New Jersey. State Water Policy Commission

The ground-water supplies of Middlesex County, New Jersey

1943.

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STATE OF NEW JERSEY

# STATE WATER POLICY COMMISSION

## SPECIAL REPORT 8

# THE GROUND-WATER SUPPLIES OF MIDDLESEX COUNTY, NEW JERSEY

Prepared in cooperation with the United States Department of the Interior, Geological Survey

1943

State of New Jersey

State Water Policy Commission

Howard T. Critchlow, Engineer in Charge

# The Ground-Water Supplies of Middlesex County New Jersey

With Special Reference to the Part of the Coastal Plain Northeast of Jamesburg



*By*

Henry C. Barksdale

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Roger C. Baker

Edward J. Schaefer

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*Prepared in cooperation with the*

*United States Department of the Interior,*

*Geological Survey*

New Jersey State Water Policy Commission

28 West State Street, Trenton, N. J.

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| George S. Burgess, *Chairman* | Madison |
| Thurlow C. Nelson | Highland Park |
| Herbert K. Salmon | Stanhope |
| Forster W. Freeman | Paterson |
| Ernest J. Howe | South Orange |

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John Wyack, *Secretary*

Howard T. Critchlow, *Chief Engineer*

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## LETTER OF TRANSMITTAL

*Mr. George S. Burgess, Chairman*
*State Water Policy Commission*

DEAR SIR:

I am transmitting herewith a report on ground-water supplies of Middlesex County, N. J., prepared by Henry C. Barksdale, Hydraulic Engineer, U. S. Geological Survey. The report contains the information which has been assembled on ground-water conditions in that portion of Middlesex County adjacent to Raritan Bay and extending up the valleys of Lawrence Brook and South River. It discusses the public water supplies and many of the private supplies which are derived from the ground-water horizons designated in the report as Farrington (No. 1) sand and Old Bridge (No. 3) sand. Special Report No. 7 published in 1937 was a preliminary report on the water supplies from the No. 1 sand in the vicinity of Parlin.

The report points out the danger to the water supplies in this area from salt water intrusion and emphasizes the importance of reducing the draft on the No. 1 sand in order to avoid further pollution. It warns against further development in the No. 3 sand, the safe yield of which has been reached in this area. It is important that the municipalities and other public agencies be acquainted with this situation in order that the valuable ground water resources in this area may not be ruined by overdraft.

I therefore recommend that this report on ground-water supplies of Middlesex County be published as a special report of the Commission in order that the information contained therein may be made available to the people of the State.

Respectfully submitted,

H. T. CRITCHLOW,
*Engineer in Charge.*

June 11, 1943.

# ABSTRACT

Ground-water investigations have been carried on in parts of Middlesex County since 1923. This report is based upon detailed observations of ground-water conditions in that part of the coastal plain between Jamesburg and Perth Amboy, and upon a generalized survey of ground-water conditions in the remainder of the county. It deals primarily with the factors affecting the safe yield of the more important aquifers in the county.

Roughly the northwestern third of the county is underlain by rocks of the Newark group of Triassic age and the southeastern two-thirds by sands and clays of the coastal plain, which are of Cretaceous age and are largely unconsolidated. The rocks of the Newark group dip toward the northwest, but they are so badly fractured that the dip is of very little significance from a hydrologic standpoint. Intruded into the rocks of the Newark group is a diabase dike, that is of no importance as a water-bearing formation, but stood as a ridge on the surface upon which the Cretaceous deposits were laid down. Hence the lowest of the Cretaceous sands (the Farrington sand member of the Raritan formation) is almost divided into two parts by it. To a considerable extent this ridge has been effective in retarding the advance of salt water into this sand from the estuary of the Raritan River. The beds of the coastal plain formations dip to the southeast, and alternating layers of permeable sands and relatively impermeable clays provide a setting under which water supplies are frequently encountered under artesian conditions. Both the Cretaceous formations and the older rocks of the Newark group are overlain throughout much of the county by various Quaternary deposits. These latter deposits are relatively unimportant as water-bearing formations. Their principal importance lies in their ability to absorb water and transmit it to the underlying materials, or in a few places to prevent the absorption of water by the underlying bed.

Early developments of ground water in the county were primarily in the form of relatively shallow dug wells, and in the improvement of existing springs. Drilled wells similar to those generally in use today were not developed to any considerable extent until the end of the last century. The development of large supplies of ground water has depended to a considerable extent upon the development of well drilling methods and upon the improvement of well pumping machinery. In 1941 more than 37 million gallons of water a day was pumped from wells for industrial and municipal water supplies in Middlesex County. Of this amount about 22 million gallons a day was used exclusively for industrial purposes and the remainder for public water supplies.

The quality of water obtained from wells in Middlesex County is generally satisfactory for all ordinary purposes. It sometimes requires treatment for the removal of iron or for the reduction of hardness. In some areas the ground waters have been contaminated by sea water that has been drawn into the aquifers by heavy pumping. Where this contamination has been severe, the waters are of little value except for cooling.

In the course of these investigations records of water levels have been obtained in a great many wells. Some of these records now cover a period of more than twenty years. Included in this group are some wells not affected by pumping that have been used as a standard for comparison with the fluctuations in the other observation wells. They have also proved valuable as indices of the amount of water naturally stored in the ground at various times. As such they are useful outside the scope of this report for the prediction of minimum stream flow and for similar purposes. At the Perth Amboy Water Works, at Runyon, a record of precipitation, temperature and evaporation has been obtained for approximately 20 years.

Of the various aquifers within the county three are of major importance. The rocks of the Newark group are the principal source of ground water in the northwestern part of the county. The Old Bridge and Farrington sands, both members of the Raritan formation, are the principal sources of water supply in the southeastern two-thirds of the county. The other aquifers are of relatively little importance either because of the limited area in which they are available or because they are not capable of yielding substantial supplies.

The Old Bridge sand is the most important aquifer within the county. It supplies more than half the total water used for industrial and public water supplies. In 1941 a total of more than 19 million gallons a day was withdrawn from this sand in Middlesex County and 2 or 3 million gallons a day was taken from wells tapping this sand outside the county, bringing the total yield to 21 or 22 million gallons daily. In 1942 the total pumpage had increased to 25 or 26 million gallons daily. Studies made of this sand indicate that natural recharge probably could not supply this large yield of water. Fortunately, however, at least two major developments include works for artificially recharging this sand. Even so, it is believed that the safe yield of this sand has been reached. The pumpage from this sand should not be increased except in instances where it is possible and desirable to recharge the sand with surface water in an amount essentially equivalent to the additional water to be taken from wells.

The Farrington sand yielded about 8.5 million gallons daily to municipal and industrial wells during 1941. The safe yield of this sand appears to have been exceeded for a considerable period in the past. Its capacity is limited not by the amount of natural recharge or by its ability to transmit water, but rather by the fact that it is exposed in numerous localities to the intrusion of salt water from surface sources. A considerable part of this sand now contains water that is contaminated by salt water. In at least three areas the water in this sand is severely contaminated. There is substantial evidence supporting the belief that the areas of contamination will expand with continued pumping from the wells tapping this sand. A few wells that drew from this sand have already been abandoned because of salt-water contamination, and it seems probable that a considerable number of others will have to be abandoned at some time in the future. After this has occurred and the total pumpage from the sand has thereby been reduced materially, it may be possible to develop some new water supplies from this sand in areas near its intake area and remote from bodies of surface water containing salt.

The rocks of the Newark group yield water to a large number of wells in the county. In localities where they are covered by permeable material they yield substantial quantities. In areas where they are not covered by such deposits

or where they are covered by impermeable materials, the yield is very low. The water that these rocks yield comes almost entirely from cracks which form a small part of their total volume so that their storage capacity is low. Substantial yields are safely obtained only in areas where the overlying material is capable of absorbing and storing considerable amounts of water and of transmitting it freely to the underlying rock.

It seems probable that no more large ground-water developments can be made within Middlesex County. Possibly some additional water may be obtained from the Newark group, but this should not be attempted without a careful study of conditions in the vicinity of any proposed development, because draft on these rocks is already heavy. Some additional water can be developed from the Englishtown sand in the southeastern corner of the county, but care should be exercised not to injure water supplies derived from this sand down the dip in Monmouth County. On the whole it seems probable that any large additional supplies of water for Middlesex County will have to come from surface water, and very possibly from sources outside the county. The appraisal of sources of surface water is, however, outside the scope of this report.

Future studies of the Old Bridge sand should be directed primarily toward ways of increasing its intake capacity by artificial recharge. Those of the Farrington sand should be concerned primarily with the salt-water instrusion in this sand. Intensive quantitative studies should be made of the Newark group in order to estimate more accurately its safe yield in different localities. Measurements should be continued at the evaporation station at Runyon and in the Morrell and other water-table wells. A few additional observation wells should be established in parts of the county where there is no effect of pumping.

# INTRODUCTION

*Cooperation and personnel.*—This report is one of a series[1] of reports on the ground-water resources of New Jersey that are being prepared in cooperation with the Geological Survey, United States Department of the Interior. The location of the area covered by this report and other areas in which studies are being made, are shown on Figure 1. This is the seventh report in the series, but the first to cover an entire county. Many of the best aquifers in New Jersey extend over several counties. In the final analysis, the safe yield of the whole formation and not of any part of it is the important thing to be considered. This would require a complete and detailed coverage of the whole area in which the aquifer occurs. The study of the area on a county-wide basis is a convenient way of achieving this coverage.

The investigations that have preceded this report have, for the most part, been conducted in cooperation with the Geological Survey, although they were carried on by the State alone for a part of the time. From the beginning of the work in July, 1923, to June, 1927, it was carried on cooperatively by the Geological Survey and the New Jersey Department of Conservation and Development. From July, 1927, to June, 1931, the work was carried on by the State alone, at first by the Department of Conservation and Development and later by the State Water Policy Commission, to which matters pertaining to water supply were transferred by an Act of the Legislature in 1929. Cooperation with the Geological Survey was resumed by the State Water Policy Commission in July, 1931, and has been maintained since that time.

H. T. Critchlow, engineer in charge, New Jersey State Water Policy Commission and formerly chief of the Division of Waters, New Jersey Department of Conservation and Development, and O. E. Meinzer,

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[1] Reports previously issued:

Thompson, D. G., Ground-water supplies of the Atlantic City region: N. J. Dept. Cons. and Devel. Bull. 30, 1928.

Thompson, D. G., Ground-water supplies in the vicinity of Asbury Park: N. J. Dept. Cons. and Devel. Bull. 35, 1930.

Thompson, D. G., Ground-water supplies of the Camden area: N. J. Dept. Cons. and Devel. Bull. 39, 1932.

Thompson, D. G., Ground-water supplies of the Passaic River Valley near Chatham, N. J.: N. J. Dept. Cons. and Devel. Bull. 38, 1932.

Barksdale, H. C., Sundstrom, R. W. and Brunstein, M. S., Supplementary report on the ground-water supplies of the Atlantic City region: N. J. State Water Policy Comm., Special Report 6, 1936.

Barksdale, H. C., Water supplies from the No. 1 Sand in the vicinity of Parlin, N. J.: N. J. State Water Policy Comm., Special Report 7, 1937.

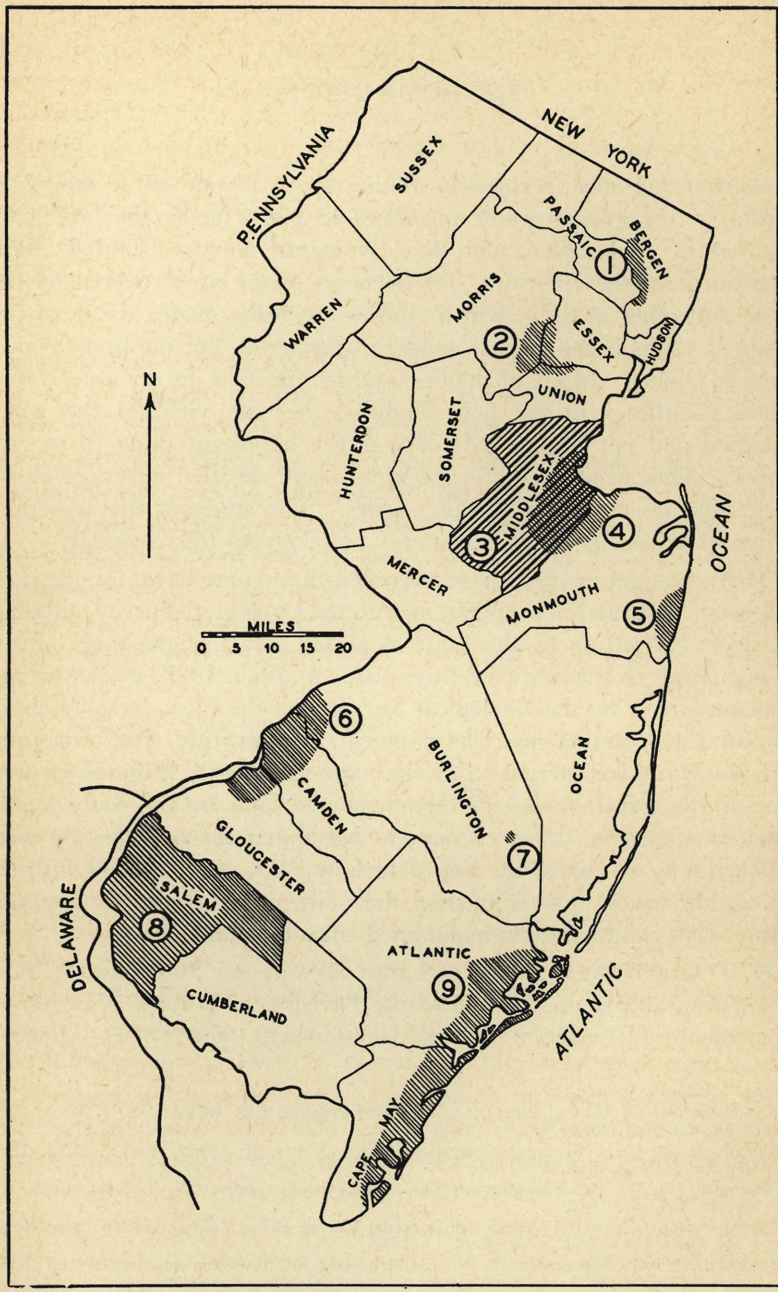


FIGURE 1.—Map of New Jersey showing county boundaries and, by shading, the areas in which ground-water conditions are being studied.

Numbers on the map refer to the areas as follows: 1. East Paterson area; 2. Canoe Brook area; 3. Middlesex County; 4. Parlin area; 5. Asbury Park area; 6. Camden area; 7. Southern Interior; 8. Salem County; 9. Atlantic City area.

geologist in charge, Division of Ground Water, of the Geological Survey, have exercised general supervision of the work since its beginning. From 1923 to 1927 the work was in charge of David G. Thompson of the Geological Survey who was assisted at different times by Henry C. Barksdale, and Ernest W. Downs, both of the Geological Survey. From 1927 to date the work has been in charge of Mr. Barksdale, who was assisted at various times since 1931 by Raymond W. Sundstrom, Roger C. Baker, Edward J. Schaefer, George D. DeBuchananne, and Jerome M. Ludlow, all of the Geological Survey.

*Authorship.*—The preparation of different sections of this report was assigned to different individuals, but each of the authors has been helped by consultation with the others. Most of the report was written by Mr. Barksdale. The outline of geology and the geologic descriptions of the different formations were written jointly by Meredith E. Johnson, State Geologist, and Roger C. Baker of the Geological Survey. The section on the well and pumpage inventory and most of the discussions of development and pumpage of the principal aquifers were written by Edward J. Schaefer. The sections on precipitation and evaporation and on the fluctuations of the water table were written by George D. DeBuchananne.

