probably caused or at least much accelerated by the very considerable increase in the amount of water pumped from the sand. It was facilitated by the absence of a continuous covering of impermeable material beneath the nearby salt marshes, but it might easily have occurred eventually even if this cover had been continuous for several miles, if the rate of pumping maintained in the summer of 1931 had been continued long enough. Owing to the unfortunate location of wells 6 and 8, near the source of the salt water, the pumping of these wells may have drawn it in somewhat faster. However, it seems probable that if wells 6 and 8 had never been pumped, salt water would now be moving into the old well field much as it is, owing to the higher rate of pumpage in that direction. It is also probable that wells 6 and 8 would have become salty regardless of any pumpage elsewhere. It is possible or even probable that the rate at which the old wells were pumped was exceeding the safe yield and drawing the salt water toward them and that they might have yielded salt water in the course of time without any increase of pumpage. The high chlorides found in the water from wells A-27 and A-29 early in the investigation strongly suggest that the salt water had been drawn in as far as these wells by the earlier pumping. If this had occurred it might easily have escaped notice, because of dilution of the water from these wells with that from other sources and the total lack of frequent and regular analytical checks before the establishment of the Atlantic City Water Laboratory.

It is most unfortunate that the new wells were drilled without first exploring the territory around them thoroughly with test wells, to ascertain the presence and position of the salt water in the formation. It is also unfortunate that all the new wells were put into use at one time, so that the pumpage was suddenly increased greatly without opportunity to observe the effect of a gradual increase in pumpage. Thompson (1, pp. 127-132), in his report on the ground-water conditions in this region, specifically pointed out the danger of salt-water intrusion if the shallow sands at the Atlantic City Water Works were developed further without first thoroughly exploring the vicinity by means of test wells and gave a warning against too hasty a development of these sands. This warning was ignored, at a cost to Atlantic City, in the form of abandoned wells or remedial measures, considerably greater than that of an adequate system of test wells. If these precautions had been taken it is probable that wells 4, 6, and 8 would not have been drilled, and it is possible, though by no means certain, that wells 2 and 13 could have been pumped for a good many years without drawing in an objectionable amount of salt water. However, inasmuch as the intrusion has occurred, it is now most important to decide how it came about, so that the best possible remedial measures can be suggested.

The results of the work done to date indicate that the salt water is not entering the sand around the 100-foot wells at the Atlantic City Water Works through leaks in the casings of the active wells or through abandoned old wells. It is either moving up through the formation from the direction of the ocean, where it was present in the sand before pumping began, or is entering the sand through some break in the overlying lenses of impervious material.

If salt water were being drawn into the well field from the direction of the ocean it would normally be expected to advance in a fan-shaped tongue, with its point toward the pumping wells. Normally, if salt water had access to the sand equally at all points along the coast the axis of this tongue would lie in a direction parallel to the dip of the formation and roughly perpendicular to the shore line. It might, however, follow some more indirect line of least resistance. The water along this tongue would be increasingly salt toward the ocean, and the concentration of salt water would tend to be greatest toward the bottom of the formation. However, the vertical distribution might be modified by the varying permeability of the sand, which might permit the salt water to advance faster at some higher level than at the bottom. The tongue of salt water would widen out in the direction of the ocean and therefore would be more easily found in test wells in that direction than in the immediate vicinity of the well field. It would require considerable time to draw the salt water into the pumping wells after the cone of depression had extended far enough to start it in motion, because it would be necessary to remove, by pumping, some of the fresh water lying between the salt water in the sand and the wells.

On the other hand, if the salt water were entering the sand through holes in the overlying clay in the nearby marshes, the shape and position of the salt-water body would depend largely on the location and shape of the holes, and it would not have any particular relation to the dip of the formation or the shore line. The water in the sand would be saltest near the point of intake and might be much fresher nearer the ocean.

If there were many points of entrance for the salt water, its distribution in the formation might be very irregular or spotty. The vertical distribution of salt water in the formation would be governed by the relative permeability of the different parts of the sand, but it would also be very much affected by the position of the pumped wells relative to the salt-water intake and would therefore tend to be much more irregular than if salt water were moving in through the formation from the ocean. If the holes in the protective clay were near the pumped wells, the salt water would reach the wells very quickly after pumping was started.

It was found that the salt-water body lay in a narrow and very irregular strip under the marshes along Conovers Run. No test wells were drilled in the marsh along Absecon Creek near well 8, but salt water probably occurs beneath it also. The long axis of the salt-water body so far as it has been defined by test wells is perpendicular to the dip of the formation and parallel to the shore line. The saltiest water was found in the test wells far up in the marshes along Conovers Run; and the water from the line of wells that follows Shore Road and Ohio Avenue was much fresher than that found farther upstream, in the meadows. The vertical distribution of salt water in the test wells was most irregular, and the horizontal distribution of the salt water was also irregular and spotty, except that the water of highest salt content was found near Conovers Run. The salinity of the water from well 6 began to increase almost as soon as the well was put into service and ran up to more than 600 parts per million within less than 2 months of actual operating time, indicating that the salt water, or a hole that might admit it, was within 200 or 300 feet of this well when pumping from it began. The survey of the stream bottoms revealed a fairly thick and highly permeable sand bed outcropping in the bottom of Conovers Run not very far from well 6, and the results of test well T-13 indicated that the water in the sand about 300 feet from well 6 was very high in chloride content.

From these facts it is concluded that the salt water that is contaminating the fresh water in the 100-foot sand at the Atlantic City Water Works is entering the sand through holes in the overlying clay beneath the salt marshes along Absecon Creek and Conovers Run and very probably through holes in the bottoms of the streams themselves. It probably is not being drawn in from any considerable distance through the formation from the direction of the ocean.

RECOMMENDATIONS

Basis of recommendations.—Atlantic City has invested in its five 100-foot wells a considerable amount of money, which will be practically lost if the water in the sand is permitted to become salt while they are still new. More important still, the 100-foot sand should be capable of yielding a limited amount of good water over an indefinite length of time if its development is properly carried out, and the great value of such a resource cannot easily be estimated. The increase in salinity of the water from wells 2 and 4 indicates that the salt water is moving in toward the wells in the old well field. It may destroy the usefulness of the remaining wells there before many years unless the present system of operation is modified or unless some steps are taken to stop the intrusion of salt water. Remedial action should be planned with two purposes in view—first, to preserve the usefulness of the sand from complete destruction by salt-water contamination, and second, to reclaim, as far as possible, the wells that have been abandoned because of salt-water contamination. It is with this idea in view that the recommendations set forth below are made. Remedial action should be taken in logical steps, and the results of each step should be observed before the next is undertaken. However, recommendations 2 and 3 should both be carried out as soon as possible and concurrently.

Recommendation 1. Continued observations.—It is recommended that the wells at the Atlantic City Water Works be kept under close observation and that any action taken on the other recommendations made below be modified, if necessary, in accordance with the results that may be obtained in the future. There are so many indeterminate factors involved that the results of the study to date cannot be considered final, although it is believed that the basic facts and the proper method of procedure have been determined. The salt-water encroachment into the 100-foot sand cannot be stopped without constant vigilance. No remedy is so sure that it can be applied and then forgotten.

In general, the observations on the 100-foot sand already begun should be continued with some changes or additions. Samples of water for determination of chloride content should be collected at regular intervals from each of the five new 100-foot wells after an adequate and uniform period of pumping. Samples of water from the test wells that have been driven or that may be driven in the future should also be collected and analyzed regularly, to give a better idea of the movement of the salt-water body in the formation. Observations of water level should be continued and expanded, where possible, in order to define the extent of the cone of depression of the active wells and indicate the danger of further contamination.

The existing network of test wells should be strengthened by additional wells driven in the old well field between wells 2, 4, and 13, and perhaps along the eastern edge of the marshes along Conovers Run and along Shore Road and Ohio Avenue. In one or two key localities several test wells should be driven close together with their screens at different depths, and samples should be collected from them regularly in order to determine how the changes in salinity at different depths compare with those being observed at the bottoms of most of the test wells.

Recommendation 2. Use of 100-foot wells for peak load only.—In view of the fact that the demand for water in Atlantic City is highly seasonal, reaching a peak for only 2 or 3 months and being comparatively low for the remainder of the year, it is recommended that none of the wells to the 100-foot sand be used except to care for the peak load, and that they all be permitted to stand idle for the remainder of the year. It is further recommended that even during the peak season these wells be shut down during the hours of minimum demand whenever they can be spared. This procedure might possibly permit the fresh-water head to force back the salt water far enough for necessary active pumping to be carried on without damage during the season of peak demand. Even if there should be no forcing back of the salt water, this procedure would give the city the best return for its investment in these wells, because it must have capacity to meet the peak load and because if any of the wells are pumped continuously, even at a much reduced rate, enough salt water will probably be drawn into them to make them unusable after a very few years. The longer wells 2, 4, and 13 are pumped continuously, the nearer the salt-water body will be drawn to them. This recommendation involves comparatively little expense to the city and should be carried out immediately.

It is further recommended that when wells 2 and 13 are pumped, well 6 or well 4, or both, be pumped also. This protective pumping will tend to remove the salt water from the formation before it reaches wells 2 and 13 and may postpone the time when it will be necessary to abandon them. Twice when well 4 has been shut down the salinity of the water from well 2 has increased, and twice when the pumping of well 4 was resumed, the salinity of the water from well 2 returned to approximately its original range. However, these facts do not furnish conclusive evidence as to the ultimate effects of protective pumping in this well field.

Recommendation 3. Fresh-water pond over salt marshes along Absecon Creek.—It is recommended that the city authorities of Atlantic City consider building a dam across Absecon Creek and the marshes bordering it above Ohio Avenue, to flood with fresh water the present salt marshes not only along that creek, but also along Conovers Run. This will tend to freshen the salt marshes by subjecting them constantly to fresh water under head. In the same manner it will tend to prevent a possible advance of salt water through the formation under the dam and will make the continued use of the 100-foot sand safer from encroachment from areas farther out toward the ocean. This is one of the principal advantages a fresh-water pond would have over any of the other plans suggested, because it must not be forgotten that, even though the present encroachment has been attributed to holes in the clay beneath the marshes, the danger still exists that renewed heavy pumping might draw salt water from the direction of the bay or ocean. The pond could be maintained with water that would otherwise be wasted over the spillway of Doughty Pond, and at least some part of this water would probably be absorbed by the 100-foot sand and made available for use. Dams similar to the one suggested here have been used successfully on Long Island for many years to protect shallow ground-water supplies. The carrying out of this recommendation would involve a considerable expenditure both for property rights and for construction, but the writers believe that it would permanently restore the usefulness of the 100-foot sand. Before this project is undertaken the cost of the work should be carefully estimated and compared with the ultimate value of the water from the 100-foot sand and also with the cost of an additional supply to take the place of this water. It would be obviously foolish to spend more money to save the 100-foot sand from contamination than the water supply from it is worth, especially as there is no evidence of a shortage of sources of water supply for the region for many years to come. To leave out of consideration, for the moment, the economic aspects of the problem, this plan is believed to be the most effective remedial measure that can be adopted. It is therefore strongly recommended.

Recommendation 4. Fresh-water pond over salt marshes along Conovers Run.—In case the larger development recommended above is found to be unjustifiable because of its cost, it is recommended that the establishment of a smaller fresh-water pond over the marshes along Conovers Run be considered. Such a project would necessarily involve the abandonment of well 8 and would not be as sure of success as the construction of the larger pond. However, it would probably prevent the further intrusion of salt water into the area around wells 2, 4, and 13 and might also save well 6. If it is undertaken, the dam should be situated as far as possible down Conovers Run, and the movement of salt water should be very carefully watched by means of an adequate system of test wells, especially when well 6 is being pumped. The smaller pond would have one further disadvantage compared with the larger pond in that it might have to be filled, at least partly, with water diverted from Doughty Pond through the city's transmission line. However, this could probably be successfully accomplished during the night, when the demand for water is low. The smaller pond along Conovers Run would be more effective if it were constructed in conjunction with the tide gate proposed under recommendation 5.

Recommendation 5. Tide gate on Absecon Creek.—If, on investigation, it appears uneconomical to install a dam across Absecon Creek and the surrounding marshes and submerge the marshes with fresh water, it is recommended that the city construct a tide gate on Absecon Creek. This gate should be so designed that it will permit the flow of water out of the marshes above it at low tide and will prevent salt water from Absecon Bay from flowing into the marshes at high tide. It would, of course, be necessary to build an embankment across the meadows high enough to prevent the highest tides from flowing around or over the tide gate and submerging the meadows. This arrangement would prevent the regular submersion of the marshes with salt water and would permit them to be freshened gradually by rainfall. Similarly it would permit the stream beds to fill up with fresh water instead of salt water, as at present. The tide gate would be less expensive than a dam and fresh-water pond, mainly because it would require the purchase of less property. The salt water already in the formation cannot, of course, be removed except by pumping, but if the continual addition of salt water from high tides is stopped, it should be possible gradually to pump the salt water out of the formation. The total amount of salt water under the marshes is not so great that its removal would involve undue cost or difficulty. This result could be accomplished by pumping wells 6 and 8 at times of peak load, when the salt water from them can be diluted with water from other sources. In any event, after the salt-water intake is shut off, well 6 should be pumped as much as possible when wells 2, 4, and 13 are in service, to retard the movement of salt water into the old well field and protect the wells there from yielding water too high in salt. If the idea of a fresh-water pond over the whole of the marshes has to be abandoned on account of cost, the tide gate should be constructed. Even if the smaller pond along Conovers Run is constructed a tide gate would provide an additional measure of protection that would be well worth while. A tide gate would not be as effective as a dam and fresh-water pond, and it is recommended as a substitute only in case the fresh-water pond proves to be unfeasible.

Other remedial schemes.—Two other plans for shutting out the salt water from the sand around the active wells have been suggested. Although they are not considered by any means as practical as those covered by recommendations 2 to 5, they are mentioned here for consideration in case they seem to be applicable in some special situation.

First, it has been suggested that if the holes in the overlying clay could be located, they might be sealed with clay. The principal objections to this plan are that it would be extremely difficult to locate all the holes and block them completely, and that compared to recommendations 3 to 5 above, it is merely a negative measure in that it does not substitute fresh water for salt water above the possible points of intake, nor even remove the salt water without substituting fresh water.

Second, it has been suggested that if the salt water were found to be coming in through the formation under the dam or barrier recommended above, it might be prevented by artificial recharge of the formation through a line of wells along Shore Road and Ohio Avenue. It would be possible to do this with a very low head in view of the slight difference between the specific gravities of fresh and salt water. The head of the water in Doughty Pond would almost always be enough to permit filling these wells by gravity with pond water. One advantage of this plan would be that it would provide a means of storing in the sand some of the water that is wasted from Doughty Pond. The objections to this plan are that it would be difficult to keep the wells open unless the water used in them were filtered and sterilized and that this would involve a continuing expense. On the other hand, it might be possible to seal the entire sand along this line and create an impermeable protective curtain by permitting enough wells to clog up the sands around their screens or better still by injecting clay into the sand through them. However, it is doubtful whether this plan would be economically feasible, particularly as it should be possible to obtain a fresh-water barrier by means of recommendation 3 even if it were necessary to dredge down to the water-bearing sand in order to give the fresh water in the pond access to the sand, so that the head of the fresh water in the sand could be raised.

THE 200-FOOT SAND AT THE ATLANTIC CITY WATER WORKS

INCREASED DEVELOPMENT SINCE 1930

When the old wells at the Atlantic City Water Works were abandoned in 1930 and the new system installed, the capacity of the wells to the 200-foot sand was increased from about 3 to about 11 million gallons daily. This increase in capacity was not, however, concentrated in the old well field or in any one spot. There are seven new large-capacity wells to the 200-foot sand, which are shown on figure 11 as wells 3, 5, 7, 9, 10, 11, and 12. They are situated along the pipe line between the pumping station and Doughty Pond at intervals of a little more than a quarter of a mile, so that the interference between them is not very great. This arrangement would be ideal if the wells were located in a line at right angles to the natural slope of the formation and parallel to the shore line, so that each well would have an opportunity to draw water from the direction of the landward outcrop of the sand without interference by any other well. However, the pipe line from Doughty Pond to the pumping station for most of its length runs approximately southeastward, in the general direction of the dip of the formation. The result is that six of the new 200-foot wells are almost on a line that lies directly along the dip of the formation. This arrangement probably causes a greater interference between these wells than would otherwise occur. It may also increase the danger of salt-water intrusion into this sand by increasing the draw-down in the direction of the ocean on this line.