*Acknowledgments.*—Ground-water investigations are necessarily closely related to the geology of the area studied. During the early years of the investigation, the Department of Conservation and Development, of which Dr. H. B. Kümmel, then the State Geologist, was the director, was primarily interested in the work and a geologist from the Geological Survey was in charge of it. For some time after the work was transferred to the State Water Policy Commission, it was carried on by engineering personnel, and the advice of Dr. Kümmel and of his successor, Meredith E. Johnson, was frequently sought and freely given. The fact that it was possible to carry on the investigations for approximately nine years without the assistance of a geologist assigned directly to the project, is ample evidence of the effectiveness of this generous and informal cooperation. Evidence of its substantial nature may be found in the fact that the senior author of the geologic section of this report is the State Geologist. This assistance is gratefully acknowledged.

The authors gratefully acknowledge the assistance of numerous individuals, municipalities and industrial companies, that have assisted in one way or another in the preparation of this report and in the investigation that preceded it. The late David G. Thompson not only began the first studies at Runyon but also gave helpful advice on many

details of the investigation since that time and on the preparation of the report as well. John N. Brooks, assistant division engineer of the State Water Policy Commission, has also given valuable advice and assistance on numerous phases of the work. W. D. Collins, chemist in charge of the Quality of Water Division, and O. W. Hartwell, District Engineer of the Surface Water Division, both of the Geological Survey, have been helpful in many ways. Jerome M. Ludlow, assistant engineering aid of the Geological Survey, drew most of the diagrams for the report. H. L. Dieker, chief engineer at the Perth Amboy Water Works, and his son, E. V. Dieker, have assisted greatly in the investigation that preceded this report, and have given the authors much information about the ground-water conditions in the county and about the history of the early ground-water developments therein. Gordon E. Linn, of the E. I. duPont de Nemours & Co. at Parlin, now in charge of the Duhernal water supply, furnished much information and assistance during the course of the investigation. The authors are also indebted to George R. Shanklin, senior hydraulic engineer and J. C. Merrill, senior engineering draftsman, both of the State Water Policy Commission; John J. Reager, superintendent of the Perth Amboy Water Department; E. L. Thoenges, of the Hercules Powder Company; A. L. Burke, of the duPont Company; George B. Coale, of the National Lead Company; Robert C. Austin; John H. Poulsen; John Lemke; and to many other individuals for advice and assistance.

*Area described.*—Middlesex County lies in the east-central part of New Jersey between latitudes 40°15′ and 40°37′ and longitudes 74°13′ and 74°38′. The easternmost part of the county lies along the south shore of Raritan Bay. It lies on both sides of the Raritan River as far west as New Brunswick and on the north side of the river almost to Bound Brook. The area of the county is 312 square miles.

The population of Middlesex County according to the census of 1940 was 217,077. Of the 21 counties in the State, Middlesex is the 7th in population and the 12th in area. Its density of population is approximately 695 persons per square mile. About nine-tenths of the population of the county is concentrated along the Raritan River or north of it. In this area the density of population is more than twice that of the county as a whole, and it is here that the problems of additional water supplies, both municipal and industrial, are most acute.

The favorable location of the northern half of the county with respect to tide-water and its proximity to the metropolitan area surrounding New York City, has produced a steady growth of population and industry there. This growth was most rapid during the period from 1900 to 1920 when the population of the county more than doubled. There are now four cities and two townships in the county with populations of more than 10,000 and six other cities and one township having more than 5,000 inhabitants. All of these are in the northern part of the county. The largest cities are Perth Amboy with a population of 41,242 and New Brunswick with 33,180 inhabitants in 1940.

The county is the seat of many industries, most of which are concentrated near the Raritan River or north of it. This is due in large part to the exceptional transportation facilities available, which include three of the main railroad lines converging upon the New York City area and many miles of sheltered coast line accessible to ocean-going vessels. Many of the industries concentrated along the waterfront have developed their own water supplies from wells, and heavy pumping combined with repeated deepening and maintenance of the waterways has produced serious contamination of some of the aquifers by salt water. A wide variety of products are manufactured within the county. Some of the more important industries are the smelting and refining of copper, the manufacture of chemicals and of brick, tile and terra cotta, and the refining of petroleum. In the case of the ceramic industries the principal raw material, clay, is mined within the county.

The southern half of the county is devoted largely to agriculture. Favorable soil and climatic conditions and easily accessible markets have encouraged truck gardening, dairy farming and poultry raising. There are many highly specialized farms, some of which have been commercialized and are very large. One such is devoted entirely to the production of certified raw milk. Others combine dairying with general or truck farming. The very large farms are, however, the exception and most of the area is occupied by ordinary farms some of which are specialized although the majority are used for general farming. Almost without exception the farmers draw their water supplies from underground sources. On a few farms ground water is pumped for the irrigation of special crops, but this practice is exceptional and the total withdrawal of ground water for this purpose is not large.

The township and municipal boundaries within the county are shown on the map in Figure 2. This map also shows the names of the various places mentioned in the text and the principal water courses. The locations of some of the more important wells and well fields are also shown, especially the ones that are not shown on any of the more detailed maps.

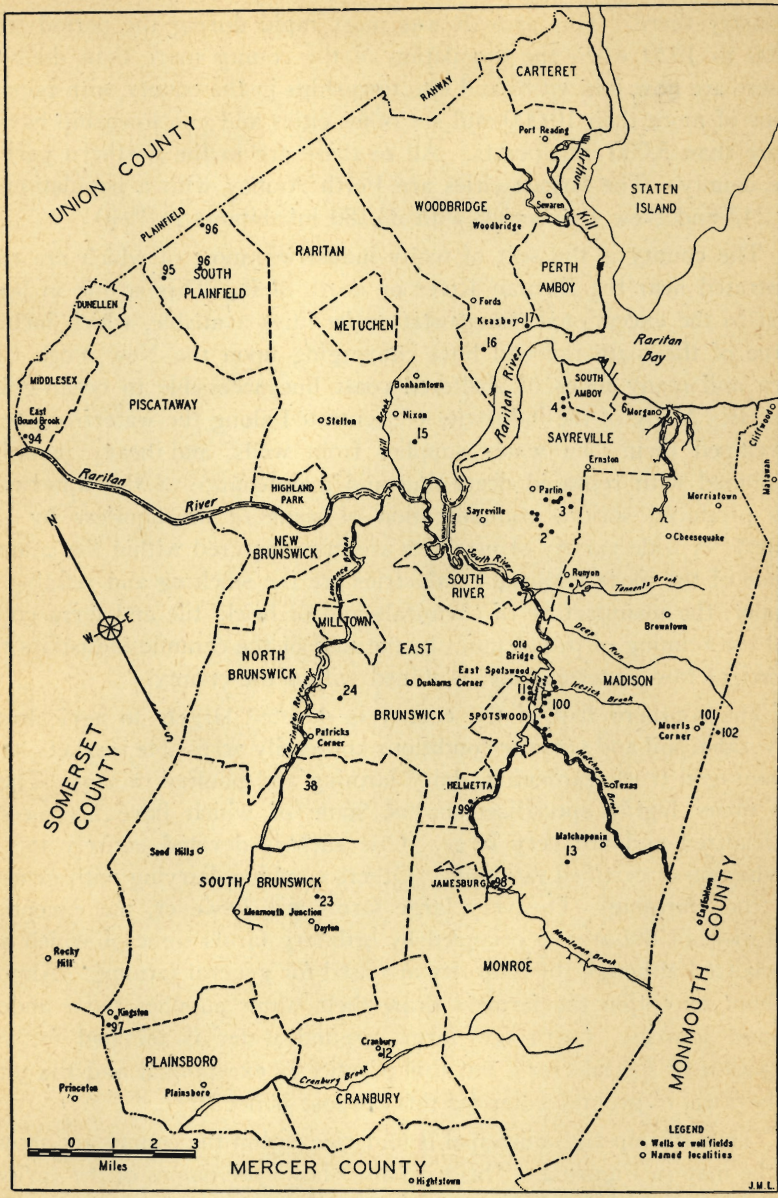


FIGURE 2.—Map of Middlesex County, showing municipal boundaries, the location of important wells or well fields, and places referred to in the text.

KEY TO WELL NUMBERS (Figure 2)

1. Perth Amboy Water Department
2. Hercules Powder Company
3. E. I. duPont deNemours & Co.
4. National Lead Company
6. South Amboy Water Department
7. South River Water Department
11. Peter J. Schweitzer Company
12. Cranbury Water Company
13. State Home for Boys
23. Kufka test well
24. Fischer test well
38. Beecher test well
94. Elizabethtown Water Company, Piscataway well field
95. Plainfield-Union Water Company, Clinton Avenue wells
96. Middlesex Water Company well fields
97. Kingston Water Company
98. Jamesburg Water Company
99. Helmetta Water Company
100. Duhernal water supply
101. Morrell well
102. Hulsart well

*Scope of report.*—This report is based upon detailed observations of ground-water conditions which were begun at the Perth Amboy Water Works at Runyon in 1923, and have been gradually expanded to cover much of the industrial area along the estuary of the Raritan River, and upon a more generalized survey of ground-water conditions in the remainder of the county which has been carried out mainly during 1941 and 1942. Detailed field studies have been made of the geology and hydrology of the part of the county that lies in the coastal plain northeast of Jamesburg. It is in this area that most of the ground-water development in the county has taken place, and the major part of the report deals with the conditions there. For the remainder of the county, the report is more generalized.

The quality of the ground water of the area is discussed briefly in a section of the report devoted to that topic. Samples of water have been collected from representative wells tapping each of the more important aquifers and have been analyzed for their mineral content in the Water Resources Laboratory of the Geological Survey. The results of these analyses are included in tabular form. No attempt is made to determine the sanitary or bacteriological quality of the water as these features are usually not due to conditions inherent in the aquifer but to extraneous causes or to the treatment of the water after it has been pumped to the surface.

During the investigation on which this report is based much information on water levels and artesian pressure was collected. Many thousands of individual measurements of water level or artesian pressure were made and continuous records of water levels were obtained by means of automatic water-stage recorders at one time or another in about thirty wells. Most of these records have been published by the Geological Survey in its annual reports on water levels and artesian pressure.[1] The remaining records will be published in forthcoming

[1] Meinzer, O. E., Wenzel, L. K., and others, Water levels and artesian pressure in observation wells in the United States: U. S. Geol. Survey Water-Supply Papers 777, 817, 840, 845, 886, 906, 936, etc. (Annual volumes since 1935.)

volumes of the same series. For this reason, water-level records are presented in this report mainly in graphical form and only when they serve to clarify the points under consideration.

## HISTORY OF GROUND-WATER DEVELOPMENT

### Public Water Supplies

The first ground-water supplies to be developed in Middlesex County were undoubtedly obtained from springs and shallow dug wells for domestic use. In fact it is probable that this was the principal form of ground-water development for about 200 years after the settlement of the county by the white men in 1666. The first form of public water supply was probably the town or public well. For example, funds were appropriated for the digging of public wells in Perth Amboy in 1774. Some of these wells were reported to be still in existence in 1856.[2] It is very likely that similar public wells furnished a part of the supply for other towns, although some may have depended entirely upon surface water or springs.

The water supply of Perth Amboy appears to have been drawn from dug wells or springs within the city until about 1881, when a water company was organized to supply surface water from a small stream within the present city limits. In 1890 the city purchased this supply and in 1891 it established its Runyon pumping station to deliver surface water from Tennent Brook. In 1897 the first wells at this station were drilled to the Farrington sand which then contained water under artesian head, so that it was not necessary to pump the water from the wells. As the demand increased additional wells were drilled, but the increased draft resulted in a lower head and it finally became necessary to pump from the wells. The high iron content of the water from the Farrington sand caused some complaint, and when pumping became necessary it was decided to seek a supply from the shallow non-artesian sands in the vicinity of the pumping station in the hope of improving the quality of the supply. In 1902 the first wells drawing from the Old Bridge sand were drilled and this sand has since become the principal source of water supply for the City of Perth Amboy.

The early settlers at New Brunswick also appear to have obtained some of their water supply from springs and shallow dug wells, although it is probable that some of it came from the Raritan River, which was then relatively pure and, due to the wooded nature of its watershed, probably carried much less sediment than at present. In 1801 a com-

[2] Whitehead, Wm. A., History of Perth Amboy, 1856.

pany was organized in New Brunswick to supply spring water to a part of the city through a system of wooden pipes.[3] This venture was abandoned after a relatively short time, and thereafter the town's water supply was obtained mainly from wells within the city until a supply of surface water was developed from Lawrence Brook in 1867. In 1941 an average of 6.6 million gallons daily was drawn from Lawrence Brook to supply New Brunswick, Highland Park and some adjacent territory.

The history of the water supplies of the other municipalities in the county is similar to that of Perth Amboy and New Brunswick. The demand for public water supplies other than the town well and its pump has sprung up very largely within the last half a century. Prior to that time most of the population of the county was rural and the small urban centers derived their water supplies principally from springs and shallow dug wells. Much of the northern part of the county is now supplied by the Middlesex Water Company, which began operations about 1897. Small parts of this area are also served by the Plainfield-Union Water Company, which began delivering water about 1890 and by the Elizabethtown Water Company, which operates a supply established in the northwestern part of the county about 1897. The urban areas south of the Raritan River are more widely scattered than those north of the river and are served by local water companies or by municipal water supplies, some of which have been developed since 1900, and most of which use ground water.

The development of large ground-water supplies in Middlesex County as elsewhere, has coincided with, and to a large extent has depended upon the development of efficient machinery for pumping water from deep wells and of improved methods of drilling wells. The earliest installations depended upon pumping from the wells by direct suction or by means of deep-well reciprocating pumps. The introduction of the air lift about the beginning of the present century provided an impetus to the development of ground-water supplies and many plants still use this method of pumping. The perfecting of the deep-well centrifugal or turbine pump made possible still more efficient pumping from wells. The methods of well drilling have also been greatly improved, and wells yielding one or two million gallons of water a day from some of the better aquifers are no longer exceptional.

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[3] Wall, John P., Chronicles of New Brunswick, 1931.

### Industrial Water Supplies

Industrial water supplies from wells now account for the major part of the ground water used within the county, exceeding even the total quantity withdrawn for public supplies. This heavy development has occurred very largely within the last 25 or 30 years and almost entirely within the last 50 years. Like other ground-water developments, it has coincided with the development of efficient machinery for pumping water from deep wells. The most rapid increase, however, in the industrial use of ground water in Middlesex County began about 1914 when the demand for water for war-time industries was felt. New and improved manufacturing processes and products are constantly being developed and the demand for industrial water has increased greatly. The ease with which apparently substantial supplies of ground water can be developed in favorable localities has encouraged the construction of numerous industrial wells.

The largest industrial water supply in the county is the so-called "Duhernal" development, which is operated jointly by the E. I. du Pont de Nemours & Company, the Hercules Powder Company, and the National Lead Company to assure a satisfactory and permanent water supply for their factories in the Borough of Sayreville. The name "Duhernal" is also used in this report in a broader sense to refer to the combined water supplies of the three companies, which together constitute one of the dozen or so largest water supplies in the State. The Duhernal water supply is not a utility organized for the sale of water but rather an outstanding example of cooperation toward a common end by companies that are to a considerable extent competitive in other matters.

The history of the Duhernal water supply and that of the other water supplies of the three companies is naturally an important part of the record of water-supply development in the county. It shows how industrial over-development may occur in the absence of detailed knowledge of ground-water conditions. It also furnishes an excellent example of the way intelligent conservation measures may be applied by industrial cooperation when the nature of the ground-water conditions affecting their water supplies is understood.

In 1904 the du Pont factory was established at Parlin. At about the same time some wells were drilled to supply a part of the water used in the plant, although some water was obtained from other sources. The activities at this plant were greatly increased during the first World War, beginning in 1914, and most of the water was then taken from wells. No record is available of the amount of water consumed at that time, but it is probable that an average of no more than 1 or 2 million gallons daily was used. This water was taken from the Farrington sand.

Several years after the war the Hercules Powder Company sought a suitable location for a new plant. Transportation facilities and other factors were, of course, considered, but it is understood that the final decision to locate the plant in Sayreville was based to a considerable extent upon the belief that a large supply of excellent water was available and could be obtained at relatively little expense by the construction of a suitable number of wells. This belief must have been based mainly upon the capacity of wells in that area to yield water rather than upon any serious consideration of the safe yield of the aquifer. It resulted in almost doubling the draft upon the Farrington sand in the Borough of Sayreville in a very short time. Even so it probably would not have resulted in exceeding the safe yield of the sand except for the unrecognized danger of salt-water contamination and the subsequent dredging operations, especially in the Washington Canal, which accentuated it.

The National Lead Company's plant was established in 1935. The studies of the Farrington sand up to that time seemed to indicate that its safe yield would not be exceeded by the additional draft that this plant would require. Even at that time the danger of salt-water intrusion had not been recognized and it was believed that the additional draft would probably do no material harm since the wells would be at some distance from other centers of pumping and the interference with existing wells would not be very great.

During 1935 the draft upon the Farrington sand at the du Pont and Hercules factories was increased somewhat above the previous draft. The pumpage at the three plants and at the Perth Amboy Water Works caused the water levels to be drawn down to such an extent that some concern was felt about the permanency of the supply. As a result an intensive study of the conditions affecting this sand in this area was undertaken and a report was issued on the subject in 1937.[4] Data collected in connection with this study indicated that there might be danger of salt-water intrusion from the vicinity of the Washington Canal, and this fact was pointed out in the report. Subsequent investigation showed that the salt-water intrusion from this direction was well advanced, and indicated that there was imminent danger of the destruction of some of the water supplies unless the rate of pumping could be reduced substantially.

[4] Barksdale, Henry C. Op. Cit. Special Report 7.

Faced with this serious condition, the three companies constructed the Duhernal supply to develop water from the Old Bridge sand in the area between Old Bridge and Spotswood, and to pump the water to the three plants. This development now supplies the major part of the water used by the three companies in this area. For the purpose of conserving water, both the new wells near Old Bridge and the old wells at the three plants are operated under one general management. The entire group of wells is operated in such a way as to maintain a low rate of withdrawal from the Farrington sand so that the advance of salt water may be retarded, and the time when the sand may have to be abandoned as a source of water supply may be postponed. The Duhernal management even goes so far as to adjust the rate of pumping from the wells owned by the three companies that draw from the Farrington sand to compensate for the pumpage of others over whom it has no control. As an additional measure of conservation, arrangements have been made to reuse water in the various plants whenever practicable and in at least one instance, water that cannot be used again in one plant is transferred to another and reused there.

The Duhernal development in the Old Bridge sand together with the wells tapping the Farrington sand at the three plants are a very important part of the whole water-supply structure in the county. Their history provides one of the best examples known to the authors of industrial cooperation in the interest of conservation. They will be discussed in more detail in the sections of this report dealing with these sands.

## NEED FOR REGULATED GROUND-WATER DEVELOPMENT

All too often the development of ground-water resources has been carried on with little, if any, consideration of the possibility that the safe yield of the various aquifers might be exceeded. This has been due primarily to public ignorance of the nature of the problem. The scientific quantitative study of ground-water problems is still relatively new, and although great advances have been made, it is not yet possible to arrive at very exact results. It now appears that certain aquifers in Middlesex County have been over-developed and that the development of others is probably approaching their safe yield. Nevertheless, a great majority of the people and even many who have contact with water-supply matters, still think in terms of the many successful developments that were made in the past and assume that more and more water can be drawn from the same aquifers by the simple process of drilling more wells. Hence communities vie with one another for new industries and the assurance is freely given that plentiful water supplies are available. The tremendous amount of water held in storage in the productive aquifers makes each new development appear successful and safe. Only after years of pumping may the effects of heedless overdevelopment become evident. When that occurs the industries so eagerly sought can, and probably will, move to other areas, leaving the community poorer not only in industrial development but very possibly in water resources also.

Middlesex County is by no means unique in this respect. In the humid eastern part of the United States there is a widespread tendency toward heedless overdevelopment of ground-water aquifers, especially for industrial use. This tendency is fostered by public indifference to the problem and by a general belief that the supply of ground water is inexhaustible. It is aggravated by antiquated laws and legal principles that do not permit adequate control of the withdrawal of ground water for private or industrial uses. In many areas the situation has become so serious that the public interest demands impartial control of all withdrawals of ground water. Only in the more arid western part of the country has the value and limited nature of the ground-water supply been generally recognized and legal action taken to protect it from destructive overdevelopment.

If carefully developed our ground-water supplies will last indefinitely. On the other hand if wantonly and wastefully overdeveloped, they may be destroyed altogether or their usefulness very much impaired. The extent of their development can no longer safely be decided solely on the basis of how profitable it may be or how desirable a new industry that is dependent upon a supply of ground water may seem. In the public interest the maintenance of a rate of withdrawal that will assure the permanency of the supply should be the first consideration in passing upon a proposed new development. A continuous, though limited, supply of ground water is much more valuable than a larger supply that may be taken from the aquifer for a brief period of years.

It is beyond the scope of this report to suggest the form that the regulation and control of ground-water development should take. Nevertheless, it should be pointed out that in the final analysis the critical factor will be the safe yield of whole aquifers rather than of small parts of them. Regulation of the ground-water developments in Middlesex County, for example, would be helpful but much of its value might be destroyed by unregulated development of the same aquifers in adjacent counties. Effective control should therefore be State-wide and the regulation of inter-state aquifers may require inter-state cooperation. Effective control should also be broadly inclusive. Restrictions applied to one class of water users and not to another would be futile as well as unfair. No diversion of ground water should be made without the prior approval of some unbiased agency empowered to safeguard this valuable natural resource against injurious overdevelopment.

## OUTLINE OF GEOLOGY

### Physical Divisions

Middlesex County lies within two major physiographic provinces, the Coastal Plain Province and the Piedmont Province. This division is based largely on rocks and structure projected from nearby regions, for in Middlesex County the topography would not warrant this subdivision, mainly because it has been modified by Quaternary deposits. The part of the county which is in the Coastal Plain Province is, roughly, that which lies southeast of a line from Plainsboro to Carteret. In this area the bed rock consists of unconsolidated or poorly consolidated sands and clays of Cretaceous age (see Stratigraphic Table, page 18, for geologic time-table) which dip at low angles to the southeast.

The Piedmont Province includes the area to the north and west of the Coastal Plain Province. It is underlain by relatively hard Triassic rocks, which in most regions stand up as rounded hills above the flat coastal plain. The prominences at Sand Hills are capped by outliers of the formerly more extensive Cretaceous sediments which have been protected from erosion by the numerous consolidated layers of "ironstone" (ferruginous sandstone) and the resistant Triassic diabase to the south. Farther north and east the Triassic shales have been eroded nearly as low as the Cretaceous sediments. This feature, together with the blanket of Quaternary deposits, has left little difference in the topography of the two provinces.

### Geologic History

The geologic history of Middlesex County as observed from the rocks within its borders is necessarily far from complete. Much of it, however, can be read from rocks in nearby areas although other events are forever lost. References to the length of time which has elapsed since the deposition of some of the formations are of necessity approximate. They are based on age determinations from radio-active minerals and are given to indicate the slowness with which geologic processes operate, the vastness of the intervals in which there are no geologic records within the county and, to some extent, the relative age of the existing formations.

The gneiss of the Wissahickon formation, known only from well logs in Middlesex County, gives us the first chapter in the geologic history of the county. In pre-Paleozoic time, at least 600 million years ago, muddy sediments were deposited, which later were folded and metamorphosed (altered) and then intruded by highly heated molten rock. This igneous activity further metamorphosed and recrystallized the sediments so that they little resembled the original deposits.

A long period of erosion followed, during which the existing mountains and hills were reduced to a fairly level plain. This was followed by the development of a depression which extended from the Gulf of Mexico northeastward through the Appalachian belt and Canada, and which was occupied by an arm of the sea for many millions of years. The record of those years is read in the sediments which were deposited in the depression and in which we find today the fossils, or preserved remains of animals which lived and developed during that period (the Paleozoic era). Since these sediments are today found only northwest of Middlesex County, the presumption is that either this area was above sea-level during that entire period, or that such sediments as were deposited have since been entirely removed by erosion. Whichever assumption is right, the second oldest rocks which we find in Middlesex County today are the generally red-colored rocks of Triassic age, which are believed to be at least 400 million years younger than the Wissahickon formation.

The Triassic sediments in Middlesex County are believed to have been deposited in an intermontane valley in the latter part of that geologic period. During this same time there was considerable igneous activity, the most important of which was the intrusion of the thick sill of diabase known along the Hudson River as the Palisades. This sill is continuous in the Triassic rocks in Middlesex County from Carteret to Rocky Hill, but is found at the surface only from Deans to Rocky Hill. The Triassic rocks were later tilted, faulted and eroded during an interval of about 100 million years. This interval spanned all of the Jurassic period and more than half of the Cretaceous period.

In early Upper Cretaceous times the land surface in Middlesex County consisted of a plain of moderate relief sloping to the southeast at about 60 feet to the mile. The bed rock in the southern third of the area consisted of the Wissahickon formation and the rest consisted of Triassic rocks, above which the resistant diabase sill stood as a ridge. Then the land was submerged and Upper Cretaceous sands and clays were deposited on it in alternating layers dipping to the southeast. These sediments tended to thicken oceanward so that the older sediments dipped parallel to the underlying plain while the higher formations were more nearly horizontal. During this period there were fluctuations in the depth of water, as indicated by the alternation of shallow and deep water fossils in the Cretaceous formations. The general relationship of the various rocks in the county is shown on the geologic section in figure 3.

In the Tertiary period which followed, there were intervals of deposition and of erosion, but any sediments which may have been deposited in Middlesex County have since been removed by erosion, together with much of the older Cretaceous deposits.

In the Quaternary period, which dates from the beginning of the Ice Age and in which we are now living—a period of some 2 million years—there were four advances of great ice sheets moving from centers in Canada into the northern part of the United States, interspaced with times of partial submergence and deposition. In Middlesex County there is evidence of only the last ice sheet. This consists of the Wisconsin drift which blankets the northern third of the county. The oldest non-glacial Quaternary deposits have been entirely removed from the county. The Pensauken formation, which is much older than the Wisconsin drift, is found capping the hills and higher divides but has been removed from the larger stream valleys. The Cape May formation, which is probably slightly older than the Wisconsin drift, is found mainly in stream valleys. Since the retreat of the Wisconsin ice sheet there have been only relatively slight physiographic changes in the county.

## Outline of the Stratigraphy

The areal geology of Middlesex County is shown on figures 4, 5 and 6 on pages 19, 20, and 21. The geologic formations shown thereon range from soft, unconsolidated alluvial deposits formed within the last few thousand years, to compacted rocks whose origin dates back many millions of years. The following stratigraphic table, arranged in normal sequence (i. e. youngest formation at the top) includes a still older formation (the Wissahickon) which has been penetrated by a number of deep wells within the county. Detailed descriptions of the formations are given in the section on hydrology and geology of the rock formations beginning on page 52.

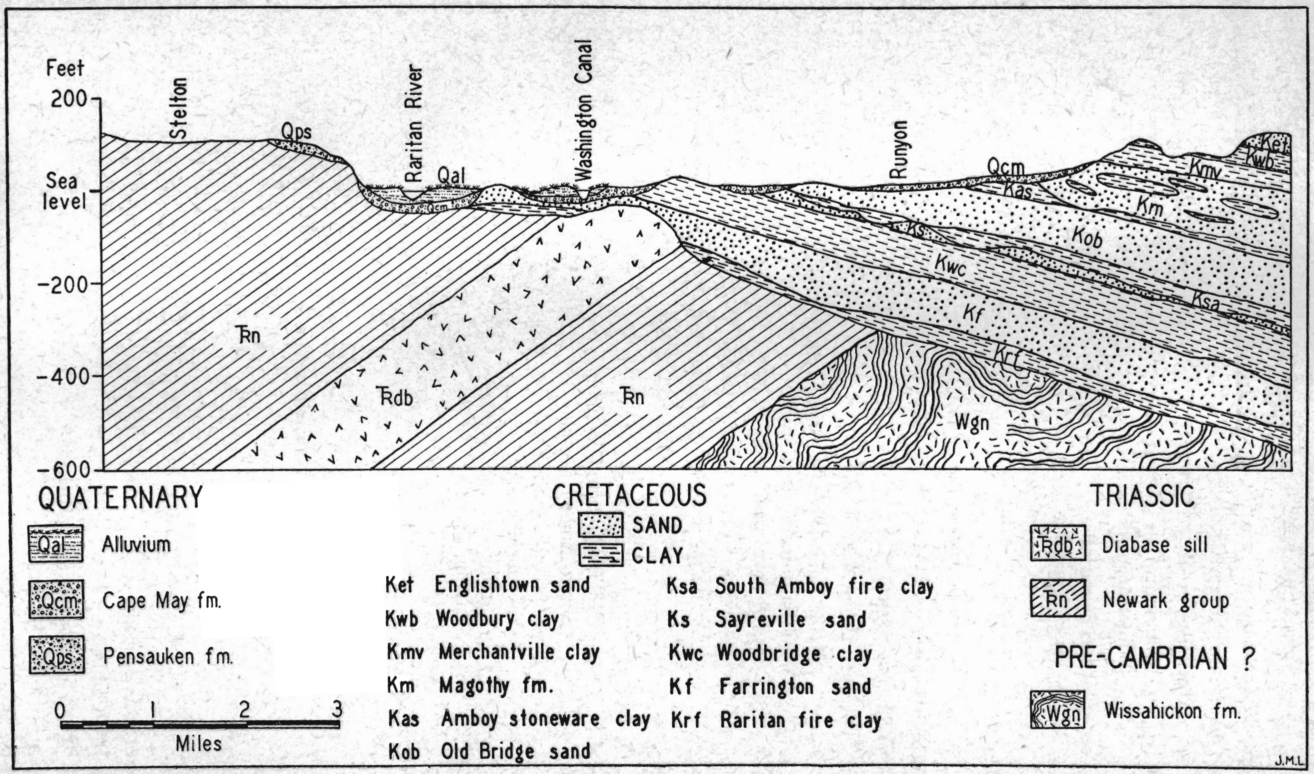


FIGURE 3.—Generalized geologic section from Stelton through Runyon to the county line.

STRATIGRAPHIC TABLE FOR MIDDLESEX COUNTY, N. J.