WATER-LEVEL FLUCTUATIONS UNDER OLD AND NEW SYSTEMS

A water-stage recorder was maintained on well A-28 in the Atlantic City Water Works well field from the middle of December, 1923, to early in July, 1924, and from March, 1930, to the present time. This well draws water from the 200-foot sand. The difference in the type and range of fluctuations of head in the 200-foot sand under the two systems of operation is similar to that in the 100-foot sand. The fluctuations in the 200-foot sand are, however, wider and sharper than those in the 100-foot sand. The fluctuations of water level observed in well A-28 from 1924 to 1934 are shown in figure 15.

Under the old system the water levels in the 200-foot wells fluctuated very little, except when all the wells were shut down, as in April and May, 1924. Between December, 1923, and April, 1924, the water level in well A-28 fluctuated between 1 and 5 feet below sea level. When the wells were shut down in April, 1924, the water level in this sand rose to a little more than 9 feet above sea level. It was not possible during this test to obtain a true static level in wells to the 200-foot sand, because the elevation of 9 feet above sea level was 2 or 3 feet above the tops of the casings of many of the 200-foot wells, so that these wells flowed and reduced the head on such wells as could be measured to a higher elevation. When the first of the new 200-foot wells, the present well 12, was drilled near Doughty Pond, the casing was carried up to an elevation high enough to measure the static water level. The water level in this well rose to 14 feet above mean sea level. At that time there were no pumped wells within more than 1½ miles of this well, so that this figure doubtless represents approximately the static level in this sand. It is probable that if a more accurate determination could have been obtained during the test of April and May, 1924, the static water level would have approached this figure.

After the operation of the new wells was begun, the water level in well A-28 fluctuated over a much wider range than ever before. During 1930 it ranged from about 5 feet above sea level to about 17 feet below sea level, and the fluctuation on a single day amounted to more than 8 feet. During 1931 the water level in this well showed an even wider fluctuation, ranging from about 1 foot above sea level to about 23 feet below sea level, with a maximum observed daily fluctuation of almost 11 feet. During 1932, 1933, and 1934 the range of fluctuation was somewhat less and the minimum water levels were not as low as in

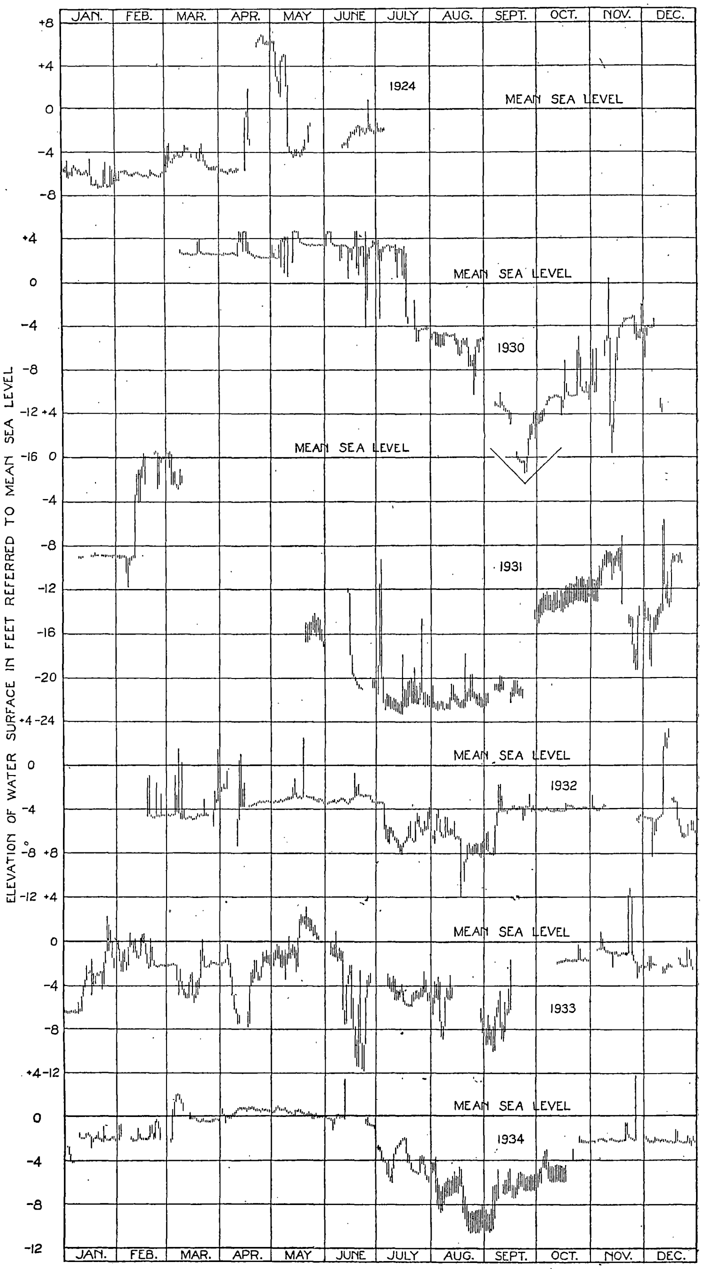

FIGURE 15.—Daily fluctuations of water level observed in 200-foot well A-28 at the Atlantic City Water Works, 1924 and 1930-34. The daily range in altitude of the water surface is indicated by vertical bars.

the two preceding years. This was due to two facts—first, that the wells near the observation well were pumped at a somewhat more uniform rate, and second, that not quite so much water was taken from the sand during these later years.

SHAPE AND EXTENT OF THE CONE OF DEPRESSION

Because the water level in the 200-foot wells at the pumping station quickly rises when pumping is discontinued until the water flows over the tops of the casings, it has been impossible to determine very accurately the slope of the piezometric surface under static conditions or the shape of the cone of depression around a pumped well in this sand. No attempt has therefore been made to map the piezometric surface in this sand, either under pumping or under static conditions, but such observations as have been made seem to indicate very clearly that the cone of depression in this sand extends much farther than that in the 100-foot sand. This is to be expected because the clay overlying the 200-foot sand is much more extensive than that overlying the 100-foot sand, and the cone of depression of an artesian sand must extend into the intake area before constant conditions can be established, and because the permeability of the 200-foot sand is less than that of the 100-foot sand. Fluctuations of almost 6 inches in the water level in well A-28 have been observed when well 12, which yields about 2 million gallons daily, was started or stopped. The distance from well 12 to well A-28 is about 1¾ miles. It is therefore probable that the cone of depression of a well to the 200-foot sand, being pumped at a rate of 2 million gallons daily, extends for considerably more than 2 miles. When all 200-foot wells except well 3 are shut down, well 12 flows at a rate of about 200 gallons a minute through an overflow pipe below the floor of the pump house. The pumping of well 9, which is more than three-quarters of a mile from well 12 and yields water at a rate of about 1.5 million gallons daily, will stop the flow of water at well 12. The specific capacity of well 12 is about 27 gallons a minute per foot of draw-down. A flow of 200 gallons a minute would therefore indicate a head in well 12 of about 7.5 feet above the discharge pipe. When the flow is stopped by pumping well 9 the head in well 12 must be lowered at least 7.5 feet. This is further evidence of the wide extent of the cone of depression in this sand.

During this investigation test well B-5 (see fig. 11) was driven about 2 miles above the head of Absecon Pond and about 3½ miles from well 9, which may be considered the center of the 200-foot well field. This well encountered no substantial clay beds, although it reached a depth that should have penetrated almost to the bottom of the 200-foot sand. The clay beds in the Cohansey formation are exceedingly irregular, and although this well may merely have penetrated a hole in the overlying clay, its log certainly seems to indicate that the clay bed overlying the 200-foot sand does not extend that far. If so, the intake area of the 200-foot sand is not very far from the present wells at the Atlantic City Water Works. As the confining bed of clay over this sand is not very extensive, it is probable that the cone of depression caused by pumping the 200-foot wells at the Atlantic City Water Works extends rather quickly to the intake area.

PROBABLE CAPACITY OF THE 200-FOOT SAND

The full capacity (11 million gallons daily) of the new wells to the 200-foot sand at the Atlantic City Water Works has not at any time been utilized for a long enough period to warrant any positive statement as to whether it is within or exceeds the safe yield of this sand. The rapidity with which the water level in the sand recovers when pumping is discontinued suggests that the capacity of this sand to yield water has not been seriously impaired by the pumping that has already been done. On the other hand, a consideration of the probable intake facilities and transmission capacity of this sand seems to indicate that it may not be capable of yielding 11 million gallons a day continuously and that it certainly cannot do so without grave danger of drawing in salt water from the direction of the ocean.

The capacity of an artesian sand to yield a certain quantity of water permanently to wells depends primarily upon two factors—its intake capacity and its ability to transmit water from the intake area to the wells. In view of the generally sandy nature of the Cohansey formation and its wide areal extent, it is probable that the intake area of the 200-foot sand is large enough and permeable enough to admit a very considerable quantity of water. It is instructive, however, to estimate the size of the intake area required for the development of the full capacity of the present 200-foot wells at the Atlantic City Water Works. The average annual precipitation at Atlantic City is 40.2 inches. At least half of this amount is accounted for by evaporation and transpiration, leaving 20 inches or less available for ground-water recharge and stream flow. If, as is highly improbable, all of this were absorbed as ground-water recharge, it would require an intake area of over 11½ square miles to supply continuously a yield of 11 million gallons daily, the capacity of the present 200-foot wells at the Atlantic City Water Works. Actually much of the water not discharged by evaporation and transpiration is carried off by streams, so that the amount available for ground-water recharge is considerably less than 20 inches, and the intake area needed would be much larger.

If the edge of the clay overlying this sand is near test well B-5, it would be necessary for the cone of depression of the 200-foot wells to extend more than 6 miles from the center of the present well field in order to encompass 11½ square miles of intake area. It follows, therefore, that if it is intended to use the present 200-foot wells at anything like their total capacity, any additional wells to the Cohansey sands should be situated beyond the probable extent of the cone of depression of the existing wells, which is more than 6 miles inland from the present well field.

The capacity of a sand to transmit water to a well field depends upon its permeability, its cross-sectional area, and the hydraulic gradient from the intake area to the wells. The permeability of the 200-foot sand was not determined experimentally during this investigation. However, a comparison of the specific capacities of wells to this sand with those of similar wells to the 100-foot sand indicates that the average permeability of the 200-foot sand is probably only about two-thirds that of the 100-foot sand. The tests conducted on the 100-foot sand indicated an average permeability of about 1,000. The average permeability of the 200-foot sand may therefore be estimated conservatively at about 600. The average thickness of the 200-foot sand in the wells at the Atlantic City Water Works is about 46 feet, and its cross-sectional area is therefore about 242,880 square feet to the mile. Assuming adequate intake area, the maximum yield of the sand will be obtained by increasing the rate of pumping until the hydraulic gradient is as steep as it can be made without unwatering the sand. The distance from well 9 to test well B-5 is 3½ miles. The water table at well B-5 is about 45 feet above sea level, and the top of the 200-foot sand at well 9 is about 150 feet below sea level. The maximum hydraulic gradient is therefore about 56 feet to the mile.

With a coefficient of permeability of 600, a hydraulic gradient of 56 feet to the mile, and an average thickness of the sand of 46 feet, it is estimated that the transmission capacity of the 200-foot sand is slightly more than 1.5 million gallons daily for each mile of the sand measured at right angles to the direction of flow. On this basis it would require a section of the sand about 7 miles long to transmit 11 million gallons a day.

From these facts it appears improbable that the 200-foot sand will be able to yield the full capacity of the present wells continuously. In order to do this, it would be necessary for the cone of depression of these wells to extend far enough to include an intake area of considerably more than 11½ square miles. This would mean that it would have to extend more than 6 miles from the center of the well field if the edge of the clay is at test well B-5 and extends continuously along the strike of the formation. Of course, if the edge of the overlying clay is more or less distant than well B-5 the necessary extent of the cone of depression would be greater or less than this figure, but the intake area required would be unchanged. Furthermore, if the overlying clay is continuous, it would be necessary to draw into the wells all the water entering the sand for seven miles along its strike. It does not seem probable that the cone of depression could extend far enough to meet these requirements without at the same time extending far enough toward the ocean to draw salt water into the wells.

It is possible that the 200-foot wells might be capable of yielding their full capacity for a brief period each year without exceeding their safe yield. However, such a seasonal use at full capacity would probably necessitate a more or less complete cessation of pumping from this sand for a considerable period at other times during the year, in order to permit the head of the water in the sand to recover. Otherwise, the cone of depression created by the higher rate of pumping might be partly maintained during each season of low pumpage and progressively extended during the following season of high pumpage, until it might be impossible to pump 11 million gallons daily at any time. It should be possible to determine approximately, by further observations and study, the rates at which the wells to this sand should be pumped at different seasons of the year, in order to insure the maximum benefit from their use.

DANGER OF SALT-WATER CONTAMINATION

In the preceding discussion of the capacity of the 200-foot sand to yield water, no detailed consideration has been given to the danger of contamination by salt water. In view of the wide extent of the cone of depression in this sand and the small extent of the overlying clay, it is highly probable that the danger of salt-water contamination, rather than the ultimate ability of the wells to obtain water, will limit the safe yield of the 200-foot sand.

In this investigation five test wells were drilled to this sand to determine the extent of the overlying bed of clay. The location of these wells (B-1, B-2, B-3, B-5, and B-7) is shown on figure 11. A study of their logs and of such other well logs as were available seems to indicate that although the clay extends several miles in a northeast-southwest direction, it may not extend so far in a northwest-southeast direction. Well B-5, situated above Absecon Pond in a general northwesterly direction from the pumping station, did not encounter the overlying clay bed. Test well B-1, which is on the edge of the salt marshes about three-fourths of a mile southeast of the Atlantic City Water Works, did not encounter any appreciable thickness of true clay overlying the 200-foot sand. It did, however, encounter a considerable thickness of sandy clay, which was probably watertight at that point. The log of this well suggests that the clay overlying the 200-foot sand is grading into a sand in the direction of the bay and ocean. If this is true, probably within 2 or 3 miles of the Atlantic City Water Works the 200-foot sand is connected with other Cohansey sands that contain salt water, and salt water may even now be moving toward the well field.

All the Cohansey sands contain salt water at Atlantic City, which is about 5 miles from the pumping station, and salt water is probably present in these sands even nearer to the well field. It follows that even if the overlying impermeable bed extends for many miles oceanward, it would not be effective in protecting the sand from salt water if the wells were pumped at anything like their total capacity, because the cone of depression would probably extend seaward considerably beyond Atlantic City.

Test wells B-1, B-2, and B-3 were intended primarily as "outpost wells." They were equipped with screens and have been left in condition to be pumped for sampling. They should be sampled at regular intervals in the future, in order to detect, if possible, any movement of salt water toward the 200-foot wells at the Atlantic City Water Works. It is also recommended that additional wells be put down between these wells and that the line be extended at both ends, to decrease the likelihood of salt water passing unnoticed between or around them. Periodic observations of water levels should also be made on these test wells, in order to obtain some idea of the extent of the cone of depression in the direction of the ocean. Furthermore, water-stage recorders should be installed on wells B-5 and B-2, which have 4½-inch casings, in order to obtain more definite information on the extent of the cone of depression.

RECOMMENDED PROCEDURE FOR FUTURE DEVELOPMENT OF THE SHALLOW SANDS

The demands for water supply in Atlantic City will probably increase in the future. Furthermore, the Atlantic City Water Works may be called upon at rather short notice to supply the water now being furnished by the wells to the 800-foot sand in the city, and possibly to assist the neighboring municipalities in case of salt-water intrusion into the 800-foot sand. In view of these facts it is recommended that a comprehensive plan for future development at the Atlantic City Water Works be prepared. If this plan involves a further development of the Cohansey sands on the mainland, it is recommended that a comprehensive program of drilling test wells be undertaken as soon as possible and that the location of any additional wells to these sands be based upon the results of this test-well program, which should cover the entire area under consideration. It is further recommended that, if possible, the development of these sands proceed gradually, in order that the effect of pumping the first wells can be observed and the plan modified, if necessary, before too great an investment is made in the development. Such a program might involve the laying of pipe lines larger than necessary in its earlier stages; otherwise it would not involve any expenditure for works that could not be fully utilized as soon as they were completed.

INTERRELATION BETWEEN 100-FOOT AND 200-FOOT SANDS

Thompson (15) observed in 1924 that the starting of the wells to the 100-foot and 200-foot sands at the Atlantic City Water Works produced a sudden upward surge in the water level in the Atlantic City Water Works 600-foot well and that stopping them produced a sudden downward surge in the 600-foot well. Similar effects have since been observed in New Jersey from time to time, at the Atlantic City Water Works, at the Whitesville plant of the Monmouth Consolidated Water Co. near Asbury Park, as well as at several localities on Long Island. The same type of surge has occurred both when the pumped well drew its water from a sand above the sand in which the screen of the observation well was situated, and when it drew from a sand below this sand. The movement of the water level in the observed well is exactly the reverse of the movement that would ordinarily be expected if there were a connection between the two sands, or if the changes in pressure were transmitted through the intervening clay.