- Cenozoic sequence
  - Quaternary system
    - Recent series
      - Alluvium
      - Eolian deposits
    - Pleistocene series
      - Wisconsin drift
      - Cape May formation
      - Pensauken formation

UNCONFORMITY

- Mesozoic sequence.
  - Cretaceous system
    - Upper Cretaceous series
      - Mount Laurel and Wenonah sands
      - Marshalltown formation
      - Englishtown sand
      - Woodbury clay
      - Merchantville clay
      - Magothy formation
      - Raritan formation
        - Amboy stoneware clay
        - Old Bridge sand member
        - South Amboy fire-clay
        - Sayreville sand member
        - Woodbridge clay
        - Farrington sand member
        - Raritan fire-clay

UNCONFORMITY

  - Triassic system
    - Upper Triassic series (Newark group)
      - Brunswick shale
      - Lockatong formation
      - Stockton formation

UNCONFORMITY

- Proterozoic sequence (?)
  - Pre-Cambrian (?)
      - Wissahickon formation

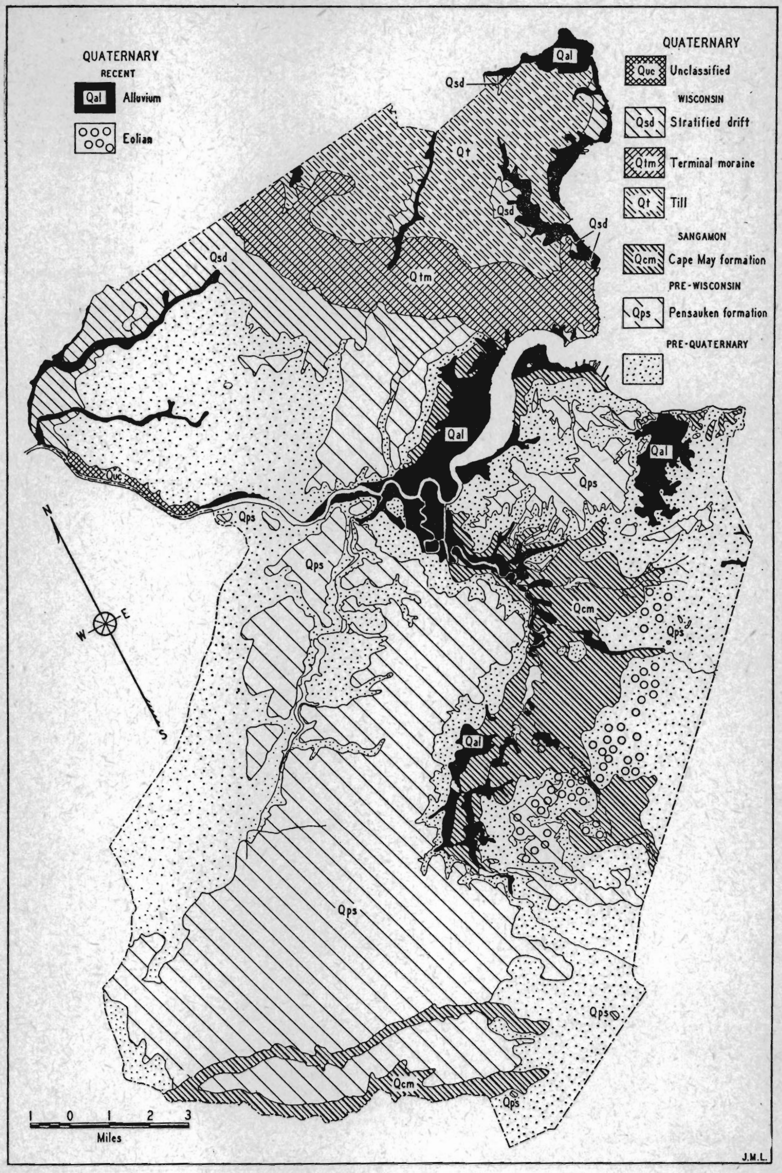


FIGURE 4.—Map of Middlesex County showing the areal distribution of the rocks of the Quaternary system. Small quantities of good water are obtained from the eolian deposits, the stratified drift, the Cape May and Pensauken formations, and the unclassified deposits.

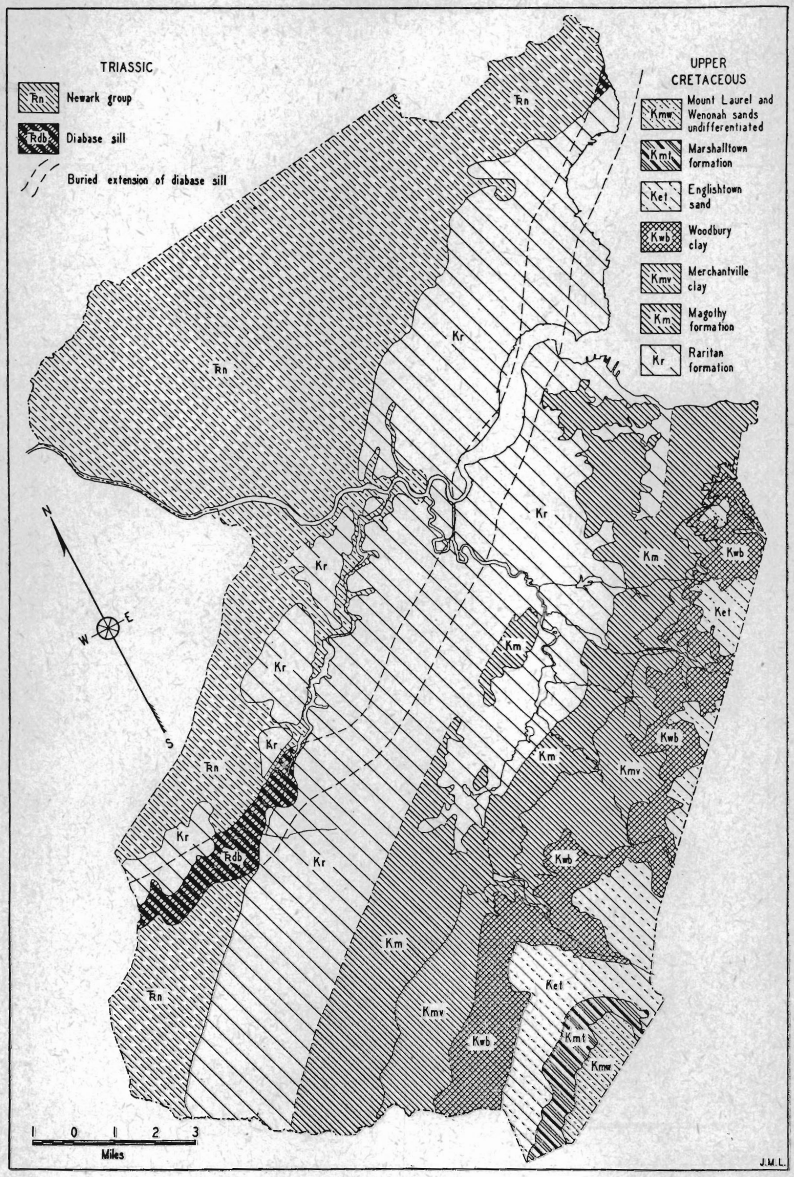


FIGURE 5.—Map of Middlesex County showing the exposures of the rocks of the Triassic and Cretaceous systems. Small quantities of good water are obtained from the Mount Laurel and Wenonah sands, the Englishtown sand and the Magothy formation within the county. Substantial quantities are derived from the Raritan formation and the rocks of the Newark group.

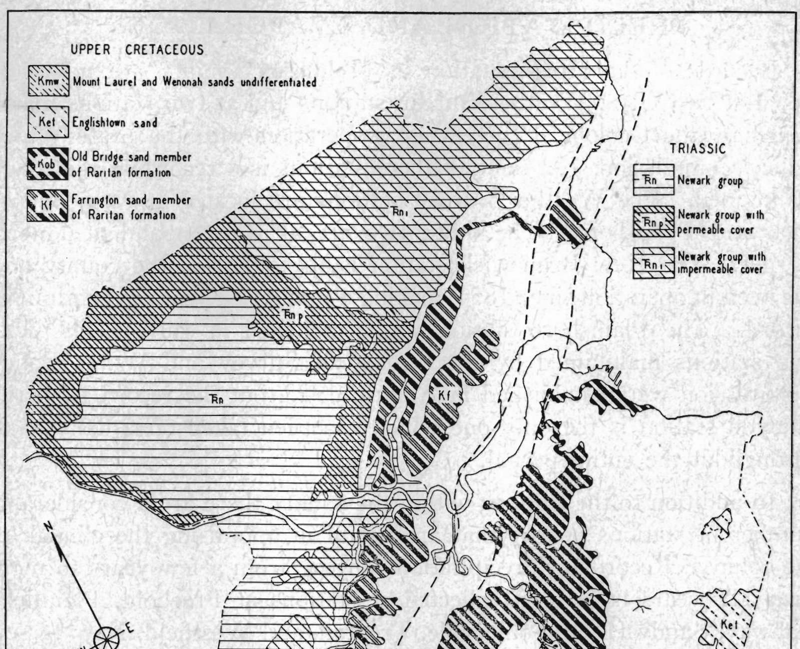


FIGURE 6.—Map of Middlesex County showing the intake areas of the important aquifers. Large quantities of good water are obtained from the Old Bridge and Farrington sand members of the Raritan formation. Small quantities are obtained from the Englishtown sand and the Mount Laurel and Wenonah sands. The rocks of the Newark group yield moderately large supplies where overlain by permeable materials, but elsewhere their yield is small.

## PRECIPITATION AND EVAPORATION

Records of daily precipitation in Middlesex County are now collected at two U. S. Weather Bureau stations and at two stations maintained by the Geological Survey in cooperation with the State Water Policy Commission. At none of these stations is a recording rain gage maintained. The Weather Bureau stations are located at New Brunswick and Plainsboro. The other two are at Runyon and at Moerls Corner. The New Brunswick station is the oldest in the county and has been in operation since 1854, making a total of 88 years of continuous record. The Plainsboro station was established in July, 1941. The two stations maintained by the Geological Survey and Water Policy Commission were established in August, 1923, but the record from the Runyon station is the only one which has been taken on a daily basis throughout the entire period.

In addition to the stations within the county there are a considerable number of stations nearby that are useful in appraising the climate of the county. Records of precipitation ranging from a few years to more than 117 years have been collected at stations at Freehold, Plainfield, Rahway, Sandy Hook, Somerville, Trenton, and Westfield, New Jersey, and at New York, New York. Records of precipitation at all of these stations are published monthly by the Weather Bureau.[5]

The Runyon station is a standard Weather Bureau Class A evaporation station established as part of the investigation on which this report is based. Mr. H. L. Dieker has been the observer at this station since it was first started. The monthly precipitation at Runyon is included in table 1 on pages 23-28.

The annual normal precipitation for this station is 44.37 inches. Of this amount about 24 inches falls between April 1 and September 30 when the demands of vegetation for water are highest. In spite of this, the ground-water levels usually fall during this time because most of the water from precipitation goes to supply the needs of vegetation or to direct runoff.

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[5] U. S. Department of Commerce Weather Bureau, Climatological Data, New Jersey and New York Sections. See also U. S. Department of Agriculture Climatological Summary, New Jersey and New York Sections 1934.

TABLE 1

Precipitation, evaporation from land pan, wind movement, and mean temperature at Runyon, New Jersey, 1923 to 1942

| | Precipitation (inches) | Evaporation (inches) | Wind[a] (miles) | Temperature[b] (degrees F) |
|---|---|---|---|---|
| *1923* | | | | |
| September | .... | 1.68 | .... | .... |
| October | 4.26 | 2.63 | .... | .... |
| November | 2.02 | .97 | 1675 | .... |
| December | 4.61 | .... | .... | .... |
| *1924* | | | | |
| January | 5.19 | .... | 3292 | 26.5 |
| February | .... | .... | .... | 31.0 |
| March | 2.30 | .38[c] | 2263 | 44.0 |
| April | 5.71 | 3.53 | 3076 | 55.0 |
| May | 6.25 | 4.06 | 3243 | 56.7 |
| June | 3.45 | 4.50 | 1236 | 66.8 |
| July | 1.13 | 5.96 | 1058 | 70.3 |
| August | 9.48 | 4.52 | 861 | 70.6 |
| September | 4.36 | 2.98 | 1205 | 62.4 |
| October | .20 | 2.53 | 743 | 51.8 |
| November | 1.51 | 1.18 | 1498 | 44.1 |
| December | 2.35 | .64[d] | 2082 | 31.5 |
| *1925* | | | | |
| January | 3.38 | .... | 2109 | 25.1 |
| February | 2.02 | .... | 1520 | 36.4 |
| March | 3.22 | .... | 2184 | 42.5 |
| April | 2.18 | 3.92 | 2165 | 49.6 |
| May | 2.81 | 4.56 | 1802 | 56.2 |
| June | 2.40 | 7.08 | 1432 | 73.0 |
| July | 4.03 | 5.23 | 986 | 71.4 |
| August | 1.75 | 4.88 | 914 | 70.1 |
| September | 2.91 | 4.15 | 1152 | 68.0 |
| October | 4.59 | 2.06 | 1605 | 53.8 |
| November | 3.10 | 1.54 | 2178 | 38.0 |
| December | 3.01 | .32[e] | 2938 | 32.3 |
| *1926* | | | | |
| January | 2.78 | .... | 2156 | 29.6 |
| February | 5.46 | .... | 2419 | 29.2 |
| March | 2.17 | .... | 2505 | 35.4 |
| April | 2.02 | 3.97 | 2674 | 46.4 |
| May | 2.67 | 6.12 | 2082 | 58.0 |
| June | 2.94 | 4.89 | 1293 | 59.2 |
| July | 3.96 | 5.43 | 1025 | 72.4 |
| August | 7.58 | 4.03 | 840 | 72.4 |
| September | 3.31 | 3.61 | 1010 | 63.2 |
| October | 6.03 | 2.42 | 1373 | 52.2 |
| November | 3.80 | 1.40 | 2152 | 41.9 |
| December | 3.30 | .13[f] | 2843 | 27.2 |

| | Precipitation (inches) | Evaporation (inches) | Wind (miles) | Temperature (degrees F) |
|---|---|---|---|---|
| *1927* | | | | |
| January | 3.32 | .... | 1460 | 28.6 |
| February | 2.18 | .... | 1487 | 36.0 |
| March | .85 | .... | 1763 | 39.8 |
| April | 3.26 | 3.94 | 2415 | 46.5 |
| May | 3.59 | 4.69 | 2393 | 57.1 |
| June | 2.49 | 5.93 | 1628 | 64.0 |
| July | 4.33 | 5.73 | 1684 | 71.4 |
| August | 11.24 | 4.31 | 1089 | 65.7 |
| September | 1.65 | 4.15 | 903 | 64.8 |
| October | 9.69 | 3.59 | 1439 | 54.9 |
| November | 3.37 | 2.52 | 1706 | 46.4 |
| December | 4.62 | .25[g] | 1789 | 34.6 |
| *1928* | | | | |
| January | 1.90 | .... | 2448 | 31.2 |
| February | 4.20 | .... | 1780 | 31.5 |
| March | 2.82 | .... | 2654 | 36.9 |
| April | 5.85 | .... | 2233 | 47.3 |
| May | 2.22 | 5.03 | 1723 | 56.0 |
| June | 6.89 | 4.58 | 1194 | 67.8 |
| July | 9.37 | 5.02 | 830 | 73.8 |
| August | 6.17 | 4.84 | 774 | 79.0 |
| September | 4.34 | 3.34 | 900 | 61.3 |
| October | 1.84 | 3.01 | 850 | 57.4 |
| November | 1.69 | 1.86[h] | 1188 | 43.9 |
| December | 1.52 | .... | 1138 | 38.2 |
| *1929* | | | | |
| January | 3.74 | .... | 1878 | 30.2 |
| February | 5.17 | .... | 1174 | 31.0 |
| March | 2.40 | .... | 2329 | 42.6 |
| April | 7.80 | 3.23 | 2867 | 51.1 |
| May | 4.55 | 5.82 | 1903 | 61.5 |
| June | 3.92 | 5.67 | 846 | 66.2 |
| July | 2.78 | 6.40 | 928 | 74.5 |
| August | 1.72 | 5.92 | 705 | 63.0 |
| September | 4.37 | 3.99 | 812 | 59.0 |
| October | 5.19 | 2.55 | 1468 | 46.0 |
| November | 2.65 | 1.44[i] | 1469 | 38.0 |
| December | 3.30 | .... | 1220 | 31.0 |
| *1930* | | | | |
| January | 2.27 | .... | .... | 36.0 |
| February | 3.64 | .... | .... | 36.0 |
| March | 2.68 | .... | .... | .... |
| April | 1.90 | 4.33 | .... | 47.5 |
| May | 2.38 | 5.48 | .... | 65.0 |
| June | 3.81 | 5.10 | .... | 74.0 |
| July | 4.66 | 5.25 | .... | 74.0 |
| August | 2.91 | 5.01 | 829 | 69.0 |
| September | 1.60 | 4.36 | 679 | 68.0 |
| October | 2.26 | 3.18 | 726 | 49.7 |
| November | 3.75 | 1.10 | 1260 | 42.0 |
| December | 2.94 | .... | 1155 | 32.3 |

| | Precipitation (inches) | Evaporation (inches) | Wind (miles) | Temperature (degrees F) |
|---|---|---|---|---|
| *1931* | | | | |
| January | 2.34 | .... | 1064 | 30.1 |
| February | 2.59 | .... | 1038 | 35.6 |
| March | 3.84 | 1.30[j] | 2050 | 38.9 |
| April | 3.03 | 4.48 | 1972 | 49.7 |
| May | 3.45 | 4.70 | 1279 | 61.4 |
| June | 5.70 | 5.01 | 620 | 69.7 |
| July | 3.80 | 5.09 | 427 | 75.8 |
| August | 4.78 | 3.98 | 412 | 74.1 |
| September | .86 | 4.44 | 729 | 69.2 |
| October | 3.70 | 2.88 | 555 | 56.3 |
| November | 1.04 | 2.88[k] | .... | 47.4 |
| December | 2.61 | .... | .... | 32.3 |
| *1932* | | | | |
| January | 5.36 | .... | .... | 41.7 |
| February | 1.90 | .... | 1016 | 33.5 |
| March | 6.27 | .... | 2003 | 36.1 |
| April | 2.41 | 2.22[l] | 1753 | 48.7 |
| May | 2.98 | 5.81 | 1281 | 59.2 |
| June | 4.95 | 5.86 | 632 | 68.0 |
| July | 2.24 | 6.86 | 501 | 67.5 |
| August | 1.67 | 5.58 | 632 | 72.9 |
| September | 3.07 | 4.15 | 733 | 63.8 |
| October | 5.28 | 2.59 | 1319 | 54.4 |
| November | 8.83 | 2.03[i] | 1228 | 41.5 |
| December | 2.79 | .... | 1018 | 32.8 |
| *1933* | | | | |
| January | 1.91 | .... | 1456 | 37.0 |
| February | 2.81 | .... | 1493 | 32.9 |
| March | 5.59 | .... | 1882 | 38.0 |
| April | 4.19 | .... | 1893 | 47.7 |
| May | 6.12 | .... | 980 | 63.1 |
| June | 5.71 | 4.52 | 615 | 61.1 |
| July | 3.06 | 5.83 | 649 | 72.8 |
| August | 8.28 | 4.43 | 769 | 72.2 |
| September | 5.55 | 3.20 | 635 | 67.6 |
| October | 1.63 | 2.52 | 558 | 38.3 |
| November | 1.06 | .28[m] | 1104 | 39.8 |
| December | 3.78 | .... | 1008 | 28.6 |
| *1934* | | | | |
| January | 3.44 | .... | 1284 | 32.7 |
| February | 3.01 | .... | 1062 | 15.4 |
| March | 3.39 | .... | 1604 | 36.2 |
| April | 3.57 | .... | 1397 | 48.8 |
| May | 4.47 | 5.76 | 1301 | 62.7 |
| June | 4 13 | 6.36 | 868 | 72.5 |
| July | 6.89 | 6.17 | 533 | 70.4 |
| August | 2.05 | 4.55 | 656 | 69.3 |
| September | 10.90 | 3.24 | 697 | 66.1 |
| October | 2.91 | 2.30 | 803 | 52.1 |
| November | 1.30 | .61[l] | 1068 | 45.4 |
| December | 2.64 | .... | 1080 | 31.1 |

| | Precipitation (*inches*) | Evaporation (*inches*) | Wind (*miles*) | Temperature (*degrees F*) |
|---|---|---|---|---|
| *1935* | | | | |
| January | 3.76 | .... | 1041 | 28.7 |
| February | 3.11 | .... | 1070 | 28.3 |
| March | 2.73 | .... | 1325 | 41.5 |
| April | 3.25 | .... | 1712 | 48.6 |
| May | 1.98 | 4.77 | 1109 | 57.2 |
| June | 3.48 | 4.54 | 794 | 69.6 |
| July | 4.03 | 5.78 | 612 | 75.4 |
| August | 1.40 | 4.66 | 520 | 71.2 |
| September | 4.70 | 3.12 | 475 | 62.1 |
| October | 4.67 | 3.00 | 716 | 53.7 |
| November | 6.21 | 1.06 | 949 | 46.7 |
| December | 1.36 | .... | 1180 | 28.2 |
| *1936* | | | | |
| January | 6.08 | .... | 1639 | 29.0 |
| February | 2.70 | .... | 1445 | 23.8 |
| March | 4.13 | 2.92[n] | 1689 | 47.0 |
| April | 2.68 | 4.87 | 1912 | 48.7 |
| May | 3.04 | 6.23 | 1444 | 63.6 |
| June | 4.57 | 4.75 | 736 | 69.4 |
| July | 1.88 | 6.45 | 624 | 79.7 |
| August | 3.48 | 5.43 | 697 | 68.0 |
| September | 5.42 | 3.82 | 1380 | 66.8 |
| October | 3.20 | 2.73 | 1381 | 54.0 |
| November | 1.22 | 1.12[j] | 1630 | 39.4 |
| December | 6.64 | .... | 1690 | 30.5 |
| *1937* | | | | |
| January | 5.70 | .... | 1499 | 38.9 |
| February | 1.72 | .... | 1820 | 30.5 |
| March | 2.69 | .... | 3024 | 33.1 |
| April | 4.61 | 3.53[i] | 2428 | 45.8 |
| May | 2.69 | 5.98 | 1436 | 62.7 |
| June | 3.84 | 5.73 | 959 | 70.2 |
| July | 2.90 | 6.11 | 572 | 72.5 |
| August | 7.41 | 4.99 | 710 | 74.8 |
| September | 3.13 | 3.54 | 391 | 63.9 |
| October | 4.48 | 2.21 | 996 | 54.3 |
| November | 2.87 | 1.12[o] | 1074 | 41.9 |
| December | 1.79 | .... | 896 | 31.0 |
| *1938* | | | | |
| January | 3.58 | .... | 998 | 28.8 |
| February | 2.36 | .... | 1086 | 35.1 |
| March | 2.14 | .... | 1494 | 41.0 |
| April | 3.22 | .... | 1401 | 48.0 |
| May | 3.56 | 4.36 | 1193 | 56.5 |
| June | 7.15 | 5.60 | 893 | 67.0 |
| July | 9.18 | 5.28 | 588 | 73.0 |
| August | 2.29 | 5.41 | 405 | 69.2 |
| September | 9.39 | 4.58[p] | 739 | 62.0 |
| October | 2.90 | 2.96 | 753 | 55.9 |
| November | 3.65 | 1.26[k] | 855 | 41.9 |
| December | 2.27 | .... | 1007 | 32.0 |

| | Precipitation (inches) | Evaporation (inches) | Wind (miles) | Temperature (degrees F) |
|---|---|---|---|---|
| *1939* | | | | |
| January | 4.16 | .... | 1237 | 28.0 |
| February | 5.66 | .... | 1307 | 35.5 |
| March | 4.91 | .... | 1546 | 39.0 |
| April | 3.73 | .... | 1714 | 46.6 |
| May | .53 | 6.36 | 1339 | 62.1 |
| June | 3.37 | 6.38 | 915 | 68.4 |
| July | 2.09 | 6.78 | 771 | 72.4 |
| August | 4.71 | 5.43 | 750 | 73.5 |
| September | 1.55 | 3.79 | 750 | 64.5 |
| October | 4.27 | 2.41 | 789 | 53.9 |
| November | 1.73 | .13[f] | 1158 | 38.5 |
| December | .98 | .... | 1236 | 33.2 |
| *1940* | | | | |
| January | 2.00 | .... | 1252 | 19.4 |
| February | 3.22 | .... | 1290 | 30.3 |
| March | 4.19 | .... | 1651 | 33.1 |
| April | 5.78 | .... | 1382 | 43.3 |
| May | 6.50 | 4.22 | 1323 | 58.6 |
| June | 4.31 | 5.70 | 866 | 68.6 |
| July | 1.91 | 6.05 | 634 | 72.2 |
| August | 7.41 | 4.54 | 570 | 67.1 |
| September | 4.91 | 4.06 | 359 | 61.1 |
| October | 3.11 | 2.08 | 597 | 48.7 |
| November | 4.35 | 1.42[k] | 922 | 40.8 |
| December | 2.98 | .... | 777 | 35.6 |
| *1941* | | | | |
| January | 4.14 | .... | 1164 | 27.8 |
| February | 2.75 | .... | 1198 | 17.6 |
| March | 3.48 | .... | 1454 | 32.9 |
| April | 2.56 | .... | .... | 54.4 |
| May | 1.85 | 5.58 | 772 | 60.0 |
| June | 5.02 | 5.52 | 720 | 66.7 |
| July | 6.23 | 5.35 | 650 | 71.1 |
| August | 3.42 | 6.03 | 552 | 68.4 |
| September | .02 | 5.84 | 630 | 65.9 |
| October | 1.70 | 3.40 | 578 | 58.8 |
| November | 3.42 | 1.31[i] | 788 | 43.8 |
| December | 3.15 | .... | 920 | 35.4 |
| *1942* | | | | |
| January | 3.05 | .... | 929 | 25.1 |
| February | 2.83 | .... | 1187 | 29.1 |
| March | 6.13 | .... | 1713 | 40.1 |
| April | 1.37 | .... | 1083 | 52.5 |
| May | 2.21 | 5.87 | 772 | 62.4 |
| June | 5.46 | 5.58 | 285 | 68.7 |
| July | 7.27 | 5.42 | 393 | 71.0 |
| August | 4.60 | 4.54 | 352 | 72.0 |
| September | 4.47 | 3.89 | 453 | 63.0 |
| October | 2.91 | 2.04 | 688 | 59.0 |
| November | 5.53 | 1.78 | 684 | 42.0 |
| December | 4.30 | .... | 933 | 27.5 |

| | Precipitation (inches) | Evaporation (inches) | Wind (miles) | Temperature (degrees F) |
|---|---|---|---|---|
| | *Monthly averages* | | | |
| January | 3.61q | .... | 1583 | 30.2 |
| February | 3.28q | .... | 1376 | 30.5 |
| March | 3.32q | .... | 1452 | 38.8 |
| April | 3.62q | 3.90 | 2005 | 48.7 |
| May | 3.42q | 5.30 | 1521 | 60.0 |
| June | 4.34q | 5.44 | 918 | 67.9 |
| July | 4.14q | 5.80 | 748 | 72.7 |
| August | 4.88q | 4.90 | 686 | 70.7 |
| September | 4.00q | 3.80 | 770 | 64.4 |
| October | 3.78q | 2.65 | 945 | 52.9 |
| November | 3.03q | 1.42 | 1294 | 42.3 |
| December | 2.95q | .... | 1384 | 31.9 |

a. Wind movement just above pan from Weather Bureau publications and from the files of the Trenton Ground-Water office.
b. Mean temperatures obtained by averaging the mean high, and mean low temperatures published by the Weather Bureau.
c. 10 Days.
d. 19 Days.
e. 9 Days.
f. 3 Days.
g. 5 Days.
h. 26 Days.
i. 24 Days.
j. 17 Days.
k. 23 Days.
l. 13 Days.
m. 6 Days.
n. 18 Days.
o. 20 Days.
p. 8 Days.
q. U. S. Weather Bureau normal.

When the plants are dormant during the winter season they take very little of the water from precipitation and the water table receives much more recharge. About 10 per cent of the annual precipitation is in the form of snow which does not have a high runoff factor so that still more water is available for ground-water recharge.

The lowest monthly precipitation recorded at the Runyon station was 0.02 inch during September, 1941. This was 3.98 inches below the normal for that month. During October of that year only 1.70 inches fell. The deficiency below the normal rate for these two months was 6.06. This was one of the most severe and extended dry periods recorded.

The highest monthly precipitation recorded at the Runyon station was 11.24 inches during August, 1927. This was 6.36 inches above the normal for that month. Usually the monthly precipitation is distributed among several storms, none of which are excessive. It is interesting, however, to note the intensity of some of the most severe storms. Records of all severe storms have been compiled for the New Brunswick station.[6] The largest amount of precipitation to fall on one day was 4.91 inches on July 20, 1921. The most severe two-day storm occurred on August 16 and 17, 1909, when 8.19 inches fell.

Much of the detailed data collected at the evaporation station has been published by the Weather Bureau in the New Jersey Section of the Climatological Data. Table 1 gives in addition to the monthly precipitation, the evaporation in inches from a land pan, the wind movement in miles, and mean temperature in degrees Fahrenheit for each month of the years 1923-1942. Average monthly figures have been computed for each of the elements presented in the tables. In the case of evaporation, however, records are available only during the warmer months. The evaporation pan was removed from service for a part of each winter to avoid damage by freezing.

From the table it is evident that temperature has more of an effect upon evaporation than does wind movement. It is also apparent that there is a progressively decreasing amount of wind movement from 1923 to 1942. This is explained by the fact that the anemometer, which is set directly above the evaporation pan to record the wind movement near the water surface, is gradually being blocked off from the prevailing winds by the growth of trees west of the station.

When the evaporation station was originally established at Runyon, the following special features were also installed: a lysimeter, 3 soil evaporation pans, and a floating evaporation pan. No satisfactory records were obtained from the lysimeter and the soil evaporation pans, and unforeseen operational difficulties made it impossible to continue the experiments. The floating evaporation pan was operated successfully for a few months. Unfortunately however, this evaporation pan was located on the west side of the pond where it received the prevailing wind directly from the land rather than from the pond itself. It was, therefore, essentially another land evaporation pan.[7]

During the growing season the average evaporation from the land pan for the nineteen years of record was about 8 percent more than the average precipitation. Thus it is apparent that more water was

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[6] Shanklin, G. R., Unpublished manuscript on "Hydrologic Studies of the Elizabeth and Rahway Rivers."

[7] The following record of evaporation from the floating pan is presented for whatever it may be worth, but it is probably not representative of evaporation from a water surface.

| 1923 | | 1924 | |
|---|---|---|---|
| September | 3.16 inches | August | 4.431 inches |
| | | September | 2.888 inches |
| | | October | 2.472 inches |
| | | November | 1.172 inches |

evaporated from the pan than fell upon it. Many attempts have been made to determine the ratio between the rate of evaporation from the surface of a pond or lake and the rate of evaporation from a land pan. In the computations in this report, it is assumed that the evaporation from a pond or lake is about 70 percent of that from a land pan. In view of the fact that the application of any sizeable correction would bring the total evaporation from a water surface below the total precipitation during the growing season, and further that the evaporation during the colder months is probably much less than during the warm months, it seems probable that there would be an excess of precipitation over evaporation on a pond such as the Runyon Pond during the course of a year.

## WELL AND PUMPAGE INVENTORY

*Summary and Scope.* It is estimated that an average of more than 37 million gallons of water a day was pumped from wells in Middlesex County during 1941 for public and industrial supplies. Of this amount about 10 million gallons a day was withdrawn from wells north of the Raritan River and about 27 million gallons a day from wells south of the river. All this water was pumped from 293 wells, making an average consumption of approximately 127 thousand gallons a day from each well. Since most of the wells were not pumped continuously, their potential yield is probably much greater. Because of increased industrial activity caused by the present war, the pumpage was greater in 1941 than in 1940. It is probable that the rate of pumping from wells in the county will continue to increase with the expansion of industrial activity.

These estimates do not include approximately 500 thousand gallons of water withdrawn daily from wells for the supply of individual homes or small farms. Although there are a large number of wells of this type in the rural and suburban sections of the county, the ground-water resources of the county are not appreciably affected by them. They are widely scattered and the amount of water withdrawn from each is relatively small.