The best opportunity afforded thus far to study the nature and extent of this surge was during the test on the 100-foot sand in December, 1931. Well 3, which draws its water from the 200-foot sand and is near the center of the old well field, was pumped continuously during the period of the test, except for a shut-down from 10:39 a. m. December 11 to 2:32 p. m. December 12. This occurred near the end of the 3-week shut-down of the 100-foot wells, when the recovery of the water level in them had become very gradual. Water-stage recorders were being maintained on three of the old 100-foot wells, A-22, A-27, and A-33, and tape measurements of water level were being made several times a day on the remaining 100-foot wells. During the periods immediately before and after the shut-down and starting of well 3, more frequent tape measurements were made in some of the nearby 100-foot wells that were not equipped with water-stage recorders. The results of these observations are presented in figure 16, with a map showing the location of the wells observed and a sketch showing the relation between the two sands.

The largest surge noted in any of the observation wells was less than 0.2 foot and the effect of the surge gradually disappeared within a few hours after well 3 was started or stopped. Furthermore, this phenomenon was distinctly local in its character. A surge was observed in wells in four different directions from well 3, and at distances ranging from 165 to 400 feet, but no measurable surge occurred in well A-27 which is 665 feet from well 3.

It has been demonstrated that artesian water-bearing formations, such as those at the Atlantic City Water Works, and the clays that lie between them, are not rigid bodies but have a certain amount of elasticity and compressibility. The true explanation of the phenomenon above described is almost certainly connected in some way with the elasticity and compressibility of the water-bearing formations and their confining beds. Furthermore, it is almost surely some kind of a pressure effect. The amount of water moved in the unpumped sand is very small, possibly only enough to fill the casings of the observation wells for the depth of the surge. Two tentative explanations of this phenomenon are almost diametrically opposite in their conception of what occurs in the unpumped sand. Both explanations are presented below.

The following explanation is suggested by Mr. Thompson. The starting of a well causes a decrease in the water pressure in the sand from which the water is being drawn. This decreased pressure is transmitted through the overlying and underlying clays to the sands above and below, causing a slight reduction in the pressure against the bottom

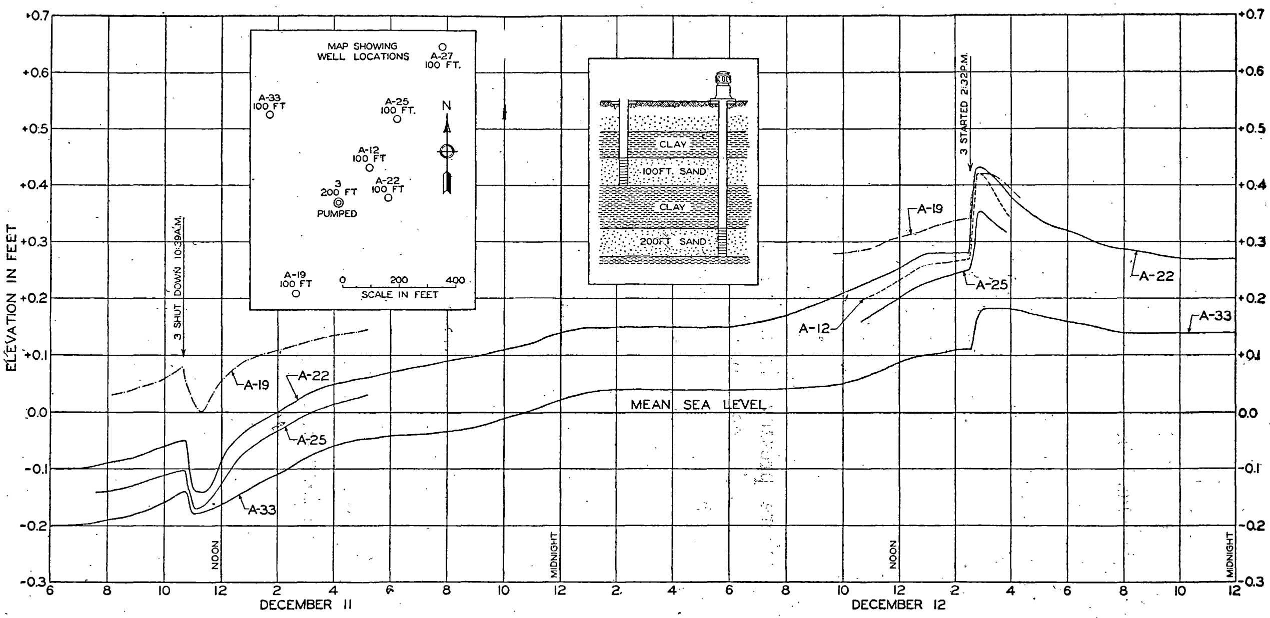

FIGURE 16.—Effect of starting and stopping a well to the 200-foot sand, at the Atlantic City Water Works, on water levels in wells to the 100-foot sand, with a map of the wells observed.

or top of these beds. The reduced pressure against these beds causes the sand grains in them to be temporarily rearranged in such a way that they cannot hold as much water as before. A little water is therefore forced up the casing of the observation well. A reverse of this procedure may explain the surge when the pumped well is shut down.

This explanation is based upon two other observed phenomena. If a rubber bag is filled with thoroughly compacted sand and completely saturated with water, the water standing above the mouth of the bag in a glass tube for observation, and if the bag is then squeezed in the hand or between parallel flat plates, the water level in the tube will drop instead of rising, as might be expected. When the pressure on the bag is removed (decreased) the water rises again. The explanation of this phenomenon is that the sand grains are forced out of their most compact arrangement, so that the volume of the pore spaces is increased. This necessarily increases the total volume of sand grains plus pore spaces and the rubber bag stretches where pressure is not being applied. Another related phenomenon, observed by many persons, is that if one steps on moist sand along a seashore, the sand suddenly appears to become dry. This is contrary to the expectation that the pressure would produce a depression into which the water previously contained in the sand would move and form a shallow pool. Actually the water that makes the sand appear wet is held up by capillary attraction and when the sand grains are rearranged under the pressure of the foot the larger pore spaces cannot hold the water and the sand is partly drained. These phenomena have been known for many years. Reynolds (16) has given the name "dilatancy" to this property of a compacted granular material to expand in total volume when subjected to lateral pressure.

Another possible explanation, suggested by Mr. Barksdale, is that the starting of the well, no matter what sand it penetrates, places a sudden load on the foundations of the pump, due primarily to the force required to lift the water to the surface and also for a brief time to the force required to accelerate the water. Similarly the stopping of a well would suddenly release the pressure on the pump base and amount to the removal of a load from it. The foundations of the pump always rest upon the material near the surface, and any load transmitted to this material would be transmitted downward to all the formations below. The effect of this loading would, of course, not appear in observation wells to the sand from which the active well was being pumped, because the draw-down or recovery effect would be much greater than any pressure effect in the opposite direction, but it might be observed in wells penetrating sands either above or below the sand from which the active well takes its water. The water level in observation wells has been observed to rise and fall when loads of other kinds were placed upon or removed from the surface near the well—for example, when a heavily loaded train passes nearby. The effect of the tidal loading and unloading at the surface of the ground has also been definitely observed in many wells near the ocean. It seems possible, therefore, that the loading and unloading of the pump foundations caused by the acceleration and lifting of the water might cause the surge that has been observed in sands not connected with the sand from which water is being pumped.

It is entirely possible that neither of these two suggestions is the true explanation of this phenomenon. They have both been presented for whatever value they may have. Each has some basis in experimental observations. The maximum load applied to the pump foundations is very small when compared to other types of loads which are known to affect the water levels in wells, but it is perhaps applied more quickly. On the other hand, if the first suggestion is accepted as the true explanation, it must be assumed that the unpumped sands expand and contract horizontally when vertical pressure is applied to, and removed from them by stopping and starting the well tapping the pumped sand. This horizontal movement would, of course, be exceedingly small because of the large volume of the sands concerned and the small amount of water displaced.

THE ATLANTIC CITY 800-FOOT SAND

RELATIVE IMPORTANCE AS A SOURCE OF WATER SUPPLY FOR THE REGION

The Atlantic City 800-foot sand furnishes a larger proportion of the total water supply of the Atlantic City region than any other source. In 1929, when the average consumption from all sources, except private wells on the mainland, reached a total of 23.5 million gallons daily, the total consumption of water from the 800-foot sand was over 9.5 million gallons daily, or about 40 percent of the total. In 1933 the total daily consumption, except for the private shallow wells on the mainland, was 19.3 million gallons, and the consumption from the 800-foot sand was 7.4 million gallons, or about 38 percent of the total. In August, 1929, the average rate of consumption from this sand reached a total of more than 14 million gallons daily. In prosperous times a little more than half of the annual average quantity of water pumped from this sand is taken by private supplies, but the summer consumption is about equally divided between public and private supplies. Since 1931 the annual rate of pumpage from the public supplies has been greater than that from private supplies. Owing to its great importance, the conditions affecting this sand were discussed in detail by Thompson (1, pp. 35-119) in his earlier report. In this section some parts of Thompson's discussion are reviewed briefly and the data on conditions affecting the 800-foot sand are brought up to date with the addition of certain studies made since 1928.

FLUCTUATIONS OF HEAD IN THE 800-FOOT SAND

DAILY FLUCTUATIONS

A study of the records of pumpage from this sand and of the water levels in wells to it was begun early in the investigation, to determine, if possible, whether or not the safe yield of the sand had been exceeded or was being approached. Preliminary observations with a water-stage recorder on a well in Atlantic City indicated that there was a daily fluctuation of several feet and a much wider fluctuation over a longer period of time. Daily fluctuations of 1 to 5 feet have been noted in practically all the unpumped wells observed in the region, and the fluctuation in pumped wells has of course been much wider, exceeding 30 or 40 feet daily in many wells pumped only a few hours at a time. This made it imperative to use water-stage recorders or to make observations of water level several times daily, in order to obtain an accurate idea of the behavior and trend of the water levels in wells to this sand.

A water-stage recorder has been maintained on an abandoned well in Longport since August, 1924. Since that time water-stage recorders have been installed on four other wells to this sand in different parts of the region. In addition to this, records of observations, made several times a day, of the water level in two wells near the center of pumpage in Atlantic City have been furnished by the operators. The results obtained from these seven observation points have provided a very good picture of the fluctuation of the water levels in wells to the 800-foot sand. A study of these records has brought out the fact that in addition to the daily fluctuations, there is a definite seasonal fluctuation of water level in all of them.

It must be borne in mind that the water in the Atlantic City 800-foot sand is under artesian head, and that the fluctuation of the water levels in a well to this sand represent changes in the pressure or head of the water in the formation at the well and not any considerable change in the amount of water stored in the sand. Under water-table conditions the rising or falling of the water level in a well indicates that the pore spaces in the sand have been filled or emptied for a thickness indicated by the range in fluctuation and consequently that there has been an increase or decrease in the amount of water stored in the formation. In an artesian sand, where the water rises in wells to a level above the elevation of the top of the sand, the pore spaces in the sand are filled with water at all times, and the fluctuation of water level in an observation well indicates primarily a change in the pressure of the water in the sand at that point. Water-bearing formations such as the Atlantic City 800-foot sand are elastic to a certain extent, so that an increase in the head of the water in the sand produces a slight increase in the volume of the pore spaces available for storing water, but this would represent an exceedingly small part of the total volume of water in the sand. Similarly when the head is reduced, unless the water surface drops below the top of the sand so that some of the pore spaces are drained, there will be only a very small change in the amount of water stored in the sand. The water in an artesian sand naturally flows toward the point of lowest pressure, and the lowering of the pressure in the sand around a pumped well causes the water to flow to the well. The real significance, therefore, of a change in the water level in an observation well to an artesian sand is that it represents a change in the head of the water in the formation at the well, and therefore a change in the rate at which water will flow into the area around the well. It does not represent a material change in the volume of water in the sand around the well.

The daily fluctuations of pressure in the Atlantic City 800-foot sand are caused by several factors. Observation wells near centers of pumping are most affected by fluctuations in pumpage. Other wells near the shore are affected mainly by tidal fluctuations. To a lesser extent barometric fluctuations probably have some effect also, but fluctuations due to the two major causes are so marked that it is usually difficult or impossible to distinguish fluctuations due to barometric pressure, although they undoubtedly occur. The charts from the recorders on four wells to the 800-foot sand, shown in figure 17, illustrate the effect of varying combinations of tide and pumpage upon the water levels.

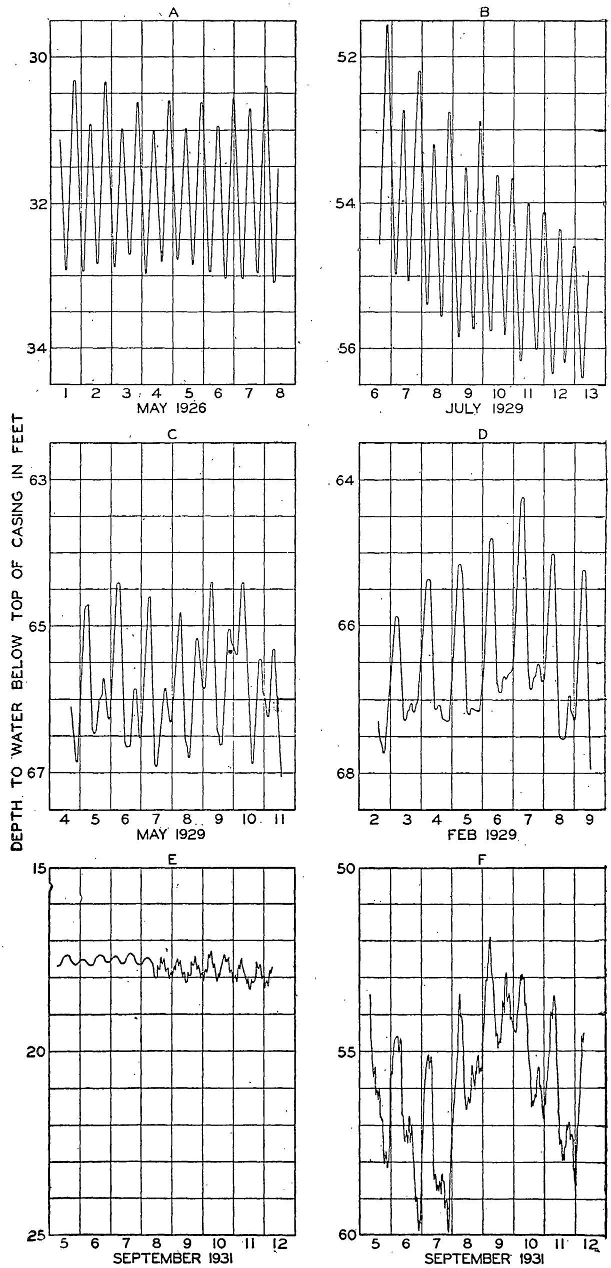

FIGURE 17.—Typical charts from four water-stage recorders on wells to the 800-foot sand in the Atlantic City region, showing the different types of daily fluctuations caused by various combinations of fluctuations of pumpage and of the tide. A, B, Longport well; C, D, Citizens Ice Co. well, Atlantic City; E, Sea Isle City well 1; F, Normandie Hotel well, Ocean City.

The daily fluctuations of water level in the well at Longport are due to tidal fluctuations in the ocean and in the bay. This well is on a narrow part of the island, only a short distance from the ocean and from the bay that lies back of the island at this point. The daily fluctuations of water level in this well are similar to the tidal fluctuations in several ways. The period of rise and fall is practically the same as that of the tides. The daily fluctuation is greatest during spring tides and least during neap tides. Furthermore, unusual tidal conditions, such as high storm tides or unusually low tides caused by off-shore winds, produce correspondingly high or low ranges of fluctuation of the water levels in this well. The range of fluctuation in the well is a little more than half of the tidal range and varies from about 1 to 3 feet. In addition to the daily fluctuation, there is a broad seasonal fluctuation of water level in this well caused by the seasonal fluctuation of pumpage in the region. Chart A covers a period when the rate of pumping in the region was changing very little, so that the average water level is about the same on each day. Chart B shows the effect of seasonal fluctuation, as well as the daily fluctuation. It covers a period in the early part of the summer when the pressure in the formation was decreasing rapidly, owing to the increasing rate of pumpage. On this chart the average water level is lower each day than on the preceding day.