The estimates of pumpage given in this report are based on data obtained from various sources. The data for public water supplies were readily available from the quarterly reports of water consumption submitted by each public water supply system in the State, as required by law. These reports are in the files of the State Water Policy Commission. Most of the public supplies are metered and those not metered use fairly accurate methods of determining pumpage in accordance with the requirements of the engineers of the Commission. Most of the large private supplies in the county are also metered and the owners have willingly supplied data for the purposes of this investigation. The records from these sources are, therefore, reasonably accurate. The remainder of the data was collected early in 1942. All the industries in the county, regardless of size, were contacted either by mail or by members of the technical staff engaged in this investigation. Many of the estimates obtained in this way were made from records of pump operation kept by the individual industries. Some were based on the yield of the individual wells as originally determined by the driller. Such estimates may at times be somewhat in error, but the aggregate amount of pumpage estimated in this way forms only a small percentage of the total. It is believed, therefore, that the totals are essentially correct.

No attempt was made to ascertain the total number of wells in the county. There are, however, in the files of the State Geologist and of the State Water Policy Commission, records of approximately 800 wells in the county. Of the 293 wells that yielded water for public or industrial purposes during 1941, there were approximately 103 wells for public supply from which an average of about 15 million gallons a day was obtained, and 190 industrial wells from which about 22 million gallons a day was obtained.

*Distribution of Pumpage.* The amount and source of water pumped from wells in each municipality in the county in 1941 is shown in table 2 on page 33. For easy reference and a clearer understanding these data are also shown in graphical form on figure 7. The total pumpage in each municipality in 1941 is represented on the map by circles, the areas of which are proportional to the amounts of water pumped. The circles are divided into segments to show the amount of water pumped from each major aquifer.

Pumpage in only four of the total of twenty-five municipalities in the county exceeded an average of one million gallons a day during 1941. These were Madison Township, the Borough of South Plainfield, the Borough of Sayreville and the city of South Amboy. Only one of these, the Borough of South Plainfield, is north of the Raritan River.

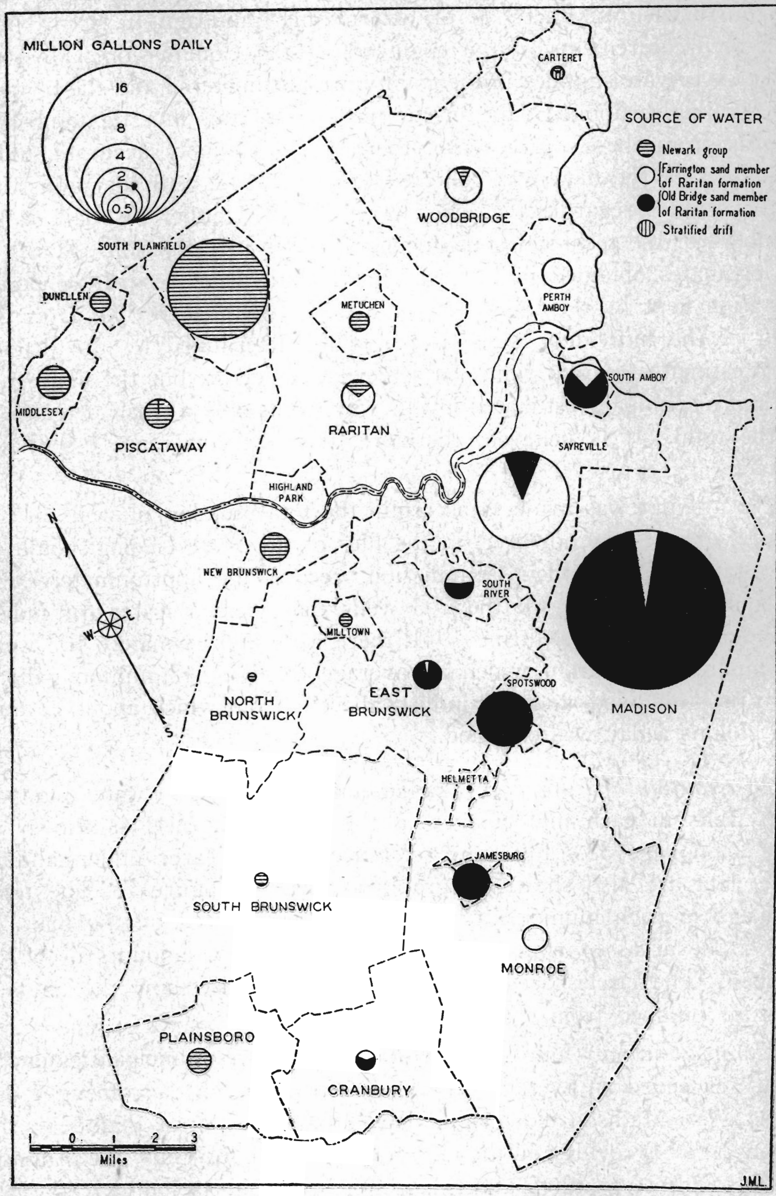


FIGURE 7.—Map of Middlesex County showing the quantity and distribution of the ground water pumped in 1941.

TABLE 2

Source and quantity of water pumped from wells for public and industrial water supplies in each political unit in Middlesex County, New Jersey, in 1941

| Political Unit | Old Bridge Sand member of Raritan formation | Farrington Sand member of Raritan formation | Newark Group | Total | Number of wells pumped |
|---|---|---|---|---|---|
| | *In thousands of gallons daily* | | | | |
| Carteret Borough .... | ... | ... | 35 | 137[a] | 7 |
| Cranbury Township .. | 122 | 73 | ... | 195 | 3 |
| Dunellen Borough .... | ... | ... | 259 | 259 | 5 |
| East Brunswick Twp.. | 412 | 22 | 8 | 442 | 4 |
| Helmetta Borough .... | 17 | ... | ... | 17 | 2 |
| Highland Park Bor. .. | ... | ... | ... | ... | 0 |
| Jamesburg Borough .. | 780 | ... | ... | 780 | 5 |
| Madison Township ... | 15,185 | 795 | ... | 15,980 | 64 |
| Metuchen Borough ... | ... | ... | 221 | 221 | 5 |
| Middlesex Borough .. | ... | ... | 638 | 638 | 13 |
| Milltown Borough ... | ... | ... | 109 | 109 | 4 |
| Monroe Township .... | ... | 352 | ... | 352 | 6 |
| City of New Brunswick | ... | ... | 535 | 535 | 19 |
| North Brunswick Twp. | ... | ... | b | b | b |
| City of Perth Amboy . | ... | 579 | ... | 579 | 6 |
| Piscataway Township . | ... | ... | 539[c] | 539[c] | 17 |
| Plainsboro Township.. | ... | ... | 322 | 322 | 5 |
| Raritan Township .... | ... | 504 | 197 | 701 | 16 |
| Sayreville Borough .. | 679 | 4,907 | ... | 5,586 | 19 |
| City of South Amboy. | 926 | 286 | ... | 1,212 | 9 |
| South Brunswick Twp. | ... | ... | 106 | 106 | 4 |
| South Plainfield Bor. . | ... | ... | 6,496 | 6,496 | 36 |
| South River Borough . | 240 | 229 | ... | 469 | 8 |
| Spotswood Borough .. | 670 | ... | ... | 670 | 7 |
| Woodbridge Township | ... | 695 | 113 | 808 | 29 |
| Totals .......... | 19,031 | 8,442 | 9,578 | 37,153 | 293 |

a. Includes 102 thousand gallons a day pumped from stratified drift.
b. Included with City of New Brunswick.
c. Includes a small amount from the stratified drift.

Over 40 percent of all the ground water withdrawn in the county was from wells in Madison Township, where a total of 16 million gallons a day was withdrawn from 64 wells in 1941. The two largest ground-water developments in this county are located in this township. They are the Perth Amboy Water Department well field at Runyon and the Duhernal well field a short distance southwest of Old Bridge. The combined ground-water withdrawals of these two supplies amounted to nearly 16 million gallons a day during 1941, accounting for practically all of the water withdrawn from wells within the township. An average of 9 million gallons a day was withdrawn by the Duhernal water supply for industrial purposes from 12 wells, and an average of about 7 million gallons a day by the Perth Amboy Water Department from 51 wells.

Since early in September, 1941, an average of 2 million gallons a day has been pumped from 7 wells in the Borough of Spotswood for industrial purposes. Five of these wells are near the Madison Township line, directly across Duhernal Lake from the Duhernal well field, so that the concentration of pumping in this area is now even greater than the figures in the table indicate.

In the Borough of South Plainfield an average of 6.5 million gallons a day was pumped from 36 wells during 1941. Most of the water was withdrawn from wells owned by the Middlesex Water Company. Smaller amounts were pumped by the Plainfield-Union Water Company and by industries in the borough.

Withdrawals in the Borough of Sayreville amounted to 5.6 million gallons a day during 1941. Practically all of it was pumped from 16 wells owned by industries in the vicinity of Parlin and South Amboy.

In addition to the Perth Amboy well field at Runyon, there are several other public water supplies in the part of the county south of the Raritan River using water from wells. These are the South Amboy Water Department, the Jamesburg Water Company, the South River Water Department, and the Cranbury Water Company. The largest is the South Amboy Water Department, which pumped an average of 878 thousand gallons a day from 4 wells during 1941.

Further data on the pumpage from the Old Bridge and Farrington sands and from the Newark group are included with the detailed discussions of these aquifers later in this report.

## FLUCTUATIONS OF THE WATER TABLE

At the start of the investigation in 1923 the need for records of the natural fluctuations of the water table was appreciated. Measurements of fluctuations of water level were, therefore, begun on a group of farm wells and in the Morrell well.

The farm wells are used for domestic purposes only and are not affected by heavy pumping. They are in a region of gently undulating terrain that ranges from 20 to 130 feet above mean sea level. There are 31 farm wells and they range from 10 to 48 feet deep. Four shallow 7-inch wells that were constructed specifically for observation purposes are included with the farm wells in the water level averages.

Since the wells are of different depths and their portals are at different altitudes, it was deemed advisable for purposes of computing average water levels to establish a comparable datum plane at each well. On a day when the water levels were low and all the wells were measured, arbitrary datum planes were established 10 feet below the water surface of each well. The average elevation of the water surface above the arbitrary datum planes on that day was, therefore, 10 feet. Measurements on other dates have since been converted to the same datum planes, and averaged to determine the average fluctuations of the water table. This procedure permits the addition of new wells or the elimination of old wells without too great a disturbance of the averages. For example, a new well might be brought into the group on a day when the average was 11.5 feet. The arbitrary datum plane at the new well would be established 11.5 feet below the water surface in the well on that day. The averages thereafter may be affected only by the fluctuations in the new well and not by widely variable factors such as its depth or the altitude of its portal. This method of averaging is subject to refinement in detail, but the fundamental principles are as outlined above.

The Morrell well is near Moerls Corner, about 4 miles southeast of Old Bridge. It is a shallow dug well on the property of Joseph Morrell and is used only for observation purposes. The surface of the land at the well is about 75 feet above mean sea level. The well is in a small, flat, almost swampy valley where the water table is very near the surface and the vegetation is quite heavy. The valley is drained by three small streams that are usually dry during the summer months. The well was originally dug about 6 feet deep into a fine clayey black sand but in September, 1932, after a summer in which the well went dry, it was deepened to 8.5 feet. A water-stage recorder has been maintained on this well since August, 1923.

In 1936, for purposes of comparison with the Morrell well, another observation well was established in an area where the water table was not so close to the surface. The new well was constructed about half a mile from the Morrell well on the property of Rulif Hulsart, and is called the Hulsart well. It is a dug well 21 feet deep. The land surface at the well is about 114 feet above mean sea level. A water-stage recorder has been maintained on the well since its construction.

In 1932, three stream gaging stations were established a few miles east of the Perth Amboy Water Works in order that the runoff from the area might be measured and compared. One station was on Tennent Brook at Perrine's Clay Pit about half a mile upstream from the head of Runyon Pond. Another was on Deep Run near Spring Valley, and the third was on Matawan Creek at Matawan. The stations on Tennent Brook and Deep Run were discontinued after several years. The station on Matawan Creek is still in operation.

The measurements of water level in the different wells discussed herein and the farm well averages are published each year by the Geological Survey.[8] Some hydrographs are shown in Figure 8. The farm wells have been separated into two groups on the basis of their depth and of the nature of the fluctuations of water level in them. The shallow group includes 30 wells that are less than 25 feet deep and the deep group includes 5 wells that are 25 feet or more in depth. The average fluctuations of the two groups are represented by the two lines near the top of Figure 8. Measurements in most of the farm wells were discontinued from 1929 to 1931 owing to pressure of other work, and the break in the hydrograph of the deep wells is due to this lack of record. Some of the shallow wells were measured throughout the period. The third and fourth hydrographs in Figure 8 show the fluctuations of water level in the Hulsart and Morrell wells respectively. The Morrell well record is one of the longest continuous records of natural water-table fluctuations on the east coast. There are some longer or earlier well records such as those collected by the Plainfield-Union Water Company at Plainfield, New Jersey, and those collected on Long Island, New York, but they are either records of wells affected by pumping or there have been breaks in them. Monthly and normal monthly precipitation at the Runyon evaporation station are plotted at the bottom of Figure 8. The normal is the one used by the U. S. Weather Bureau on the basis of records through 1940.

The water levels in the Morrell and shallow farm wells are excellent indicators of the immediate effect of precipitation and of the use of water by plants in areas of shallow water table. Barksdale,[9] after studying the Morrell well record, described the great variety of ways in which precipitation affects the water table at different times. He showed that during the growing season the consumption of water by plants is almost as important as the precipitation in determining the position of the water table.

An inspection of Figure 8 shows that the hydrograph of the shallow farm wells is similar to that of the Morrell well. This is explained by the fact that the average characteristics of the shallow farm wells are similar to those of the Morrell well. The hydrograph of the shallow wells, however, does not have the saw-tooth form that appears on the Morrell well hydrograph. This is probably due to infrequency of measurement rather than to lack of fluctuation. Both hydrographs indicate

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[8] Meinzer, Wenzel, and others. Op. Cit. Annual reports on water levels and artesian pressure.

[9] Barksdale, H. C. "A ten-year record of water-table fluctuations near Runyon, New Jersey." American Geophysical Union, Fourteenth Annual Meeting, 1933. Section of Hydrology, page 466.

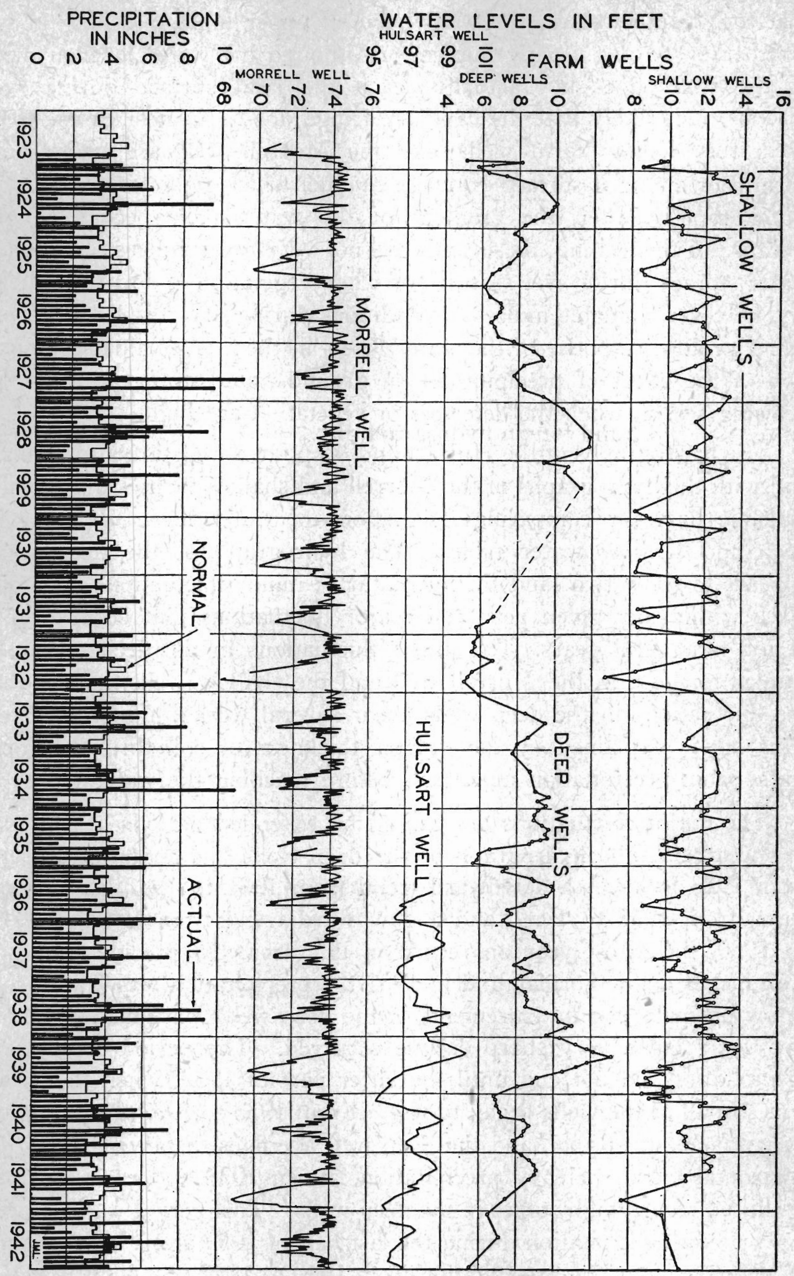


FIGURE 8.—Diagram showing the fluctuations of water levels in a group of water-table wells not affected by pumping, and the actual and normal monthly precipitation for the years 1923-1942.

that the water levels in the wells have an upper limit or ceiling above which they do not usually fluctuate. Although the water level in most of the wells does not actually reach the land surface during wet seasons, it is likely that the capillary fringe does. In most cases, however, the shallow farm wells like the Morrell well are near some natural or artificial surface drainage channel which removes the ground water rapidly when the gradient of the water table becomes high. Because of this ceiling, these wells are not very good indices of ground-water storage during wet seasons, or when vegetation is dormant. They are, however, valuable indices of conditions during dry periods. Furthermore, prompt response of the water levels in them is a valuable indication of the effect of precipitation on ground-water storage during the growing season when the demands of vegetation are high.

The hydrographs of the Hulsart and deep farm wells are also similar, and with the hydrographs of the Morrell and shallow farm wells provide valuable data for comparing fluctuations of water levels in areas of deep and shallow water tables. The hydrograph of the deep wells appears to show two kinds of fluctuations: minor fluctuations that take place within any given year and major fluctuations that occur over a period of several years. The minor fluctuations in the deep wells are similar to those in the Morrell well and the shallow wells, except that the fluctuations in the deep wells occur several weeks or months later. This lag is explained by the greater thickness of soil through which water from precipitation must pass before reaching the water table.

The major fluctuations are caused by extended periods of wet and dry weather. The hydrograph of the deep wells has an upward trend from 1923 to 1929, a downward trend from 1931 to 1932, an upward trend from 1933 to 1939, and a downward trend from 1939 to 1942. In 1930, the driest year on record in this area, the precipitation was 9.57 inches below normal, and in 1931 the precipitation was 7.23 inches below normal. No measurements of the deep wells were made in those two years but a very sharp decline occurred. The period of deficient precipitation did not end until the latter part of 1932, when the water levels in all of the wells began to rise. From 1933 to 1937 the precipitation was about normal, and the deep well averages displayed a roughly horizontal trend. Heavy precipitation late in 1938 and early in 1939 produced record high stages in the deep wells. This period was followed by very low precipitation during the last half of 1939 and a steep decline of water levels. The precipitation from 1940 to 1942 was slightly below normal, and the trend of the water levels in the deep wells was downward.

The hydrograph for the Hulsart well shows fluctuations from 1936 to the end of the record similar to that for the deep wells. The only apparent major disparity between the two is found in the last part of 1942, where the hydrograph for the Hulsart well, which is based upon continuous data, had an upward trend for the last few months, while the hydrograph for the deep wells, which was based upon occasional measurements, showed a downward trend for the same period. It is probable that this difference was caused by lack of measurements of the deep wells. If it had been possible to have measured the water levels some time within the previous month, it is believed that it would have resulted in a lower point than the last one as now plotted, and the trend would have been upward as in the Hulsart well. The most significant difference between the deep wells, including the Hulsart well, and the shallow wells, including the Morrell well, is that in the former group there is room for greater upward fluctuations and thus they can more readily indicate the effect of abnormal precipitation that extends from one year to the next.

## PHYSICAL PROPERTIES OF THE AQUIFERS

A considerable number of samples of unconsolidated materials from the different aquifers in Middlesex County have been collected and sent to Washington for analysis in the hydrologic laboratory of the Geological Survey. The results of these analyses are shown in the accompanying table of physical properties beginning on page 40. Some of these samples were from wells, others were collected volumetrically at the various exposures. Analyses of a considerable number of other samples from Middlesex County were reported by Stearns[10] in a paper published in 1927.

[10] Stearns, Norah Dowell, Laboratory tests on physical properties of water-bearing materials: U. S. Geol. Sur. water supply paper 596-F, 1927, pp. 166-167.

TABLE 3.—PHYSICAL PROPERTIES OF WATER-BEARING MATERIALS FROM MIDDLESEX COUNTY, NEW JERSEY

| Laboratory Number | Apparent specific gravity of oven dried sample | Mechanical analysis (*per cent by weight*) (*Grain sizes in millimeters*) Larger than 7.925 | 7.925-2.0 | 2.0-1.0 | 1.0-0.50 | 0.50-0.25 | 0.25-0.125 | 0.125-0.062 | 0.062-0.005 | Less than 0.005 | Porosity (*per cent by volume*) | Moisture equivalent (*per cent*) *by weight* | *by volume* | Coefficient of permeability |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | CAPE MAY FORMATION | | | | | | | | |
| 1629 | 1.59 | 13.4 | 9.0 | 3.0 | 5.4 | 35.3 | 22.4 | 6.9 | 1.5 | 2.3 | 36.8 | 4.9 | 7.8 | 275 |
| 1631 | 1.49 | .... | .... | 1.6 | 6.2 | 48.9 | 22.1 | 14.3 | 0.9 | 5.3 | 48.7 | 4.5 | 6.7 | 550 |
| 1632 | 1.70 | 12.7 | 11.8 | 6.2 | 13.2 | 37.2 | 8.5 | 5.0 | 0.9 | 4.0 | 34.0 | 4.2 | 7.2 | 445 |
| 1633 | 1.60 | .... | 1.7 | 1.8 | 10.7 | 35.4 | 36.6 | 9.9 | 1.6 | 1.9 | 44.0 | 2.9 | 4.6 | 440 |
| 1634 | 1.51 | .... | 0.6 | 2.0 | 4.3 | 39.0 | 33.7 | 14.5 | 1.5 | 2.7 | 48.0 | 4.9 | 7.4 | 350 |
| 1635 | 1.50 | .... | .... | .... | 0.6 | 9.6 | 71.3 | 16.2 | 1.5 | 0.7 | 47.6 | 1.7 | 2.5 | 550 |
| 1636 | 1.67 | 3.8 | 7.2 | 6.1 | 13.6 | 25.9 | 27.9 | 12.8 | 1.6 | 0.3 | 35.0 | 3.6 | 6.1 | 300 |
| 1639 | 1.66 | 3.5 | 4.8 | 5.3 | 19.5 | 40.2 | 15.8 | 5.8 | 3.0 | 1.6 | 38.7 | 3.3 | 5.4 | 200 |
| 1640 | 1.57 | 20.9 | 4.8 | 2.6 | 8.8 | 41.2 | 11.3 | 6.8 | 1.5 | 1.8 | 36.0 | 3.5 | 5.5 | 500 |
| 1641 | 1.47 | .... | .... | 1.4 | 2.8 | 29.1 | 34.2 | 18.8 | 7.7 | 5.5 | 45.6 | 6.7 | 9.3 | 560 |
| 1642 | 1.43 | .... | 1.8 | 2.7 | 8.7 | 44.9 | 23.2 | 10.9 | 2.6 | 4.6 | 47.6 | 7.4 | 10.5 | 200 |
| 1643 | 1.48 | .... | 10.3 | 3.0 | 5.7 | 35.5 | 21.0 | 18.4 | 2.0 | 3.4 | 46.2 | 7.3 | 10.8 | 215 |
| 1644 | 1.48 | .... | .... | 2.8 | 2.4 | 41.0 | 30.0 | 16.0 | 3.9 | 3.4 | 45.1 | 3.9 | 5.8 | 310 |
| 1575 | 1.52 | .... | 6.8 | 3.9 | 7.8 | 24.7 | 30.6 | 18.8 | 4.7 | 2.6 | 42.3 | 3.3 | 4.9 | 190 |
| 1576 | 1.82 | .... | 17.9 | 6.0 | 10.5 | 24.8 | 27.5 | 10.4 | 1.8 | 9.2 | 30.0 | 2.6 | 4.7 | 180 |
| 1578 | 1.46 | .... | 3.7 | 3.2 | 5.2 | 29.6 | 36.2 | 14.4 | 3.4 | 3.9 | 47.1 | 6.8 | 9.9 | 200 |
| 1579 | 1.54 | .... | 5.2 | 3.0 | 12.4 | 45.1 | 25.6 | 5.5 | 1.3 | 1.3 | 43.0 | 3.6 | 5.5 | 425 |
| 1580 | 1.50 | .... | 2.7 | 5.2 | 19.4 | 40.8 | 21.4 | 4.5 | 2.0 | 2.9 | 44.3 | 4.6 | 6.9 | 300 |
| 1581 | 1.49 | .... | 8.4 | 2.8 | 5.2 | 35.1 | 33.0 | 7.5 | 3.9 | 4.2 | 45.8 | 5.5 | 8.2 | 290 |
| 2182 | 1.56 | .... | .... | 2.6 | 15.6 | 61.4 | 13.9 | 1.4 | 0.8 | 3.4 | 42.0 | 3.1 | 4.8 | 900 |
| 2184 | 1.46 | .... | .... | 2.2 | 3.8 | 31.7 | 26.9 | 24.1 | 6.8 | 3.6 | 45.4 | 4.2 | 6.1 | 300 |
| 2185 | 1.52 | .... | .... | 7.8 | 6.3 | 47.7 | 26.7 | 4.2 | 3.2 | 4.1 | 42.6 | 4.7 | 7.2 | 250 |
| 2186 | 1.49 | .... | .... | 1.2 | 6.6 | 43.7 | 35.0 | 8.4 | 2.9 | 1.8 | 44.3 | 2.5 | 3.7 | 500 |
| 2188 | 1.47 | .... | .... | .... | 1.1 | 33.8 | 52.4 | 6.3 | 2.8 | 3.4 | 44.5 | 3.1 | 4.5 | 240 |

## PHYSICAL PROPERTIES OF WATER-BEARING MATERIALS FROM MIDDLESEX COUNTY, NEW JERSEY

### SOURCES OF SAMPLES

#### CAPE MAY FORMATION

1629. Runyon; test well A-41 at 9½ foot depth.
1631. do ; test well C-2.
1632. do ; test well C-3 at 7 foot depth.
1633. do ; test well D-3 at 7½ foot depth.
1634. do ; test well G-1 at 7 foot depth.
1635. do ; test well G-3 at 5 foot depth.
1636. do ; test well J-1 at 8 foot depth.
1639. Old Bridge; test well M-1 at 3 foot depth. Possibly recent alluvium.
1640. do ; test well M-2 at 3 foot depth. Possibly recent alluvium.
1641. Runyon; test well L-1 at 6 foot depth.
1642. do ; test well L-2 at 8½ foot depth.
1643. do ; test well L-3 at 8 foot depth.
1644. do ; test well N-1 at 2 foot depth.
1575. do ; test well G-1.
1576. do ; test well J-2.
1578. do ; test well B-4 at 8 to 9 foot depth.
1579. do ; test well D-1 at 8 to 9 foot depth.
1580. do ; test well D-2 at 8 to 9 foot depth.
1581. do ; test well D-2 at 10½ foot depth.
2182. do ; highway cut on Old Bridge-South Amboy highway opposite Perth Amboy Water Works, 3½ feet below surface.
2184. do ; Perth Amboy Water Works well field ¼ mile south of pond and near test well S-3, 1½ feet below surface.
2185. do ; Perth Amboy Water Works well field about ⅛ mile east of sample 2184. Depth 1½ feet.
2186. do ; Perth Amboy Water Works well field about ¼ mile west of sample 2184. Depth 1 foot.
2188. Browntown; ¾ mile NNW of, depth 1 foot.

#### PENSAUKEN FORMATION

2178. Parlin; Crossman pit, 5 feet above contact with Cretaceous sand.
2179. do ; do , 1 foot above contact with Cretaceous sand.
2180. Old Bridge; ½ mile NW of, 14½ feet above contact with Cretaceous clay; arkosic.

#### ENGLISHTOWN SAND

2189. Morristown; from highway cut 10 feet above base of formation.
2192. Browntown; 1 mile east of, from sand pit about 200 yards south of highway, about 20 feet above base of formation.
2193. do ; 1 mile east of, from cut beside by-road leading up-hill from source of sample 2192, 75 feet above base of sample.
2194. do ; 1 mile east of, from top of hill a short distance above sources of samples 2192 and 2193, near top of formation.
2195. Englishtown; 1 mile NW of, from small sand pit beside highway, 75 feet above base of formation.
2196. Moerl's Corner; ⅓ mile north of, from small sand pit beside road, 55 feet above base.
2197. do ; about ⅓ mile north of, from road cut about 55 feet above base.

### MAGOTHY FORMATION

2187. Browntown; ¾ mile west of, from road cut about ¼ mile south of highway, 25 feet above base.
2190. do ; ¾ mile west of, from same location and about 2 feet above sample 2187.
2191. Cheesequake; Perrine's pit, 8 feet above base of formation.
2198. Runyon; 1¼ miles NE of, from small sand pit about 100 yards north of highway, about 10 feet above base.
1582. Browntown; ¾ mile SE of, Dr. Ostberg's well, 160 to 165 foot depth.

### OLD BRIDGE SAND MEMBER OF THE RARITAN FORMATION

2167. South River; Marcus Wright's pit, 5 feet above water level, elevation above base of formation not determined.
2168. do ; Marcus Wright's pit, 11 feet above sample 2167.
2170. do ; do , 14 feet above sample 2168.
2171. do ; do , 24 feet above sample 2170 and 6 feet below contact with Pensauken formation.
2173. Parlin; Crossman pit, 8 feet above contact with South Amboy fire clay.
2174. do ; do , 18 feet above base of sand.
2175. do ; do , 28 feet above base of sand.
2176. do ; do , 39 feet above base of sand.
2177. do ; do , 48 feet above base of sand and 5 feet below contact with Pensauken formation.
2181. Old Bridge; South River Sand Company pit, 20 feet below contact with Amboy stoneware clay.
1630. Runyon; test well A-41, 13 foot depth.
1637. do ; test well K-1, 7 foot depth.
1638. do ; test well J-4, 7 foot depth.

### SAYREVILLE SAND MEMBER OF THE RARITAN FORMATION

2172. Sayreville; from pit near Raritan River, 3 feet above contact with Woodbridge clay and 4 feet below contact with South Amboy fire clay.