The old Citizens Ice Co. well in Atlantic City is within a short distance of the area of heavy pumpage from private wells in the city. Here the effect of pumpage partly or almost entirely masks the tidal effect, the degree depending upon the time of the tides. The rate of pumpage from the nearby wells is least in the early morning hours and reaches a maximum late in the afternoon. If there were no tidal effect, the water level would be lowest in the late afternoon and would reach a peak early in the morning each day. If a high tide occurs early in the morning or a low tide late in the afternoon, its effect is emphasized by the pumping effect. If, on the other hand, a low tide occurs early in the morning or a high tide late in the afternoon, its effect on the water level in the well is very much reduced or entirely obliterated by the pumping effect. In the period covered by chart C high tides were occurring at about 8:00 a. m. and 8:30 or 9:00 p. m. The effect of the first high tide was enhanced by the lower pumpage at that time of the day, and the effect of the second high tide was very much reduced by the higher rate of pumpage in the early evening. Chart D shows the effect of a high tide in the afternoon almost completely obliterated by the pumping effect.

The fluctuations in the Ocean City well (chart F) are similar to those in the Citizens Ice Co. well, the tidal effect being at times masked and at times emphasized by the effects of pumping. The first part of chart E, from the well at Sea Isle City, shows a fluctuation which is almost purely tidal at a time when there was practically no pumping from nearby wells. The later part of chart E shows a combined tidal and pumpage fluctuation due to the frequent starting and stopping of a well in the vicinity.

As compared to the fluctuations in the Longport well, the range of tidal fluctuation in the Sea Isle City well is very much less, owing to the fact that this well is considerably farther from a tidal body of water than the Longport well. The Longport well is within 100 feet of the bay and within 500 feet of the ocean, so that tidal loading of the formation occurs on both sides of this well and very near to it. The Sea Isle City well is about 1,300 feet from the ocean and about 3,500 feet from the bay. The tidal fluctuation in the Sea Isle City well varies from 0.2 to 0.4 foot, as compared to a fluctuation of 1 to 3 feet in the Longport well. Tidal fluctuations of about 0.1 foot have been observed in well 1 at the Atlantic City Water Works. This well draws its water from the 800-foot sand and is about half a mile from the tidal marshes along Absecon Creek, over a mile from Absecon Bay, and about 5 miles from the ocean. High and low water in this well occur at the same time as high and low tide in the nearby bodies of water and more than 2 hours later than the corresponding stages in the ocean. The tidal fluctuations in these wells fade out as the distance from tidal waters increases. This seems to indicate that they are due to the changes in pressure caused by the tidal loading and unloading of the bottom of the ocean or bay and not to an actual tidal surge in the 800-foot sand itself or to a movement of water up from its outcrop under the ocean.

SEASONAL AND LONG-TERM FLUCTUATIONS

The water level in wells to the Atlantic City 800-foot sand has a very definite seasonal fluctuation. It is highest from December to April and lowest late in August or early in September. The observed range of fluctuation varies, depending on the location of the observation wells. In wells near centers of heavy pumping the range in water level is more than 20 feet from winter to summer. In the more remote wells the seasonal fluctuation is 5 feet or less.

In order to study the seasonal fluctuation of water levels in the observation wells in the region, the daily fluctuations have been eliminated and generalized curves prepared for each of the observation wells. For the Longport well this was done by averaging the two highs and two lows that occur each day and plotting the daily average. The daily fluctuation in the Atlantic City Water Works 600-foot well is very small, and the plotting of the water level at the end of each day produces a satisfactory generalized curve. For the other wells in the region the highest and lowest water levels each day were plotted as two separate lines and a generalized line drawn between these two lines by inspection.

The most significant results of the observations made on several wells in the Atlantic City region for the period from 1924 to 1934 are shown in figure 18. This diagram shows the generalized curves for the fluctuations of water level in the Atlantic City Water Works 600-foot well, the Longport well, and the Citizens Ice Co. well, and the nonpumping and pumping levels in wells near the center of pumping in Atlantic City from 1924 to 1934. It also shows the average daily rate of pumpage each month from the 800-foot sand in the Atlantic City region by divisions, and the accumulated departure from normal precipitation since January 1, 1924. The lines representing water levels on this diagram are referred to mean sea level. If they were referred to the original static level they would be at least 20 feet lower. The Atlantic City Water Works 600-foot well is an old test well that just penetrates the top of the 800-foot sand. The Citizens Ice Co. well is near the north end of Atlantic City. The area represented by the part of the diagram showing the accumulated departure from normal precipitation includes the intake area of the Atlantic City 800-foot sand. It is evident that during most of the period shown on the diagram the precipitation has been deficient.

The similarity between the seasonal fluctuations of water levels in the several wells is striking. There is also a very close relation between the seasonal fluctuations of pumpage and water level—so close that there can be no doubt that the seasonal fluctuations of water level are caused primarily by the fluctuations in the rate of pumpage. Another fact that is apparent from this diagram is that from 1924 to 1929 the general trend of the water level was downward and from 1929 to 1934 the trend was upward. The total pumpage from the sand increased each year from 1924 to 1929 and declined each year from 1929 to 1933; there was very little change from 1933 to 1934. As it is obvious that the

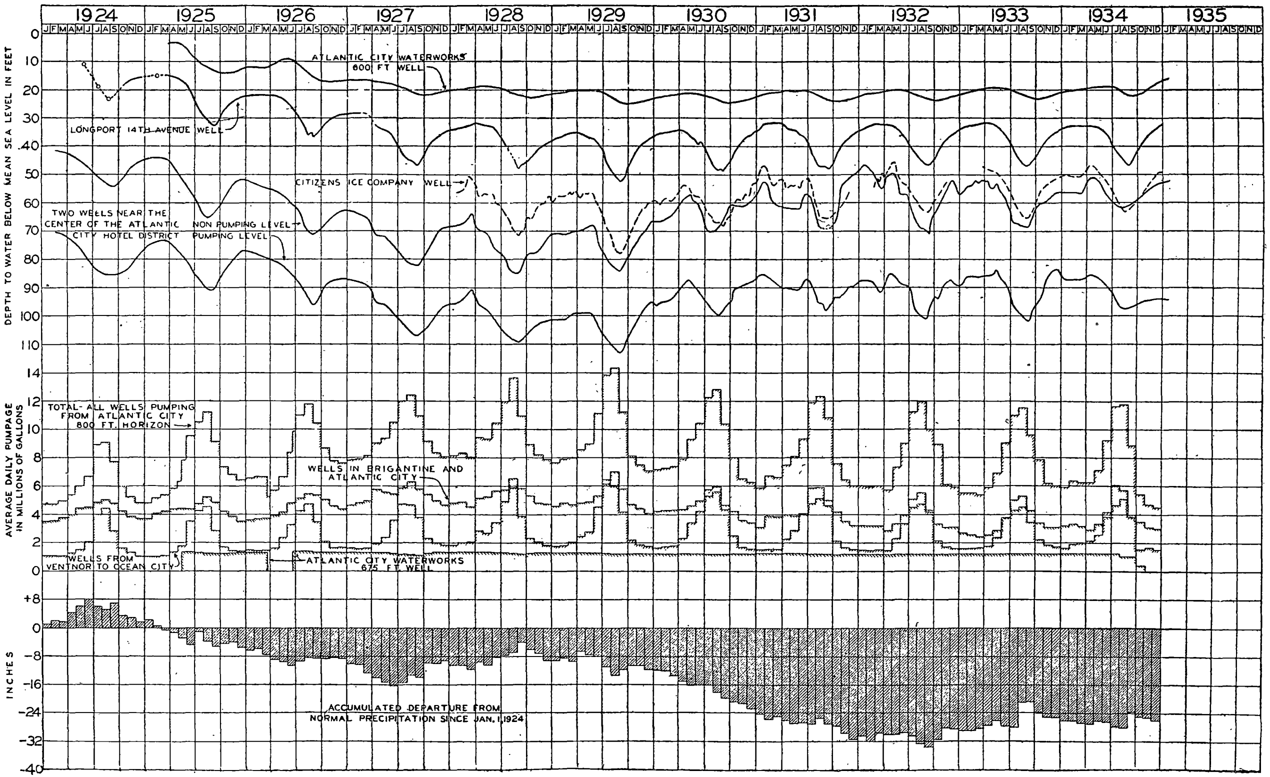

FIGURE 18.—Fluctuations of water level in and pumpage from wells tapping the Atlantic City 800-foot sand in the area between Brigantine, Pleasantville, and Ocean City from 1924 to 1934, and the accumulated departure from normal precipitation in the southern interior section of New Jersey since January 1, 1924.

seasonal fluctuation of water levels is caused primarily by the seasonal fluctuation of pumpage, it is reasonable to assume that the longer-term fluctuations of water level are also caused chiefly by changes in the rate of pumpage.

When the first wells were drilled to the 800-foot sand in the Atlantic City region, in 1888 or 1889, the water level in them rose to an elevation of 20 or 25 feet above sea level. The lower of these two figures is used throughout this report for computing the draw-down below the original static level. The information on water levels during the period from 1889 to 1924 is meager, but it indicates a gradual and persistent decline. In the summer of 1924 the water level in unpumped wells near the center of pumping in Atlantic City was about 54 feet below sea level, or about 74 feet below the original static level. The pumping level in these wells was from 15 to 30 feet or more lower than the nonpumping level, the difference depending on the amount of water drawn from the individual wells and the condition of the wells themselves. During this same summer the water level in the 14th Avenue well at Longport was about 44 feet below the original static water level. This well is about a mile from the nearest pumped well and considerably farther from any center of heavy pumpage in the region. The marked lowering of the water level in this well is therefore particularly significant.

In the summer of 1929 the water level in unpumped wells in the center of Atlantic City was about 104 feet below the original static level. The pumping level in the observation well shown in figure 18 was about 133 feet below the same level. At this time the water levels observed by means of a water-stage recorder on the Citizens Ice Co. well, an abandoned well in Atlantic City, a short distance from the center of pumpage, was about 98 feet below the original static level. Also in the summer of 1929 the water in the Longport well receded to a depth of about 72 feet below the original static level.

Since 1929 the water level in wells to the 800-foot sand has recovered somewhat, owing to a considerable decrease in the rate of pumpage from the sand. In the summer of 1934 the water level in an unpumped well near the center of pumping in Atlantic City was 82 feet below the original static level, that in the Citizens Ice Co. well was about 83 feet, and that in the Longport well was about 67 feet below the same datum. It is therefore apparent that although there has been a considerable recovery in water level, the average water level in wells to the 800-foot sand in this vicinity is still far below mean sea level and even farther below the original static level.

As pointed out by Thompson, (1, pp. 70-74) the lowering of the head of the water in the 800-foot sand extends over a wide area. It has probably reached the intake area of the sand. The water level in wells to this sand has been lowered from 20 to 100 feet below its original elevation in wells along the coast all the way from Brigantine to Wildwood, a distance of about 40 miles. In a direction perpendicular to the shore line there are not enough observation wells to define the extent of the lowering of the water level very closely. However, in the observation well at the Atlantic City Water Works the water level stood about 40 feet below the original static level in 1934, while well 1, which also penetrates the 800-foot sand, was being pumped continuously at a rate of about 1.25 million gallons a day. Furthermore, in August, 1935, after a period of 10 months during which well 1 had not been pumped, the water level in both wells stood 38 feet below the original static level. These wells are about 5 miles from Atlantic City. Before well 1 was drilled, the water level in the observation well stood at least 25 feet below the original static level, and part of the lowering since the installation of well 1, in 1925, is undoubtedly due to the pumpage in other parts of the region. In view of the fact that the slope of the cone of depression decreases with the distance from the center of pumpage, it is almost certain that the head has been lowered perceptibly over an area extending many miles farther inland. There is, of course, no information about the lowering of the head of the water in the 800-foot sand in the direction of the ocean from Atlantic City. However, it has probably been lowered materially for at least 10 miles out from the shore.

INFLUENCE OF CHANGES OF PRECIPITATION ON THE HEAD IN THE 800-FOOT SAND

In the preceding discussion the decline in the pressure of the water in the Atlantic City 800-foot sand is attributed primarily to pumpage, and the effect of variations of precipitation is not considered as a possible cause. It is extremely improbable that changes in the rate of precipitation have had any appreciable effect on the head of the water in the 800-foot sand at Atlantic City. Thompson (1, pp. 61-67) pointed out that the seasonal fluctuations of water level do not follow the fluctuations of precipitation, that there has been no gradual decline in precipitation since the first wells were drilled in the Atlantic City region, and that there has been no evidence of any serious decline of the water table in the intake area. He also showed that any given drop of the water table at the intake would produce a much smaller drop in the head of the water at Atlantic City and that, therefore, the effect of variations of precipitation on the intake area would be minimized.

If the water table in the intake area should be lowered by deficient precipitation, the water-bearing sands would unquestionably absorb an increasingly larger proportion of the existing precipitation and the flow of surface water would be affected more than the level of the water table. Streams have flowed across the permeable sands of the intake area, and probably ponds have existed on these sands during the entire period that the head of the water in this formation has been declining in the Atlantic City region. The years 1931 and 1932 were exceptionally dry years in this area, and during practically all of this 2-year period the accumulated deficiency in precipitation was increasing. The water level in wells to the 800-foot sand did not appear to be affected by this decline in precipitation but, as shown by figure 18, exhibited a gradual upward trend corresponding to the decrease in pumpage during this period. From still another angle it is obvious that most of the lowering of head in the Atlantic City region must have been due to some cause other than deficient precipitation, because it would be impossible to lower the head of the water in the formation below sea level by any drought, no matter how severe it might be. In the light of these facts it must be concluded that variations of precipitation have had at most an insignificant effect upon the fluctuations of water level in wells to the 800-foot sand at Atlantic City, as compared to the effect of pumping from wells.

RELATION BETWEEN PUMPAGE AND HEAD

GENERAL RELATION

Within certain limits there is a fairly definite relation between the yield of a single well and the lowering of the water level in the well. In a broad sense a similar relation must exist between the pumpage from a well field or a region such as the Atlantic City region and the lowering of the head in the region. A question that naturally arises is whether or not this regional relation is a definite mathematical one, and, if so, whether it can be used to determine the future lowering of head in the sand and the safe yield of the sand.

The approach to this problem for the region is not as simple as that for a single well. The principal difficulty is that although it is possible to measure accurately the amount of water pumped from the sand in the region under study, it is very difficult to arrive at an accurate figure for the regional lowering of head. If all the wells in the region were grouped in a small area the error in using the pumping levels in them would be small, because the conditions would then approach those occurring when a single well is pumped. Where the wells are scattered, pumping depresses the piezometric surface in an irregular and much warped shape, with sharp depressions around each pumped well. Under such conditions the elevation of the piezometric surface at any point is determined by the total pumpage in the region, the distances to the pumped wells, and the amount of water pumped from each well. The lowering of the water level in any single pumped well or any group of pumped wells is no more representative of the true regional lowering of head than the water level in unpumped wells in the region. In view of this fact, and because accurate measurements of water levels are more easily obtained in unpumped wells than in pumped wells, the studies here set forth have been based on the fluctuations of pumpage and of the water levels in unpumped wells. If the distribution of pumpage over the area remains the same, the fluctuations of the water level in an unpumped observation well should be proportional, within certain limits, to the fluctuations of water level in the pumped wells, no matter how many wells are pumped. However, the distribution of pumpage in the Atlantic City region varies from time to time and from season to season, so that the use of the water levels in a single unpumped observation well is subject to some inaccuracies. This difficulty can probably be eliminated to a great extent by using an average of the water levels in several wells in the region.

The safe yield of the water-bearing sand may be defined as the rate at which water may be drawn from it indefinitely without impairing the quality of the supply or decreasing its quantity. The qualitative factors that may tend to limit the safe yield of the Atlantic City 800-foot sand have to do primarily with the danger of salt-water contamination from the ocean. The quantitative factors that may limit the safe yield of the sand are its intake capacity and its ability to transmit water from the intake area to the Atlantic City region. In the following sections an attempt is made to determine, by a study of pumpage rates, water-level fluctuations, analyses of water from the sand, and other pertinent factors, whether or not the safe yield of this sand has been exceeded or is being approached.

LAG IN THE ADJUSTMENT OF HEAD TO RATE OF PUMPAGE

Figure 18 indicates definitely that the fluctuations of head in this formation are caused by fluctuations of pumpage. It is difficult, however, to determine from this figure a relation any more definite than this general statement. To study the relation between pumpage and head, Thompson (1, pp. 78-86) prepared a diagram which has been brought up to date and is presented as figure 19 in this report. In this diagram the water level in the Longport well at the end of each month is plotted against the average daily rate of pumpage for the month in the area between Ventnor and Ocean City. The points for each month on the diagram are connected in chronologic order by a line which runs from each month to the following month, and arrows placed on this line indicate the direction of progression in point of time. At the beginning or end of some years the points would have been so crowded that one or more of them have been omitted for the sake of clearness. For the same reason the curves for the years 1928, 1930, 1932, and 1934 have been omitted because they would fall on the same part of the diagram as those for 1927, 1929, 1931, and 1933, and plotting them would tend to confuse the diagram without adding anything to its value. In order to emphasize the trend from year to year, an insert has been added showing only the points for the months of March and December from December, 1924, through December, 1934. In the inset the points for December and March each year are connected in chronologic order to the points for the same months in the next year by a line, with arrows to indicate the order of progression, as in the main part of the diagram. Although figure 19 is based on the water levels in a single well and the pumpage in a part of the region, the plotting of similar diagrams based on other wells and the total pumpage in the region indicates that it is representative of conditions in the region as a whole.

One of the first things that is apparent from a study of this diagram is the characteristic shape of the yearly curves. In each year the pumpage increases gradually to a maximum in the month of August and then decreases to about the same amount as at the beginning of the year. The water level goes down as the pumpage increases and rises as the pumpage decreases, but during the part of the year after the peak of consumption the water level corresponding to a given rate of pumpage is generally considerably lower than that corresponding to the

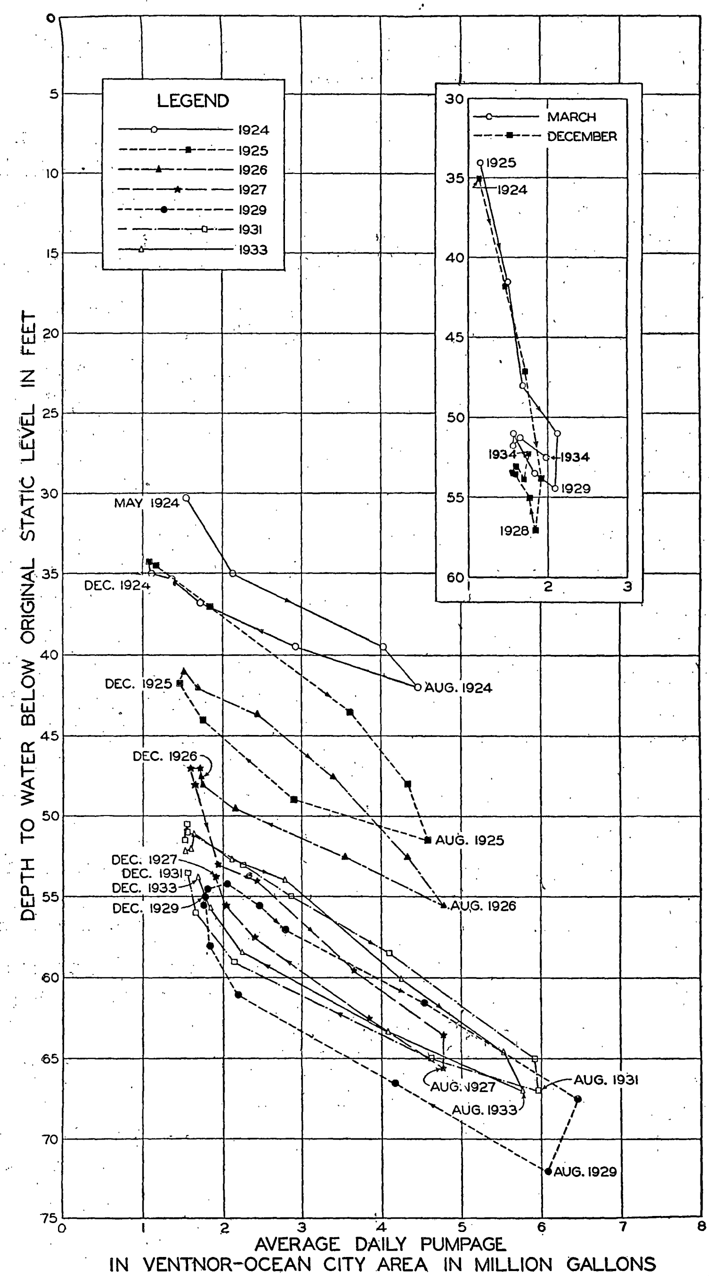

FIGURE 19.—Relation between depth to water below original static level in the Longport observation well and the average daily pumpage from the area between Ventnor and Ocean City, by successive months from May, 1924, to December, 1933 (except in 1928, 1930, 1932, and 1934), with an inset showing the relation for March and December in several years.

same rate of pumpage earlier in the year. The shape of the typical yearly curves in figure 19 seems to indicate a lag in the response of the head of the water in the formation to a change in the rate of pumpage. This lag is probably effective in the earlier part of the year, while the pumpage is increasing, as well as in the later part of the year, while the pumpage is decreasing, and thus the head does not fall as rapidly with increased pumpage or rise as rapidly with decreased pumpage as it would if the effect of pumping on the head were instantaneous. It is probable, therefore, that if the maximum rate of pumpage were continued long enough the head would drop much farther than it now does in the summer, before the effect of the lag would be substantially overcome. The maximum rate of pumpage usually lasts for only 3 or 4 weeks in late August and early September, so that the season of maximum pumpage is over before the head in the Longport well has become adjusted to the highest rate of pumpage. At the end of the season of maximum consumption the rate of pumpage decreases rapidly. From December to March the change in the rate of pumpage is not rapid, and much of the effect of lag is probably eliminated. The relation between the rate of pumpage and the head during the later part of the winter is probably, therefore, more significant than the relation at any other time of the year. However, as will be pointed out later, there is evidence that the lag extends over a period of years, so that even the winter relation is not a true one. Thompson (1, p. 82) has applied the term "hysteresis" to the lag between pumpage and water levels indicated by the curve for a typical year.

Further study of this diagram indicates that there was a considerable decline in the water level for any given rate of pumpage each year from 1924 to 1929, and that there has been only a very moderate recovery since 1929. This fact is emphasized by the inset showing points for the winter months of March and December each year. From 1924 to 1929 the annual rate of pumpage from the 800-foot sand was increasing, so that the water levels might have been expected to be lower each year than the preceding year. Since 1929, however, the average daily rate of pumpage from this sand has decreased to approximately the rate that was maintained in 1925, but the water levels have not risen much above those of 1927. From 1925 to 1929 the average rate of pumpage increased from 7.5 to 9.5 million gallons daily and the average water level dropped 18 feet. From 1929 to 1933 the average rate of pumpage declined from 9.5 to 7.5 million gallons daily and the yearly average water level rose 4 feet. This behavior seems to indicate one of two things: either there is a lag of several years in the response of the head to changes in the rate of pumpage, or the yield of the sand per foot of draw-down is decreasing.

In summary the study of this diagram brings out three significant facts. First, in each year the recovery in the water level after the season of highest pumpage is not as prompt as the decrease in the rate of pumpage; second, there was an appreciable decline in the water level for any given rate of pumpage each year from 1924 to 1929; and third, there has been no very marked recovery of the water level since 1929, despite a decrease of over 20 percent in the annual rate of pumpage. All three of these facts have a common bearing on the problem of determining the relation between the pumpage from the Atlantic City 800-foot sand and the head of the water in the sand, which is represented by the water level in wells that tap it. They seem to indicate either that there is a very considerable lag in the adjustment of the head to the rate of pumping, or that the rate at which water has been pumped from the sand in the Atlantic City region during the last 10 years or more has impaired its capacity to yield water. The lag might be explained by the hypothesis that the regional cone of depression is still expanding, so that the relation between pumpage and head has not yet become constant. The apparent decrease in the capacity of the sand might also be accounted for by this hypothesis. Other conditions that might cause the apparent decline in capacity indicated by figure 19 would be a shifting of the regional center of pumpage toward the area between Ventnor and Ocean City, or a lowering of the head at the outcrop. However, a study of the distribution of pumpage shown in figure 18 indicates that such a shift has not occurred, and there has been no evidence of a material lowering of the head at the outcrop. (See pp. 100-101.)

If the lag that is apparent in the typical yearly curve in figure 19 is equally effective on the upward and downward trends, then its effect should be substantially eliminated if the average water level for the year were plotted against the average rate of pumping for the year. In order to eliminate, at least to some extent, the seasonal lag and to include in the study the records of water levels in different parts of the region, a study was made of the relation between the average water level in three observation wells that have been maintained since 1925 and the average rate of pumpage from the 800-foot sand in the entire region each year. The results of this study are shown in figure 20.

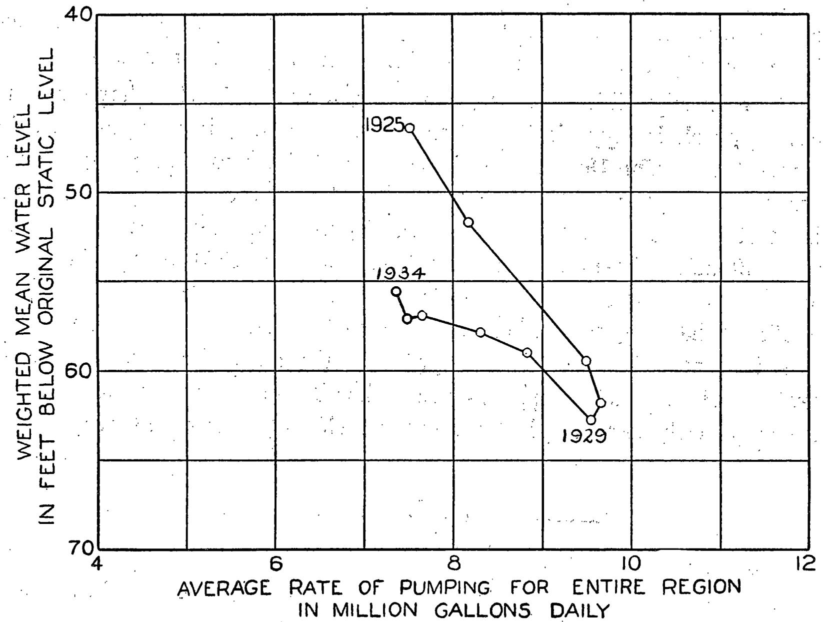

Figure 20.—Relation between the average daily rate of pumpage from the Atlantic City 800-foot sand for the entire region and the weighted mean water level in three observation wells, 1925 to 1934.

In the preparation of this diagram the average water level for each year in each of the three wells was first computed. The mean water level used in the diagram was then computed from the average water levels for the year for each of the three observation wells. Two of the observation wells are at a considerable distance from the center of pumpage in the region, and the third is practically at the center of pumpage in Atlantic City. Owing to the fact that the water levels in this third well were much lower and fluctuated more widely than those in the other two, it seemed that a straight arithmetic average of the three water levels would be unsatisfactory, for it would represent the fluctuations of head near the center of pumpage in Atlantic City more closely than those in the region as a whole. A weighted mean water level was therefore computed for the three wells, the most weight being given to the water levels in the wells that were least affected by merely local conditions and were therefore most representative of conditions in the region as a whole. In figure 20 the weighted mean water levels plotted against the average rates of pumping were connected in chronologic order by a line, in a manner similar to that used in figure 19.

The most striking thing about this diagram is the shape of the curve, which is very similar to the curves representing single years in figure 19. From 1925 to 1928 the average daily rate of pumpage increased each year and from 1928 to 1934 it decreased. The regional head of the water in the 800-foot sand decreased each year from 1925 to 1929 and increased each year from 1929 to 1934 except in 1933, when it was slightly lower than in the preceding year. This diagram confirms the inference drawn from figure 19—namely, that either there is a lag extending over several years in the adjustment of the water levels to the rate of pumpage, or there has been some impairment of the capacity of the sand to yield water for each foot of regional draw-down.

REGIONAL SPECIFIC CAPACITY

The specific capacity of a single well is its yield per unit of draw-down, usually expressed as a figure representing gallons a minute per foot of draw-down. Obviously the units used to obtain the specific capacity should be stated, if there is any danger of misinterpretation. If a well is pumped at the rate of 500 gallons a minute and the water level is lowered 50 feet, then its capacity is 10 gallons a minute per foot of draw-down, or its specific capacity is 10, if it is understood that United States units are used. Within limits that are determined by the nature of the water-bearing formation and the construction of the well, the specific capacity generally remains constant, but when the well is pumped at so high a rate that its efficiency is impaired by friction either in the well itself or in the water-bearing formation, the specific capacity decreases. If the pumpage from the 800-foot sand in the whole Atlantic City region can be compared to that from a single well, the relation between the lowering of the head of the water and the rate of pumpage from the sand expressed as a specific capacity should be significant. Figure 21 shows the regional specific capacity of the 800-foot sand based upon the average rate of pumpage each year from 1925 to 1934 and the weighted mean water level for the corresponding years in the same three observation wells used in the preparation of figure 20.

As the term "regional specific capacity" is believed to be new usage its meaning should be made clear by pointing out how it differs from the term "specific capacity" as applied to a single well. In the first place, the specific capacity of a single well is based upon the pumpage and the

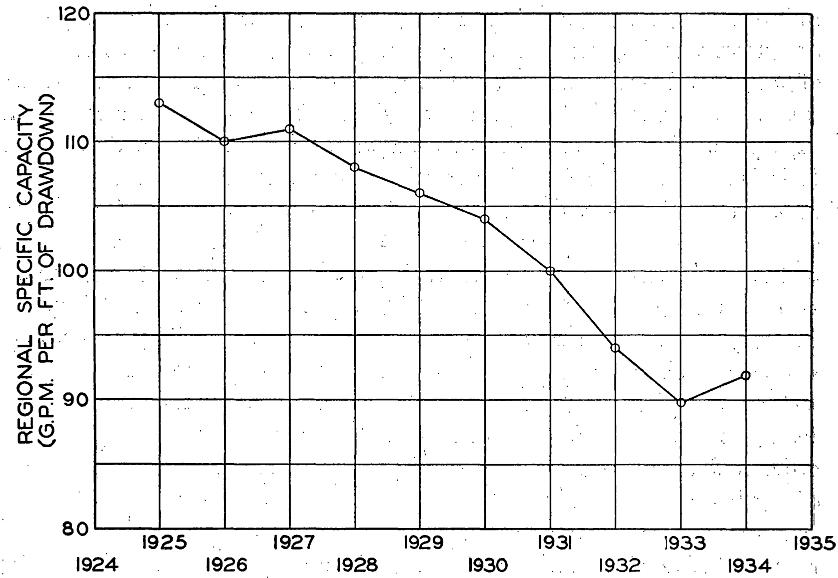

FIGURE 21.—Regional specific capacity of the Atlantic City 800-foot sand, 1925 to 1934, based upon the average daily pumpage for the year and the weighted mean of the lowering of the head below the original static level.

draw-down in that particular well. The regional specific capacity, which is designed to show the effect of regional pumpage upon the sand under consideration, is based upon the total pumpage from the sand in the region and the regional lowering of the head as indicated by the water levels in unpumped observation wells. The farther the observation wells are from the effects of merely local pumpage, the more nearly will the water level in them represent the effect of regional pumping upon the head of the water in the formation as a whole and the more significant will be the regional specific capacity thus computed. The flow to a single well is caused by the difference between the static head and the head just outside of the screen. Similarly, the flow into any region is caused by the lowering of the head at its borders. The variations of head within the region itself determine the distribution of the water after it has entered the region but do not affect the flow into the region except indirectly.

Except in 1927 and 1934, when small increases occurred, the regional specific capacity of the Atlantic City 800-foot sand has decreased in each year shown on figure 21. For a single well such a curve as this would indicate a gradual failure of the well. If the conditions in the region are strictly analogous to those in a single well, and if the observations of water level and pumpage used to prepare figure 21 have been correctly interpreted, then this diagram would indicate an impairment in the capacity of the 800-foot sand to yield water in the Atlantic City region. It is believed that the data upon which this diagram is based are fairly accurate and reasonably representative. However, it is by no means certain that the conditions in the region as a whole are strictly analogous to those in a single well. Even a single well would have to be pumped at a constant rate until all effect of lag was eliminated before its specific capacity could be accurately determined. It is evident from the preceding discussion that the lag between the pumpage and the adjustment of water levels in the Atlantic City region extends over a much longer time than has ordinarily been considered necessary to pump a single well in order to determine its specific capacity. It is quite possible that the effect of lag has not been eliminated in the Atlantic City region and therefore that the regional specific capacity as here computed is not strictly representative of the relation that may ultimately exist between pumpage and water level. It is also possible that the regional conditions are not strictly analogous to those in a single well. Nevertheless, the regional specific capacity is believed to be a valuable means of studying the capacity of a water-bearing formation to yield water, and whatever the true explanation of the decline in the regional specific capacity shown in figure 21 may be, there can be no question that the 800-foot sand in the Atlantic City region is now yielding considerably less water per foot of regional draw-down than it was 10 years ago.

The relatively close grouping of the points for the years 1932 to 1934 in figure 20 and the small variation in the regional specific capacity for those years as shown in figure 21 suggest that an approximate balance may have been reached. However, this conclusion must be confirmed by data for subsequent years before it can be applied with any degree of confidence. The increase in the regional specific capacity shown in 1934 might have been caused by a shift in the distribution of pumpage around the observation wells. Apparently something of this sort occurred in 1927, when a rise of the regional specific capacity occurred, because the figures for the later years indicated that this rise had no particular significance. Prior to 1927, however, there had been no period of relatively stable water levels and pumpage rates, such as that which occurred in the two years preceding 1934. The increase in the regional specific capacity in 1934 may therefore be more significant than that in 1927.

RELATION BETWEEN LAG AND THE COMPRESSIBILITY AND ELASTICITY OF THE AQUIFER

The phenomenon of lag or hysteresis and the tendency of the regional specific capacity to decline with the progress of time are probably both closely associated with the elasticity and compressibility of the water-bearing formation. It has been shown by Meinzer (17) that water-bearing formations, under artesian pressure, are to some extent both compressible and elastic. This is true even in aquifers composed of such relatively unyielding materials as sandstones and probably to a greater extent in unconsolidated sands. The water in an artesian aquifer is under hydrostatic pressure and carries a part of the load of the overlying beds. When the water pressure is released by pumping from wells, the solid particles composing the formation must carry a greater load, and the formation is slightly compressed. This compression decreases the volume of pore spaces between the sand grains, so that the formation is no longer capable of holding as much water as before, and some of the water withdrawn from it is taken from storage. The decrease by compression is a very small part of the volume of the pore spaces in the aquifer and an even smaller part of the volume of the aquifer itself. However, in view of the very large volume of total pore spaces available for the storage and transmission of water in an aquifer such as the Atlantic City 800-foot sand, the amount of water that can be withdrawn from storage in this manner is surprisingly large. In addition to releasing some water from storage in the sand by reducing its porosity, the compression of the sand probably reduces its permeability somewhat and thereby reduces its capacity to transmit water. To the reduction of permeability caused by compression must probably be ascribed, to some extent, the tendency of the regional specific capacity of the Atlantic City 800-foot sand to decline with the passage of time.

If the formation were absolutely rigid, the transmission of changes of head caused by changes in the rate of pumpage would be practically instantaneous, and there would be no appreciable lag between a change in the rate of pumpage and the adjustment of the head to correspond to the new rate. However, when water is withdrawn from a compressible formation, the head immediately around the well is lowered first, and the volume of the pore spaces there decreases slightly, so that a small amount of water is taken from storage near the well before the head can be lowered in the more remote parts of the formation and flow induced from those parts. As the head is lowered at points more and more remote from the well, the pore spaces in the sand there are also diminished slightly, so that more water is taken from storage. Furthermore, as the pumping continues the head immediately around the well is lowered more and more, and still more water is taken from storage in this part of the sand. It therefore requires some time for the full effect of a given rate of pumpage to appear as a change in the head of the water at any given point in the sand.

Artesian aquifers are not only compressible but to a certain extent elastic, so that when the water pressure increases with decreased pumpage, the volume of the pore spaces in the aquifer also increases slightly, although possibly not as much as it would decrease for a similar reduction of pressure. The increased volume of the pore spaces provides storage for additional water and retards the transmission of the change of pressure by making it necessary to move water to fill this storage space before the full change in pressure can be transmitted to more remote points.

It is evident, therefore, that the compressibility and elasticity of the formation tend to produce a lag in the transmission of the changes of head produced by changes in the rate of pumping. They probably account for the peculiar shape of the typical yearly curve in figure 19 and the similar curve in figure 20. The compression of the sand probably causes the regional cone of depression to expand more slowly than it would otherwise when the rate of pumpage is increased and to continue to expand for some time after a constant rate of pumpage has been established. This continued expansion would cause a progressive lowering of the regional head and an apparent decline in the regional specific capacity. In the years before the regional cone of depression had become adjusted to the higher rate of pumpage the regional specific capacity would appear higher than its true value. The decline of the regional specific capacity due to this cause would therefore be apparent rather than real. On the other hand, the decline of the regional specific capacity caused by the decreased permeability of the sand, due to compression, would represent a real impairment of the capacity of the sand to yield water.

It is estimated that from 1889, when the first wells were drilled to the 800-foot sand in the Atlantic City region, to the end of 1934 a total of about 55 billion gallons of water has been taken from this sand. An idea of the magnitude of this total may be obtained from the fact that it is about twice the amount of water required to fill the Wanaque Reservoir, in northern New Jersey. The removal of all this water from storage in the sand would have required a compression of the 800-foot sand of about 15 percent over the area of a circle of 40-mile radius drawn around Atlantic City. Such a compression would have eliminated more than half of the pore spaces in the sand and caused a settlement of the surface of about 12 feet over the whole area. Obviously nothing of this kind has occurred, as there has been no observable encroachment of the sea upon the land in southern New Jersey during the last few years, such as would have occurred if there had been a 12-foot subsidence.

As all of the water taken from this sand cannot have come from storage in the sand, it must be concluded that the cone of depression created by the pumping at Atlantic City has extended to the intake area and established a flow from that area to the Atlantic City region. A review of some of the more pertinent facts given on page 100 tends to confirm this conclusion. Southeast of Atlantic City the cone of depression is exaggerated by a small amount of local pumping, but it extends far beyond Wildwood, where the head in the sand is at least 20 feet below the original static level, even when there has been no local pumping from the sand for several months. Wildwood is about the same distance from the center of pumping in the region as the outcrop of the Kirkwood sands. The depression of the head at the Atlantic City Water Works, fully 5 miles from the center of pumpage toward the outcrop, is especially significant. Here the head of the water in the 800-foot sand has been lowered at least 25 feet and probably as much as 40 feet by the pumping on the island beaches. The slope of the piezometric surface decreases as the distance from the center of pumpage increases. It is therefore quite probable that the cone of depression extends all the way to the intake area, about 40 miles from Atlantic City. It does not necessarily follow, however, that the slope has become adjusted to the rate of pumpage, and continued pumping at the present yearly average rate may cause a further lowering of the head of the water in the sand.

It is worth while to estimate the amount of water that has probably been withdrawn from storage in the Atlantic City 800-foot sand. Meinzer (17, pp. 280-284) estimated that the Dakota sandstone in the vicinity of Ellendale, North Dakota, had been compressed about 0.2 percent for each 100 feet that the head of the water had been lowered. The Dakota sandstone is probably more rigid than the unconsolidated Atlantic City 800-foot sand, so that this figure may be used safely in making an estimate of the amount of water withdrawn from storage in the sand. Furthermore, laboratory tests by Terzaghi (18, pp. 987-990) on a compacted sample of graded quartz sand gave results that were in essential agreement with these figures. It is estimated that over an area of about

100 square miles the head in the Atlantic City region has been lowered an average of 50 feet; that over an additional area of about 250 square miles it has been lowered an average of 25 feet; and that over the remainder of the area between the well field and the intake, about 1,000 square miles, there has been an average lowering of the head of about 5 feet. These figures are based upon a rectangular strip of the 800-foot sand about 17 miles wide and 80 miles long lying between Brigantine and Ocean City and between the outcrop of the formation and a point under the ocean at the same distance from Atlantic City as the outcrop. They do not take into consideration the entire circle of influence of the pumping in the Atlantic City region, although there is probably a great deal of lowering of head on both sides of this strip. It is assumed that the lowering of head in the direction of the ocean is the same as in the direction of the outcrop. On the assumption that the sand is 80 feet thick throughout its extent, and that it is compressed 0.2 percent of its volume for each 100 feet that the head is lowered, it is estimated that the total amount of water removed from storage in the Atlantic City 800-foot sand since pumping began is about 6 billion gallons.

The highest average annual rate of consumption from the Atlantic City 800-foot sand was slightly less than 10 million gallons a day. At this rate, it would require about 1½ years to pump out of the sand all the water that has been taken from storage in it. This amount of water is about as much as all the water taken from the sand during the first 20 years that it was used as a source of supply. Of course, all this water was not removed from storage during any given period, but the sand has been yielding water from storage gradually as the head has declined. Each increase in the rate of pumping has caused a lowering of the head and the withdrawal of more water from storage. Each decrease in the rate of pumping has caused a rise in the head and the return of some water to storage.

PROBABLE EFFECT OF FUTURE INCREASES IN PUMPAGE

Quantitatively, either of two factors may limit the ultimate capacity of the Atlantic City 800-foot sand to yield water—the capacity of its intake area to admit water to the sand, or its capacity to transmit water from the intake area to the region. The 800-foot sand has not been traced all the way to the outcrop of the Kirkwood formation. However, a considerable part of the Kirkwood outcrop is composed of sand that is probably connected with the 800-foot sand. The outcrop extends as a band diagonally across the State of New Jersey for about 100 miles, ranging in width from less than a mile to more than 5 miles. It is readily apparent that a very small part of the precipitation falling on this outcrop area would be sufficient to supply all the water that is now being pumped out of this sand or is likely to be pumped in the near future. The permeability of the 800-foot sand is perhaps at least equal to that of the average water-bearing sand, but the resistance to the flow of large quantities of water through it for a distance of 40 miles or more must be considerable. The transmission capacity of the sand seems more likely to limit its economical yield than its intake capacity.

The existence of a lag, extending over several years, in the adjustment of the head of the water in the 800-foot sand to the rate of pumping from it makes it extremely difficult to predict the effect of future increases of pumpage upon the head of the water in the sand or even the ultimate effect of the present rate. Unquestionably the head would be lowered farther by increased pumping. The shape of the curve for regional specific capacity (fig. 21) suggests that the lowering would be more than proportional to the increase in pumpage. Nevertheless, the best means available to estimate the future lowering of head in the formation seems to be to assume that it will be proportional to the increase in pumpage. The estimates given below are made on that basis and are therefore probably conservative. They assume a future average annual rate of pumpage of 15 million gallons daily, which is about 50 percent greater than the rate in 1928. If it is assumed that the distribution of pumpage in the region will remain constant with increased consumption when the average rate of pumping in the whole region reaches 15 million gallons a day it will be 6.5 million gallons a day in the area between Ventnor and Ocean City.

The points for the winter months in figure 19 are not truly representative of the relation between pumpage and head, because a period of years rather than of months is required for the water level to become adjusted to a given rate of pumpage. They may, however, be used as a basis for an estimate of the lowering of the water level that might be expected with an increased rate of pumpage. A straight line can be drawn through most of the points for the winter months on the figure so that it will pass through the zero of pumpage and the original static head. If this line is extended downward, it will intersect the line for 6.5 million gallons daily at a depth of about 215 feet below the original static level, which by this method of estimating, will be the level in the Longport well when pumpage in the whole region reaches 15 million gallons daily. This estimate is based upon two assumptions; namely, that the points for the winter months in figure 19 represent a true relation between pumpage and head, and that the head would decrease in direct proportion to the increase in pumpage.

The total annual pumpage did not vary much in 1932, 1933, and 1934, and the average annual water level also remained approximately constant during these three years (fig. 20). Therefore, the regional specific capacity remained nearly the same during this period (fig. 21). These facts suggest that the lag in the adjustment of the head to the rate of pumpage has been largely dissipated during the years of reduced pumpage since 1929. If the average regional specific capacity for these three years is used to determine the ultimate regional draw-down that would be caused by pumping 15 million gallons daily from the 800-foot sand in the Atlantic City region, the regional draw-down is found to be about 113 feet. If it is again assumed that the distribution of pumpage throughout the region remains the same, an average regional draw-down of 113 feet would represent an average water level in the Longport well of 115 feet below the original static level and an average level in unpumped wells near the center of Atlantic City of 155 feet below the original static level. Thus, by two different methods of estimating, we arrive at figures of 115 feet and 215 feet for the lowering of head in the Longport well for a future average rate of pumping of 15 million gallons daily. The best that can be said is that the true answer probably lies between these two figures, and that the methods of analysis and prediction employed probably do not apply accurately to the data at hand.

Of the two figures obtained, the one arrived at by means of the curve for regional specific capacity is probably more nearly correct than the one determined on the basis of the winter points in figure 20. However, it should be borne in mind that as the head of water in the formation in the region decreases, there will be additional compression of the sand, which will probably decrease its permeability, so that the regional specific capacity will continue to decline slightly from year to year as the rate of pumping increases. This would result in a greater lowering of head than that indicated by the direct application of the average regional specific capacity for 1932-34 to a pumpage rate of 15 million gallons daily.

It should also be borne in mind that the water level determined by this method is an average water level produced by an average rate of pumping of 15 million gallons daily, and that if the normal seasonal distribution of pumpage occurred the maximum lowering of the water level would be considerably in excess of the average. An average rate of pumping of 15 million gallons a day would be approximately twice the average rate during the years 1932 to 1934 and would be about 50 percent greater than the average rate in 1928, the year of maximum consumption. If this rate of pumpage were maintained for a period long enough to overcome the effect of lag, the water level in wells to the 800-foot sand would probably stand considerably more than twice as far below the surface as it stood during these three years. This would more than double the cost of pumping water from the sand. It would also greatly increase the danger of the contamination of the formation by salt water from the ocean.

DANGER OF SALT-WATER INTRUSION INTO THE 800-FOOT SAND

It is believed that the danger of salt-water intrusion into the Atlantic City 800-foot sand is more serious than the danger of the supply failing in quantity. It seems probable that before any water was withdrawn from the sand through wells in the Atlantic City region, the fresh water and salt water had been for a long time in a state of balance similar to that in the upper sand as shown in figure 5, D, with the fresh water filling the formation for several miles out to sea, and no fresh water flowing directly into the ocean past Atlantic City. The presence of salt water in the seaward extension of the formation is indicated by a somewhat higher chloride content of the water from wells farther down the dip than Atlantic City, such as those at Sea Isle City, Stone Harbor, and Wildwood, and by the distribution of chloride in the different parts of the area in and immediately around Atlantic City. The regional cone of depression caused by the pumping in the Atlantic City region has probably extended to the intake area, about 40 miles from Atlantic City. (See p. 113.) The conclusion is almost inescapable that the cone of depression must also have extended far past the point where salt water was originally in balance with fresh water in the formation and therefore that the salt water must now be moving toward the Atlantic City region.

The information available indicates that the original head of the fresh water in the Atlantic City 800-foot sand was 20 or 25 feet above sea level. A head of 25 feet above sea level would have held sea water of average density in balance at a depth of about 1,000 feet. The dip of the sand at Atlantic City is about 25 feet to the mile. If the dip remains the same in the seaward direction the sand reaches a depth of 1,000 feet at a distance of about 7 miles from Atlantic City. Furthermore, if the sand and its overlying clay are continuous with the same dip, to the edge of the Continental Shelf, about 100 miles from Atlantic City, its sub-oceanic outcrop at the edge of the Continental Shelf would be at a depth of about 3,000 feet. Unless there is a break in the overlying clay before the sand extends to a depth of 1,000 feet, or unless the dip of the sand is very much more gentle under the ocean than it is under the land, so that it reaches the edge of the Continental Shelf at a depth of less than 1,000 feet, there could have been no flow down the dip and out into the ocean directly past Atlantic City for a long time before any water was withdrawn from wells. It seems improbable that the dip of the sand is modified enough in its oceanward extent for it to reach the edge of the Continental Shelf at a depth of less than 1,000 feet. If the dip under the ocean is approximately the same as that under the land, then any break that might have permitted a flow of fresh water past Atlantic City and into the ocean during recent times, but before any wells were drilled to the sand, must be less than 10 miles from the shore.

The Atlantic City 800-foot sand is a marine deposit and therefore originally contained nothing but salt water. The fact that it now contains very fresh water in the Atlantic City region is evidence that a large amount of water has flowed from the intake area past Atlantic City and out into the ocean at some time during the past. This is highly significant, because it implies that salt water from the ocean could flow back into the sand if the relative heads of the fresh and salt waters permitted. It is well known that the relative elevation of the land surface and the surface of the ocean have not always been the same as at present, and probably at some time in the past the intake area of the 800-foot sand was high enough above the level of the ocean to permit water to flow out into the ocean and wash the sand practically free of salt. Since that time the intake area has been lowered by subsidence or erosion, or both, to such an extent that the direct outflow of fresh water is no longer possible.

Under the conditions existing before the first wells were drilled to the 800-foot sand, the only possible way for the water in the sand beneath the Atlantic City region to have flowed directly out into the ocean under a head of 25 feet would have been the existence of a connection between the sand and the ocean at a depth of less than 1,000 feet. However, it might have been possible for fresh water to flow laterally through the sand to the points where the Kirkwood formation crops out at or near sea level, in the vicinity of Asbury Park and under Delaware Bay. Before the first wells were drilled in Atlantic City there may have been some lateral flow toward one or the other of these sea-level outcrops, but it must have been very slow in view of the considerable distances involved and the comparatively low head.

The most positive evidence that salt water exists in the formation at some point under the ocean is found in the distribution of chloride in the water in those parts of the formation to which wells have been drilled and from which it is possible to obtain samples. As pointed out by Thompson (1, pp. 115-119) the New Jersey coast line is not parallel to the strike of the 800-foot sand but cuts across it at an angle, so that wells at points along the shore south of Atlantic City encounter this sand farther down the dip than those at Atlantic City. Samples of water have been collected periodically from the 800-foot sand from wells along the shore from Atlantic City to Wildwood during most of the time since this investigation was begun, in 1923. The results of chloride determinations made upon these samples, together with the results of such earlier analyses as are available, are listed in table 4. An examination of this table indicates that the chloride content of the water is definitely higher in the wells to the south than it is in the wells at Atlantic City. The fact that these wells penetrate the sand farther down the dip than those at Atlantic City suggests that the salinity of the water in the sand offshore from Atlantic City is greater than it is at Atlantic City.

Recently the sampling program in Atlantic City has been expanded to include a semiannual collection of samples from every accessible known well to the 800-foot sand. This program was initiated to make a further study of the distribution of salt water in the region, and also to serve the useful purpose of singling out any wells that may have leaking casings, so that the owners can be warned of the condition before the wells become unfit for use. The results to date of this semiannual sampling program are shown in table 5 and on figure 22.

The most striking thing about this map is the progressive increase in chlorides in the direction of the ocean. Water from the well at the Atlantic City Water Works at Pleasantville contained 2.5 parts per million of chloride. Wells at Brigantine and on the back of Absecon Island contained from 3.5 to 4.0 parts per million, and the wells along the ocean front in Atlantic City appear to have a normal chloride content of 8 to 10 parts per million. In one group of wells near the ocean front the chloride content was much higher, running to a maximum of 112 parts per million. Although this amount of chloride does

TABLE 4.—CHLORIDE CONTENT OF WATERS FROM REPRESENTATIVE WELLS TO THE ATLANTIC CITY 800-FOOT SAND, 1905-34

[ANALYZED IN THE WATER-RESOURCES LABORATORY OF THE UNITED STATES GEOLOGICAL SURVEY, EXCEPT AS INDICATED. PARTS PER MILLION]

Date	Atlantic City: Chalfonte Hotel 1910	Atlantic City: Chalfonte Hotel 1913	Atlantic City: Supplee-Wills-Jones Dairy Co.	Sea Isle City 1	Sea Isle City 2	Sea Isle City 3	Sea Isle City 4	Stone Harbor 1	Stone Harbor 2	Wildwood, Pine and Holly Beach Aves.
1905	*8.0									
1907										†208
1910				†15						
1911	*9.7			†16–18				†16–17		
1912				†16–18				†15–16		
1913				†16–18				†16		
1914				†16				†16		
1915				†16				†16		
1916				†16–17				†16		
1917								†17		
1920				†12–16				†17		
1921				†18–25				†18		
1922				†17–18				†18		
1923				†17				†18		
Nov. 14			8.0							
1924	*10			†17				†17–20		
Feb. 21		11								
June			6.0							
1925				†18						
Aug. 18			7.0							
Dec. 2				‡17					20	181
Dec. 3		9.0								
Dec. 4		8.0								
1926									16	
Feb. 10		7.0								
May 14		5.0	5.0							
May 22								11		
June 1									18	
July 14						12			16	
July 15		6.0	5.0							
July 20										§203
Aug. 14									16	
Aug. 25		9.9	5.6			13			18	
Aug. 26										198
Sept. 28						14				201
Oct. 1		8.0								
1927										
Jan. 27		9.5	8.4			13			18	134–239
Apr. 7		5.5				14			18	200–208
Apr. 8			8.8							
July 16		7.5	5.8						18	
Sept. 1						12			18	202
Sept. 2		8.1	5.9							
Oct. 6		8.0	5.9							
Nov. 2						13				648
Nov. 3		8.5	5.5							
Dec. 16		5.8								
Dec. 21			5.5							
1928										
Jan. 18		7.5	5.4							
Feb. 24		7.0	5.2							
Apr. 29		9.2	5.4			17			19	172
May 21			5.4							
Aug. 14		8.0	5.4			13				
Aug. 15									16	204
Sept. 18		6.8	5.4							
Dec. 13						14			18	385
Dec. 14		8.8	6.2							
1929										
Jan. 22		8.9	6.9							
Feb. 20		10	6.5							
Mar. 21		8.2	5.6			15			18	
Apr. 26		8.7	10							
May 28		9.2	5.5							
June 20		7.9	5.0			13			16	236
July 29		9.4	7.9							
Aug. 30		7.8	5.0							

† Analysis made by New Jersey State Board of Health.
* Analysis made by Pease Laboratories, Inc., New York, N. Y.
‡ Composite sample from two wells.
§ 200 parts July 21, 1926.

TABLE 4.—CHLORIDE CONTENT OF WATERS FROM REPRESENTATIVE WELLS TO THE ATLANTIC CITY 800-FOOT SAND, 1905-34—(Continued)

[ANALYZED IN THE WATER-RESOURCES LABORATORY OF THE UNITED STATES GEOLOGICAL SURVEY, EXCEPT AS INDICATED. PARTS PER MILLION]

Date	Atlantic City			Sea Isle City				Stone Harbor		Wildwood, Pine and Holly Beach Aves.
	Chalfonte Hotel		Supplee-Wills-Jones Dairy Co.							
	1910	1913		1	2	3	4	1	2	
1929 (*Cont.*)										
Sept. 13	......	8.4	5.1	......	......	......	......	......	......	......
Oct. 15	......	......	......	......	......	......	......	......	19	234
Oct. 16	......	......	......	......	......	16	......	......	......	......
Oct. 17	......	9.2	7.0	......	......	......	......	......	......	......
Nov. 16	......	8.1	5.6	......	......	......	......	......	......	......
Dec. 12	......	7.5	5.2	......	......	......	......	......	......	......
1930										
Jan. 23	......	7.9	5.8	......	......	......	......	......	......	......
Jan. 24	......	......	......	......	......	13	......	......	17	208
Feb. 19	......	......	6.2	......	......	......	......	......	......	......
Feb. 20	......	7.5	......	......	......	......	......	......	......	......
Mar. 19	......	8.2	6.9	......	......	......	......	......	......	......
Apr. 23	......	......	......	......	......	13	......	......	18	211
Apr. 24	......	7.9	5.5	......	......	......	......	......	......	......
June 12	......	7.9	5.6	......	......	......	......	......	......	......
July 10	......	8.0	5.8	......	......	......	......	......	......	......
July 11	......	......	......	......	......	13	......	......	18	204
Aug. 22	......	8.2	5.6	......	......	......	......	......	......	......
Sept. 25	......	8.5	6.0	......	......	......	......	......	......	......
Oct. 22	......	......	......	......	......	......	......	......	18	1360
Oct. 23	......	......	......	......	14	......	15	......	......	......
Oct. 24	......	8.6	5.5	......	......	......	......	......	......	......
Nov. 13	......	7.8	6.0	......	......	......	......	......	......	......
Dec. 9	......	8.0	5.5	......	......	......	......	......	......	260
1931										
Jan. 22	......	7.1	5.8	......	......	......	......	......	......	203–835
Jan. 24	......	......	......	......	14	......	......	......	18	......
Feb. 16	......	......	......	......	......	......	......	......	......	208–410
Feb. 19	......	7.8	5.6	......	......	......	......	......	......	......
Mar. 26	......	8.8	11	......	......	......	......	......	......	......
Apr. 21	......	......	......	......	......	14	......	......	18	212
Apr. 22	......	7.6	6.8	......	......	......	......	......	......	......
May 20	......	7.5	6.0	......	......	......	......	......	......	......
June 9	......	9.5	6.5	......	......	......	......	......	......	......
July 7	......	7.6	6.1	......	......	......	......	......	......	......
July 9	......	......	......	......	......	14	......	......	18	204
Aug. 18	......	7.2	5.1	......	......	......	......	......	......	......
Sept 15	......	7.4	5.2	......	......	......	......	......	......	......
Sept. 16	......	......	......	......	......	13	......	......	18	200
Oct. 14	......	7.2	5.2	......	......	......	......	......	......	......
Nov. 19	......	7.0	5.2	......	......	......	......	......	......	......
1932										
Jan. 15	......	6.8	6.1	......	......	15	......	......	18	210
Feb. 16	......	7.1	6.0	......	......	......	......	......	......	......
Mar. 8	......	7.0	6.1	......	......	......	......	......	......	......
Apr. 19	......	......	......	......	......	13	......	......	18	214
Apr. 20	......	7.0	5.6	......	......	......	......	......	......	......
May 16	......	9.8	5.6	......	......	......	......	......	......	......
June 6	......	9.2	5.8	......	......	......	......	......	......	......
July 19	......	8.2	......	......	......	......	......	......	......	......
July 20	......	......	5.5	......	13	......	......	......	18	202
Oct. 8	......	7.2	5.5	......	......	......	15	......	18	202
Dec. 30	9.8	6.6	5.1	......	......	......	......	......	......	......
1933										
Jan. 26	9.9	6.2	5.0	......	......	......	15	......	18	247
Feb. 20	......	......	5.4	......	......	......	......	......	......	......
Feb. 21	......	6.6	......	......	......	......	......	......	......	......
Mar. 9	10	6.8	5.4	......	......	......	......	......	......	......
Apr. 25	......	......	......	......	......	15	......	......	18	211
May 5	9.6	6.2	5.4	......	......	......	......	......	......	......
May 24	......	......	......	......	......	16	......	......	18	208
July 18	......	......	......	......	......	......	......	......	......	205
July 19	......	8.0	6.4	......	......	16	......	......	......	......
Nov. 23	......	......	6.4	......	......	......	......	......	......	......
1934										
Jan. 18	......	......	......	......	......	......	......	......	18	210
Jan. 19	......	......	6.4	......	......	16	......	......	......	......
Mar. 7	......	6.8	5.2	......	......	......	......	......	......	......
Mar. 22	10	8.1	......	......	......	......	......	......	......	......
Mar. 28	......	......	5.2	......	......	......	......	......	......	......

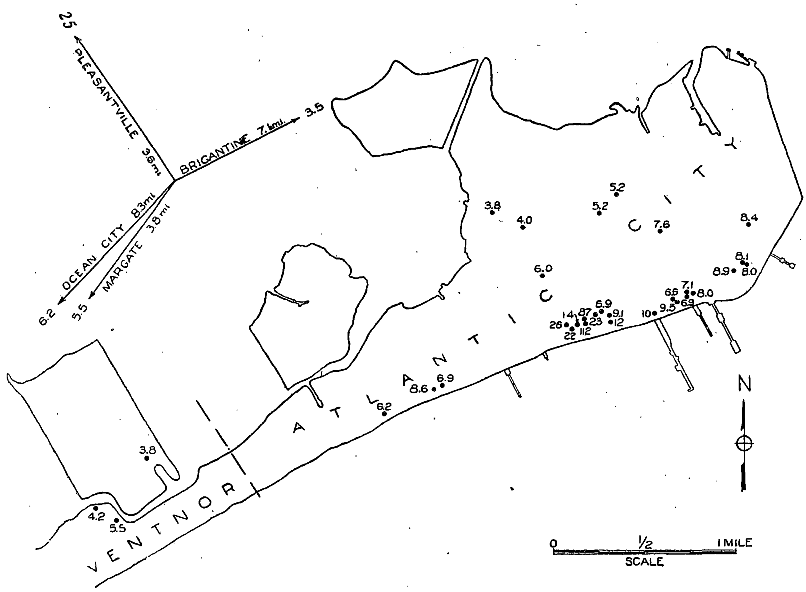

FIGURE 22.—Outline map of Atlantic City showing the location of active wells and the chloride content of the water from them as determined in 1934. Arrows indicate the direction of certain outlying wells from an arbitrary point back of the island, and the accompanying figures show the distance to these wells and the chloride content of the water from them.

not make the water from these wells objectionable it is so far above the normal that it demands careful observation and study. This group of wells is near the center of pumpage in Atlantic City and is therefore situated at the point where the salt water would be expected to arrive first from the direction of the ocean. However, there are in this vicinity at least two old wells that have been abandoned on account of leaking casings. The results of the investigation to date suggest that the high chloride content found in the water from wells in this vicinity is caused by leaks in one or more of these old wells rather than by the arrival of salt water from the ocean. However, this situation must be watched closely.

If the high chloride in this area is due to a leak in the casing of an abandoned well, it emphasizes the necessity for carefully plugging any old wells to the 800-foot sand when they are abandoned. The water in the sands above the great clay bed that overlies the 800-foot sand is very salt, and a leakage of a comparatively small quantity of this water

TABLE 5.—CHLORIDE CONTENT OF SAMPLES COLLECTED SEMIANNUALLY FROM WELLS TO THE ATLANTIC CITY 800-FOOT SAND

[ANALYZED BY W. L. LAMAR, U. S. GEOLOGICAL SURVEY]

Well owner	Date drilled*	Chloride (parts per million)				
		March, 1934	October, 1934	March, 1935	August, 1935	March, 1936
Atlantic City Electric Co., new well	1924	3.9	3.8	3.8	3.9	3.8
Atlantic City Gas Co.	1925	4.0	4.0	4.0	4.0	3.6
Supplee-Wills-Jones Dairy Co.	1923	5.2	5.2	5.4	5.2	5.0
Abbotts Dairies, Inc.	1925	5.2	5.2	5.0	5.1	5.1
Guarantee Trust Co.	1924	7.6	....	....	....	....
Chelsea Hotel	....	18	8.6	....	9.5	11
Ambassador Hotel	1919	8.0	6.9	6.8	6.9	6.6
Ritz Carlton Hotel	1925	....	....	....	7.1	....
Shelbourne Hotel, old well	†1900	26	4.2	4.8	3.5	4.9
new well	†1910	22	....	28	11	16
Dennis Hotel	1918	16	14	18	14	34
Marlborough-Blenheim Hotel, old well	....	171	112	96	155	34
new well	1922	94	87	92	118	98
Brighton Hotel	1911	6.8	6.9	5.6	5.8	5.2
Traymore Hotel, old well	1899	9.2	9.1	9.4	9.8	9.6
new well	....	9.5	12	9.2	9.5	9.0
Knickerbocker Hotel	†1900	9.8	10	9.6	10	9.5
Chalfonte Hotel, old well	1900	10	9.5	9.4	11	10
new well	1913	8.1	6.6	8.0	7.2	7.0
Haddon Hall, old well	1896	8.0	6.9	....	8.4	....
new well	1925	12	7.1	3.8	7.1	4.4
Strand Hotel	1910	8.1	8.0	8.0	8.2	7.9
St. Charles Hotel	1896	9.0	8.9	9.0	14	9.2
Breakers Hotel, old well	....	....	8.0	3.1	8.4	7.8
new well	1916	8.0	8.1	8.1	8.4	8.2
Galen Hall	1904	7.8	8.4	8.0	8.4	7.9
American Ice Co.	1927	6.2‡	6.0	5.8	5.5	5.2
President Hotel	1926	6.2	6.2	6.2	6.5	7.2
Claridge Hotel	1930	23	23	22	20	18
Warner Theater	1930	....	....	....	66	....
Flanders Hotel, Ocean City	....	....	....	....	7.6	....
American Ice Co., Ocean City	....	....	....	....	7.2	....
Atlantic City Water Works, well 1	....	....	....	....	....	2.4
Brigantine Water Department, Roosevelt Boulevard	1925	....	....	....	5.2	2.4
14th St.	1929	....	3.5	3.1	....	....
Ventnor Water Department, well 2	†1896	....	5.5	5.8	4.6	5.8
well 3	1896	....	6.4	....	....	....
well 4	....	....	5.4	....	5.4	5.6
well 5	1921	....	5.5	5.4	5.5	6.8
well 6	1923	....	4.9	....	4.9	5.1
well 7	1927	....	4.2	....	4.5	4.2
Ventnor Heights well	1931	....	3.8	....	4.1	3.9
Margate Water Department, well 1	1926	5.9	5.5	5.8	5.6	5.8
well 2	1924	4.5	9.5	5.8	4.9	5.0
well 3	1903	54	22	....	....	....
Ocean City Water Service Co., 10th St. and Bay Ave.	....	....	6.2	6.2	6.4	6.2
Ocean City Water Service Co., 3d St.	....	....	....	....	7.5	....
35th St.	1923	....	....	....	9.4	....
Corsons Inlet Water Company	1906	....	....	14	15	15
Sea Isle City Water Department, well 2	1920	....	....	12	11	13
well 3	....	....	....	....	16	....
well 4	....	....	....	....	16	....
Avalon Water Department, well 1	1898	....	....	....	52	....
well 2	1910	....	....	32	....	76
well 3	1930	....	....	....	36	20
Stone Harbor Water Department, well 2	†1923	....	....	17	17	14
Wildwood Water Department, Pine and Holly Beach Aves.	1894	....	....	214	204	217

* The date of drilling is given as a means of definite identification for the well, as the terms "old well" and "new well" will not necessarily always apply to the same wells.

† Approximate date.

‡ May 22, 1934.

would raise the chloride content of the water from a nearby well to a point where it would be unusable. Contamination of this kind in the Atlantic City region was reported by Thompson (1, pp. 98-102). As the salt water enters the wells above the great clay bed and passes through the clay by way of the well casing, it is essential that a water-tight plug be placed in that part of the casing which passes through the clay bed. A clear understanding of this requirement is a first essential in undertaking to plug a well for the protection of the 800-foot sand. The filling of the well above or below the great clay is of less importance than insuring a good seal in the part of the casing passing through the clay.

Each well presents a special problem, and no definite rules can be laid down for sealing an old well, but certain general observations may be made. The work should be done by an experienced well driller who has the necessary special equipment for it. Before being filled the well should be cleaned out to remove any lost pipe or any other obstructions that might prevent the placing of a tight seal. While the well is being filled careful measurements should be made to be sure that it is thoroughly filled from the bottom and that the material is not being placed loosely or permitted to bridge over some obstruction. Ordinary portland-cement concrete is not a good material for plugging a well, except in the hands of an expert who is equipped to do the work, because its constituents are easily separated by pouring it through water, and it cannot then form a tight seal. However, an experienced and careful well driller with the proper equipment can place a satisfactory concrete plug in a well. The methods of sealing wells with portland-cement concrete or mortar are discussed in detail by Tough (19) in a paper devoted primarily to the problems encountered in oil wells.

The success with which fluid mud has been used to seal the walls of the hole in the jetting and rotary-hydraulic methods of well drilling suggests that it might be possible to obtain a satisfactory seal in an old well by filling the well with clay. If stiff plastic clay were broken into small lumps and poured into a well a little at a time, each batch being packed with a drill bit, a seal could probably be obtained that would be entirely effective in preventing the transmission of salt water through the casing.

If the cone of depression of the pumping from the 800-foot sand in the Atlantic City region is approximately symmetrical in both landward and oceanward directions, it is probable that the head at the original zone of contact between fresh and salt water has been lowered several feet, at least, causing the salt water to move toward the pumped wells. Its rate of movement would be governed mainly by the rate of pumping from the sand, and unless it happened to reach some channel of highly permeable sand, the salt water could not arrive at Atlantic City until a considerable part of the fresh water that originally lay between Atlantic City and the zone of contact had been pumped out. The head of the water in the 800-foot sand has been lowered considerably all the way from a point some distance north of Brigantine to some point south of Wildwood. Fresh water from the intake area would normally circulate around the region and enter the wells from the direction of the ocean, but this long belt of lowered head probably tends to prevent it from doing so. It seems probable, therefore, that a considerable amount of the fresh water that originally lay in the 800-foot sand between the Atlantic City region and the zone of contact between fresh and salt water has been withdrawn through the wells in the region.

The conclusion arrived at from the facts and reasoning set forth above is that salt water is probably moving toward the wells that draw from the 800-foot sand in the Atlantic City region. Its arrival will probably be hastened by an increased rate of pumping or delayed by decreased pumpage. It is therefore suggested that the owners and operators of all wells tapping this sand cooperate to keep the rate of pumping from it as low as possible.

Furthermore, definite plans for the future water supply of the region as a whole should be made, giving particular attention to the possibility that it may be necessary to substitute water from other sources for that now taken from the 800-foot sand if the supply from this sand should be contaminated with salt water. The loss of the supply from the 800-foot sand would affect all the beach-front communities. The provision of a source of supply to replace the water from this sand would therefore seem to be a problem that is peculiarly suitable for regional cooperation. Thompson (1, p. 27) suggested some form of water supply district for this purpose and pointed out that it might be so organized that it would not place any restrictions upon the autonomy of the individual municipalities except in matters relating to water supply. Some kind of regional cooperation seems desirable for the solution of this problem, but the form which it might take and the source of water supply to be developed are matters for the officials of the various municipalities to decide after considering the advice of competent legal and engineering authorities.

METHODS OF DRILLING TEST WELLS

Test wells are always desirable and often essential in an intensive ground-water study of any type. Unfortunately, in many areas where ground-water investigations are to be made, test wells are so expensive, owing to adverse drilling conditions, that their use is prohibited. It has been the good fortune of those making ground-water studies in certain parts of New Jersey to encounter favorable conditions, under which test wells could be drilled economically.

The test-well drilling procedure in New Jersey was developed as it was needed. Several types of wells have been used for different purposes. For observations of water level where the water table was shallow—generally not more than 25 feet deep—use has been made of dug wells, driven-well points, and an auger hole cased with sheet metal, which will be referred to in this report as a "stovepipe well," because its casing resembles ordinary stovepipe. This type of well should not be confused with the so-called "California stovepipe well," which is usually much larger, deeper, and of heavier metal than anything considered in this section. For observations of water level and water sampling at greater depths, driven wells, wells drilled by churn tools, and small-diameter wells drilled by a modification of the jetting method have been used. Most of these types of wells have been used in the Atlantic City region.

The test-well drilling in the Atlantic City region was undertaken for the primary purpose of studying the problem of intrusion of salt water into the 100-foot sand around the Atlantic City Water Department's well field. This problem is discussed in a previous section of the report (pp. 52-78) and will not be discussed further here except for its bearing on the methods of drilling used. A few shallow stovepipe test wells have been bored in this locality to get measurements of water level. Several test wells have also been drilled to the 200-foot sand, for combined studies of salinity, geology, and water level.

In choosing the type of test wells to be used in the salinity studies several factors had to be considered. It was primarily necessary that truly representative samples of water be obtained from the well while it was being drilled through different parts of the formation. After considering all type of wells, it was decided that the driven-point well or the open-end well put down with churn tools would be the only types that would satisfy this requirement. The jetting or mud-seal process would have been very satisfactory for sinking wells in this region, but it could not be used because of the contamination of the water in the formation with that used in jetting, which would, of course, change the chloride content of the samples. Another determining factor in the selection of the method of drilling was the physical character of the surface of the area in which the wells were to be drilled. Most of the wells were located in a tidal marsh. If heavy well-drilling machinery had been used it would have been necessary to build roads or runways to the sites of the wells, which would have been too expensive for this investigation.

Some type of power equipment was considered essential for drilling test wells to the 100-foot sand. The high cost, large size, and great weight of a regular well-drilling rig eliminated it from consideration. The trailer-type rig shown in figure 23 was built for this work and has proved highly satisfactory. The running gear was made of the rear-wheel assembly of an old model T Ford automobile, including the universal joint. A rectangular frame 7 feet 10 inches by 3 feet 7 inches, with four cross members, was made of 4 by 4 inch wooden material and fastened to the running gear with U-bolts. The engine and hoisting

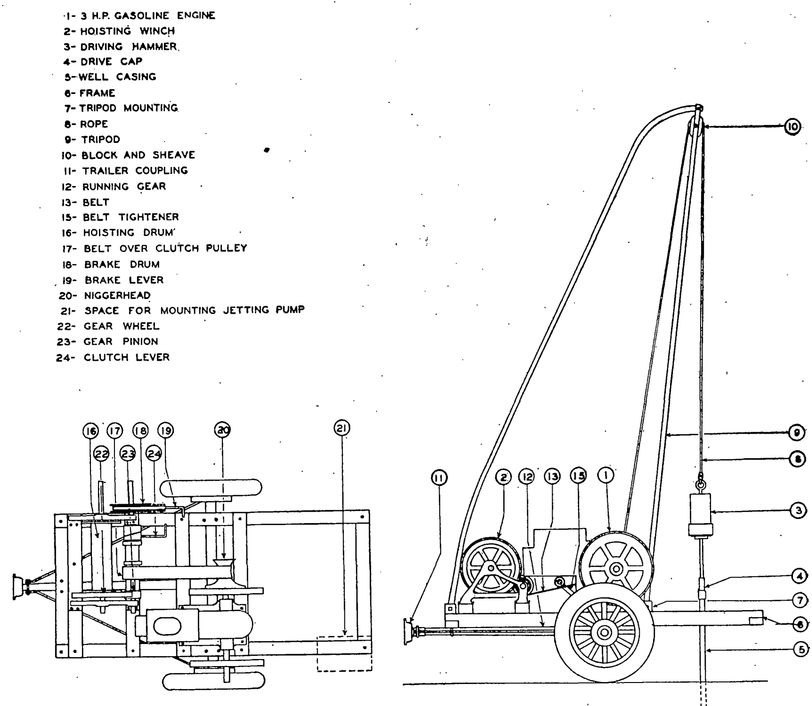

FIGURE 23.—Light drilling rig developed for the Atlantic City test-well drilling program.

winch were mounted on this framework. To serve as a derrick, a tripod 12 feet high was made of 1¼-inch pipe and bolted to the frame by means of angle-iron mountings. This tripod was made so that it could be easily dismounted and folded up, if necessary, when moving the rig. Space was provided on the rear of the framework for the installation of a jetting pump in case it should be needed in the future.

This rig was capable of handling fairly heavy tools if an independent derrick were used. However, lighter tools than those used with a standard well-drilling rig seemed more adaptable to it, and several special tools were designed. A hammer for driving 1¼-inch well points was made of a 1-foot piece of 6-inch pipe with a coupling and a malleable plug or cap attached. A ¾-inch guide rod, 4 feet long, with a ring at the top, was inserted through a hole in the cap, and the 6-inch pipe was filled with melted lead until the total weight of the hammer was 165 pounds. A light drilling tool was made up of 2-inch pipe 10 feet long with a ring in one end and a bit on the other. Standard drive clamps were used on this tool for driving casing. Special light sand buckets of standard design were made for use with this rig.

The trailer was attached to the automobile by means of the universal joint. One-half of the socket was bolted to the automobile, and the other half remained around the ball of the universal joint on the trailer. The trailer was very easily attached to or detached from the automobile by bolting or unbolting the two sockets over the ball of the universal joint. Where the ground conditions were such that the rig could not be pulled to a well site with the automobile, it was detached and pushed by hand, planks being used for a runway. This could be done easily by two or three men.

After the well rig was built, some experimental work was done in driving well points and in drilling with the sand bucket and other churn tools. At first it was considered doubtful whether well points could be driven as deep as 100 feet. The first plan was to use the driven-point wells in collecting samples in the sands above the clay bed that overlies the 100-foot sand, and to use 4½-inch wells sunk with churn tools in exploring the 100-foot sand. No difficulty was experienced in driving the first 1¼-inch driven point well (T-1) to a depth of 78½ feet by using extra heavy welded steel pipe. So successful was this well that several others of the same type were driven before a 4½-inch well was drilled.

Some interesting comparisons can be made between the 1¼-inch driven-point well and the 4½-inch well drilled with churn tools. The driven-point well was far superior for collecting samples of water for chloride determinations, because the water in the casing could be pumped out readily, and it was thus definitely known that the sample collected was representative of the water in that portion of the formation in which the well point was located. In pumping samples of water from the 4½-inch well several difficulties were encountered. The casing was large and held a considerable amount of water, so that it was necessary to pump much water to be sure that the sample was a true sample of the water entering the well at the bottom of the casing. On several occasions difficulty was experienced in collecting samples because the sand rose in the casing while the well was being pumped. Thin clay lenses also caused much trouble by sealing the bottom of the well so that no water could be pumped. The time required for drilling the 4½-inch well was about 8 days, whereas the time required to drive a 1¼-inch well ranged from 1 to 3 days, depending on its location. The 4½-inch well had the advantage that samples of the materials encountered during the process of drilling could be obtained from it. However, by using a rather coarse screen on the well point of the 1¼-inch driven well, considerable knowledge of the formation could be gained by observing the material that was pumped through the screen. Furthermore, a very good idea of the materials through which the point passes can be formed by the way the point drives and the rate at which it yields water when in sand. The 4½-inch or larger test wells also have the advantage that they can be equipped with water-stage recorders for observations of water level, whereas the 1¼-inch test wells are adapted only to tape measurements. The cost per foot of drilling the 4½-inch well was considerably greater than that of the 1¼-inch driven-point well.

Driving the 1¼-inch test wells was rather simple. The rig was set up over the site of the well, and a 2-foot well point was securely coupled to a 5-foot piece of extra heavy 1¼-inch pipe. A drive cap made of a 3-inch piece of extra heavy 1¼-inch pipe and a coupling was placed on the other end of the pipe. The well was started by sinking the point a foot or more by hand. The driving hammer was then hoisted with the engine, and the guide rod was inserted through the drive cap into the casing. The pipe was then driven down by repeated blows with the hammer until the top was about 3 inches above the ground. The hoisting and dropping of the hammer was accomplished by varying the tension on a rope around the concave slip pulley or "niggerhead" on the engine. When one length of pipe was driven, the drive cap was removed and placed on a new section of pipe. The new section of pipe was then securely coupled to the driven section of pipe and the driving operation repeated. Attempts were made to pump samples with a pitcher pump at intervals of depth ranging from 2 to 4 feet. If the screen was in sand, a sample was collected. If it was in clay, no water could be pumped, and the driving was continued until the screen reached a formation from which a sample could be obtained.

Drilling a well 4½ inches or more in diameter with churn tools was more complicated. In sand the procedure was to sink the casing by removing the sand below it with a sand bucket and allowing it to settle by its own weight. When the casing stuck it was loosened by turning. When clay or other solid material was encountered, the hole was drilled with chopping bits, and the casing was driven through the material by hitting a coupling on the top of it with drive clamps. In drilling through clay the casing was turned to keep it as loose as possible. This allowed the casing to settle freely after sand was again encountered, and the sand-bucket procedure was resumed. The exact procedure used in drilling by the churn tool method varies from well to well. Deep wells of this type require considerable experience in drilling and standard well-drilling equipment.

Several test wells were drilled to the Atlantic City Water Works 200-foot sand by the jetting method. These wells were drilled with a small portable well rig mounted on a 1½-ton truck. Some of them had a diameter at the top of 4½ inches, some 2 inches, and some 1¼ inches. All had 1¼-inch screens at the bottom. The method of drilling these wells consisted of jetting down a wash line of 1-inch pipe equipped with a bit to shape the hole, using enough clay in the jetting water to make the side wall of the well firm, so that the hole would remain open. The hole was drilled without casing to the desired depth, and the casing was inserted after the hole was completed. This is a very cheap, quick, and satisfactory method of drilling a test well for observations of water level, and is fairly satisfactory for determining the nature of the materials encountered in the drilling. However, the samples are washed by the jetting water, and the gradation of the sample collected is undoubtedly considerably different from that of the material encountered, because of the tendency of the smaller particles of the formation to rise to the surface with the drilling fluid, ahead of the coarser material.

For collecting water samples as a basis for a vertical profile of the chloride content of the water in the formation this method is not satisfactory.

The stovepipe test well, which is cased with sections of galvanized sheet metal bolted together, has been used extensively for ground-water studies in this State. The simple tools with which it is drilled make it a very advantageous type of well where the water table is within 25 feet of the ground surface and the location of the test well is not easily accessible with drilling machinery. The stovepipe well is suitable for both tape measurements and installation of a water-stage recorder. It has the disadvantage that the casing of the well is so light that it is easily bent, either during the process of drilling or after the well is completed.

The drilling of a stovepipe test well is rather simple. A hole about an inch larger in diameter than the metal casing is first bored to the water table with an auger. As a rule the auger cannot be used below the water table in a water-bearing sand, because the sides of the hole cave. When the water table is reached, the casing is inserted and is lowered further by use of a hand-operated sand bucket. Only a few wells of this type have been used in the Atlantic City region, but several have been used elsewhere in the State.

Ordinary dug wells have not been used in the Atlantic City studies. In the Runyon region they have been used for ground-water studies for several years. In one of these wells water-table fluctuations have been observed with a water-stage recorder for 12 years (20, pp. 467-471). Also a large number of existing dug wells have been used in this region for tape measurements of water level.

In the course of the ground-water studies in New Jersey 81 test wells have been drilled. The number and approximate depths of each type of well used are given in table 6.

The location of each of the test wells used in the study of salt-water intrusion is shown on figure 13. The depth of each well and the chloride content of each sample of water pumped during its construction are given in table 3. Graphic logs of six representative test wells, toegther with a graphic presentation of the chloride content of the water at different depths in them, are shown in figure 14. Other comments on these test wells are given in the section on salt-water intrusion into the 100-foot sand. (See pp. 52-70.)

TABLE 6.—TEST WELLS DRILLED FOR GROUND-WATER STUDIES IN NEW JERSEY

Type of well	Depth (feet)	Number of wells		
		Atlantic City	Runyon	Camden
Driven-well point	5-35	[a]3	23	
	65-92	[a]19		
Cased well drilled with churn tools	Less than 50		3	
	50-100	[a]1	1	
	100-160		1	1
Cased well drilled by the jetting method	Less than 65	4		
	170-196	5		
Stovepipe well	Less than 25	5	14	
Dug well	11		1	

[a] Wells drilled especially for the study of salt-water intrusion at the Atlantic City Water Works.

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