### FARRINGTON SAND MEMBER OF THE RARITAN FORMATION

2160. South River; abandoned sand pit about 1½ miles north of town, 20 feet above Raritan fire clay.
2161. Same pit as 2160, 25 feet above Raritan fire clay.
2162. Same pit as 2160, 35 feet above Raritan fire clay.
2163. South River; about 1 mile northwest of town, 2½ feet below Woodbridge clay.
2164. Same locality as 2163, 3½ feet below Woodbridge clay (represents locally coarse streak).
2165. Milltown; from highway cut about 1 mile east of town, 1 foot above Raritan fire clay.
2166. Milltown; Marcus Wright's pit, 13½ feet above Raritan fire clay.

The volumetric samples were collected by driving a sampling tube perpendicularly into a smooth flat surface of the aquifer. The depth to which the tube was driven was carefully measured. The material along one side of it was then excavated without disturbing the tube or its contents. The sample was cut off flush with the end of the sampler, transferred to a can and sealed for shipment to the laboratory. The known area of the sampling tube and the depth to which it is driven make possible a computation of the volume occupied by the sample in nature. The sampling apparatus and technique were devised by Mr. Meinzer and are described in detail by Stearns.[11] Volumetric samples are considered more reliable than samples from wells, because there is less likelihood of collecting foreign material or of losing fine particles from the sample. Furthermore in making determinations of porosity and permeability in the laboratory an attempt is made to adjust the volume of the sample to that occupied by it in nature.

A description of the laboratory procedure used to determine the various factors shown in the table and a discussion of their significance is also given by Stearns in the same paper. The significance of the coefficient of permeability and the various laboratory and field methods of determining it are further discussed by Wenzel[12] in a paper published in 1942. A brief discussion and explanation of the various features shown in the table is given below.

The apparent specific gravity is the specific gravity of an oven-dried sample of the sand including the pore spaces. It must not be confused with the specific gravity of the mineral grains composing the sand.

Mechanical analyses of granular materials are made by separating into groups the grains of different sizes and determining what percentage by weight each group constitutes. The United States Bureau of Soils[13] has adopted the following nomenclature and arbitrary limiting diameters, in millimeters:

| | |
|---|---|
| Fine gravel | 2 to 1 |
| Course sand | 1 to 0.5 |
| Medium sand | 0.5 to 0.25 |
| Fine sand | 0.25 to 0.1 |
| Very fine sand | 0.1 to 0.05 |
| Silt | 0.05 to 0.005 |
| Clay | less than 0.005 |

11 Stearns, Norah Dowell, Op. cit., p. 122.

12 Wenzel, L. K., Methods for determining permeability of water bearing materials with special reference to discharging well methods: U. S. Geol. Survey Water Supply Paper 887, 1942.

13 Mechanical analysis of soils: U. S. Dept. Agr. Bur. Soils Bull. 4, 1896. Briggs, L. J., Martin, F. O., and Pierce, J. R., The centrifugal method of mechanical soil analysis: U. S. Dept. Agr. Bur. Soils, Bull. 24, 1904. Fletcher, C. C., and Bryan, H., Modification of the method of mechanical soil analysis: U. S. Dept. Agr. Bur. Soils, Bull. 84, 1912.

Three of the ranges for the smaller sized grains as determined in the Water Resources laboratory of the Geological Survey and given in table 3, differ slightly from those listed above. For all practical purposes, however, the same arbitrary definitions may be applied to the results given in the table.

The porosity of a sample is the percentage of pore space in its total volume; that is, the percentage of space not occupied by solid mineral matter.

The moisture equivalent is the volume of water that a saturated sample of the material will hold against a centrifugal force 1,000 times as great as the force of gravity expressed as a percentage of the total volume of the sample. It is a measure of the specific retention of the formation from which the sample was taken. The term "specific retention" is used to express the quantity of water that a soil will retain against the pull of gravity if it is drained after having been saturated. The ratio of the volume of this retained water to the total volume of the sample, expressed as a percentage, is the specific retention. It is impossible to determine the specific retention of a formation from a small sample because capillary attraction holds a greater proportion of the water in a short column of a material than in a long column of the same material. For the unconsolidated material considered in this report the moisture equivalent as determined in the laboratory is probably about the same as the specific retention of the formation. The porosity less the moisture equivalent is therefore an approximate measure of the quantity of water that can be drained out of the formation under the influence of gravity.

The coefficient of permeability is a measure of the capacity of the sand to transmit water. It is based upon Darcy's law that the rate of flow in capillary tubes varies in direct proportion to the hydraulic gradient. As used by the Geological Survey and expressed in field terms, the coefficient of permeability is the number of gallons of water a day at 60° F. that would flow through a section of the sand one mile wide and one foot thick (measured at right angles to the direction of flow) under a hydraulic gradient of one foot per mile.

## CHEMICAL CHARACTER OF THE GROUND WATER

The quality of the ground waters in Middlesex County varies somewhat from one aquifer to another and to some extent from one place to another within the same aquifer. Most of it is of excellent quality, however, both for domestic and for industrial uses. Usually the water requires no treatment except to remove objectionable quantities of iron or adjust the pH. Most of the ground waters encountered in the county are slightly acid and the pH is adjusted by adding lime or caustic soda to make it more nearly neutral. In some cases softening may also be desirable. Analyses of representative samples from each of the more important aquifers are given in table 4 on page 48, and the peculiarities of the different waters are discussed along with their other characteristics in the section on hydrology and geology of the rock formations. It should be noted that the analyses given in the table, as well as the discussion herein, deal entirely with the chemical composition of the waters and not with their sanitary quality. The sanitary quality of the water, the presence or absence or harmful bacteria or organic matter, depends upon the local conditions around the well and upon the handling of the water after it leaves the well, but not usually upon the aquifer from which it is drawn.

## TABLE 4

ANALYSES OF WATER FROM THE PRINCIPAL WATER-BEARING FORMATIONS OCCURRING IN MIDDLESEX COUNTY, NEW JERSEY.
IN PARTS PER MILLION.
ANALYZED IN THE WATER RESOURCES LABORATORY OF THE U. S. GEOLOGICAL SURVEY.

| Sample No. | Date Collected | Silica $SiO_2$ | Iron Fe | Manganese Mn | Calcium Ca | Magnesium Mg | Sodium Na | Potassium K | Bicarbonate $HCO_3$ | Sulphate $SO_4$ | Chloride Cl | Nitrate $NO_3$ | Total Dissolved Solids | Total Hardness as Calcium Carbonate $CaCO_3$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 7/17/23 | 5.6 | 1.0 | .... | 4.6 | 1.4 | 5.3 | | 2.4 | 16 | 5.0 | trace | 46 | 17 |
| 2 | 4/14/33 | 4.4 | .35 | .15 | 7.2 | 2.3 | 4.7 | 1.2 | 0 | 23 | 7.0 | 2.2 | 58 | 27 |
| 3 | 11/12/24 | 11 | .10 | .... | 32 | 7.2 | 9.4 | | 100 | 32 | 4.0 | trace | 138 | 110 |
| 4 | 11/13/24 | 10 | .10 | .... | 32 | 6.6 | 6.9 | | 98 | 34 | 3.0 | trace | 139 | 107 |
| 5 | 11/13/24 | 9.1 | .69 | .... | 25 | 5.7 | 7.3 | | 99 | 12 | 3.0 | trace | 109 | 86 |
| 6 | 11/13/24 | 9.5 | 1.7 | .... | 26 | 5.4 | 8.3 | | 85 | 25 | 2.0 | trace | 124 | 87 |
| 7 | 4/18/33 | 2.0 | 34 | 0.2 | 2.9 | 1.5 | 2.8 | .4 | 12 | 1.4 | 6.0 | .10 | 27[a] | 13 |
| 8 | 6/ 6/41 | 1.1 | 107 | .... | 6.2 | 3.3 | 3.0 | 5.1 | 30 | 1.3 | 4.2 | 11 | 50[a] | 29 |
| 9 | 4/14/33 | .... | .02 | .0 | .... | .... | 5.9 | | 2.0 | 6 | 5.0 | 4.7 | 25 | 6 |
| 10 | 11/13/42 | 5.9 | 3.2 | trace | 1.1 | 1.4 | 3.0 | 1.1 | b | 12 | 5.1 | .1 | 29[a] | 8.5 |
| 11 | 11/13/42 | 7.1 | 3.2 | trace | 1.0 | .9 | 1.9 | .8 | c | 8.1 | 2.6 | .0 | 22[a] | 6.2 |
| 12 | 11/13/42 | 7.1 | 5.3 | .05 | 1.6 | 1.5 | 2.8 | 1.2 | d | 15 | 4.5 | .5 | 34[a] | 10 |
| 13 | 4/16/33 | .... | 5.8 | .0 | 11 | 3.1 | 2.9[e] | | 3.0 | 34 | 6.0 | .2 | .... | 40 |
| 14 | 4/18/33 | .... | .77 | .0 | <6 | .... | 5.6[e] | | 6.0 | 10 | 6.0 | .5 | 29[e] | 12 |
| 15 | 4/18/33 | .... | 5.2 | .0 | <6 | .... | 3.0[e] | | 0 | 8 | 5.0 | .1 | 19[e] | 9 |
| 16 | 4/15/33 | 5.4 | 2.1 | .0 | 5.0 | 1.7 | 2.9 | .07 | 0 | 19 | 5.0 | .5 | 42 | 19 |
| 17 | 7/18/23 | .... | .87 | .... | 9.0 | 2.6 | 1.2[e] | | 2.4 | 23 | 7.0 | .... | 65 | 33 |
| 18 | 4/14/33 | 5.0 | 1.6 | .0 | 2.4 | .9 | 2.5 | .4 | 0 | 9.9 | 3.0 | .1 | 25 | 9.7 |
| 19 | 4/14/33 | .... | 1.9 | 0.1 | .... | .... | 4.1[e] | | 18 | 9 | 4.0 | .1 | 34[e] | 21 |
| 20 | 4/14/33 | .... | 3.5 | 0.1 | .... | .... | 4.3[e] | | 7.0 | 9 | 3.0 | .1 | 23 | 10 |
| 21 | 10/ 4/42 | .... | .... | .... | .... | .... | ... | ... | 14 | 9[f] | 2.1 | .... | .... | 16 |
| 22 | 10/ 7/42 | .... | .... | .... | .... | .... | ... | ... | 12 | 13[f] | 13 | .... | .... | 28 |
| 23 | 7/18/23 | 8.0 | 4.4 | .... | 2.9 | .9 | 5.0 | | 6.1 | 11 | 3.0 | trace | 38 | 11 |
| 24 | 4/15/33 | 8.7 | 6.0 | .0 | 3.8 | .9 | 2.1 | .4 | 5.0 | 10 | 3.0 | .1 | 37 | 13 |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 25 | 8/18/42 | .... | .... | .... | .... | .... | ... | ... | 94 | 89 | 13 | 9.3 | .... | 158 |
| 26 | 8/18/42 | .... | .... | .... | .... | .... | ... | ... | 146 | 112 | 10 | 1.5 | .... | 189 |
| 27 | 8/14/42 | .... | .... | .... | .... | .... | ... | ... | 106 | 63 | 34 | 6.6 | .... | 147 |
| 28 | 8/14/42 | .... | .... | .... | .... | .... | ... | ... | 190 | 43 | 88 | 29 | .... | 300 |
| 29 | 8/14/42 | .... | .... | .... | .... | .... | ... | ... | 184 | 10[f] | 24 | .6 | .... | 153 |
| 30 | 8/14/42 | .... | .... | .... | .... | .... | ... | ... | 150 | 103 | 34 | 30 | .... | 204 |
| 31 | 6/ 6/41 | 19 | .04 | .... | 32 | 14 | 50 | 2.6 | 114 | 91 | 26 | 27 | 308 | 137 |
| 32 | 8/18/42 | .... | .... | .... | .... | .... | ... | ... | 160 | 83 | 10 | 5.8 | .... | 183 |
| 33 | 8/14/42 | .... | .... | .... | .... | .... | ... | ... | 122 | 149 | 7.8 | .9 | .... | 147 |
| 34 | 8/18/42 | .... | .... | .... | .... | .... | ... | ... | 254 | 26[f] | 16 | .3 | .... | 150 |

a. Does not include iron which was nearly all precipitated at time of analysis.
b. Acid equivalent to 4.0 parts per million free sulfuric acid.
c. Acid equivalent to 0.8 parts per million free sulfuric acid.
d. Acid equivalent to 5.6 parts per million free sulfuric acid.
e. Calculated.
f. By turbidity.

## SOURCE AND DESCRIPTION OF SAMPLES REFERRED TO BY NUMBER IN TABLE OF ANALYSES

### SURFACE WATER

1. Old Bridge. Deep Run at Deep Run pumping station, Perth Amboy Water Works. Analyzed by C. S. Howard.
2. Runyon. Tennent Brook at stream gaging station. Analyzed by K. T. Williams.

### MOUNT LAUREL AND WENONAH SANDS

3. Avon-by-the-Sea. Avon-by-the-Sea Water Department. Well 503 feet deep. Analyzed by C. S. Howard.
4. Neptune Township. Ocean Grove Water Works. Several wells 480 feet deep. Analyzed by C. S. Howard.

### ENGLISHTOWN SAND

5. Belmar. Belmar Water Department. Well 650 feet deep. Analyzed by C. S. Howard.
6. Neptune Township. Asbury Park Water Department. Well 600 feet deep. Analyzed by C. S. Howard.

### MAGOTHY FORMATION

7. Browntown. George Wiem. Well 95 feet deep. Analyzed by K. T. Williams.
8. Browntown (¾ mile southeast). Dr. Eric Ostberg. Well 165 feet deep. Flourides 0.4 p.p.m. Analyzed by Margaret D. Foster.

### OLD BRIDGE SAND MEMBER OF RARITAN FORMATION

9. Old Bridge. Anheuser Busch Co. Well 100 feet deep. Analyzed by K. T. Williams.
10. Old Bridge. Duhernal Water Supply. Well 1. Well 76 feet deep. Flouride .0 p.p.m., pH 4.1. Analyzed by E. W. Lohr.
11. Old Bridge. Duhernal Water Supply. Well 11. Well 94 feet deep. Flouride .0 p.p.m., pH 4.8. Analyzed by E. W. Lohr.
12. Old Bridge. Duhernal Water Supply. Mixed samples from all operating wells. Flouride .0 p.p.m., pH 3.9. Analyzed by E. W. Lohr.
13. Runyon. Perth Amboy Water Department. Well 36. 50 feet deep. Analyzed by K. T. Williams.
14. Runyon. Perth Amboy Water Department. Well 93. 60 feet deep. Analyzed by K. T. Williams.
15. Runyon. Perth Amboy Water Department. Well 73. 72 feet deep. Analyzed by K. T. Williams.
16. Runyon. Perth Amboy Water Department. Well 2. 62 feet deep. Ignition loss 6.5 p.p.m. Analyzed by K. T. Williams.
17. Runyon. Perth Amboy Water Department. Mixed water from all wells tapping the Old Bridge sand. Analyzed by C. S. Howard.
18. Runyon. Perth Amboy Water Department. Mixed water from all wells tapping the Old Bridge sand. Analyzed by K. T. Williams.

FARRINGTON SAND MEMBER OF RARITAN FORMATION

19. Old Bridge. Anheuser Busch Co. Well 300 feet deep. Analyzed by K. T. Williams.
20. Parlin. E. I. duPont deNemours & Co. Well 5. 300 feet deep. Analyzed by K. T. Williams.
21. Parlin. E. I. duPont deNemours & Co. Well 5. 300 feet deep. Flouride .0 p.p.m. Analyzed by J. D. Boreman.
22. Parlin. Hercules Powder Co. Well 235 feet deep. Flouride .0 p.p.m. Analyzed by J. D. Boreman.
23. Runyon. Perth Amboy Water Department. Well 260 feet deep. Analyzed by C. S. Howard.
24. Runyon. Perth Amboy Water Department. Well 300 feet deep. Analyzed by K. T. Williams.

NEWARK GROUP

25. Dunellen. Art Color Printing Co. Well 304 feet deep. Analyzed by J. D. Boreman.
26. East Bound Brook. Air Reduction Corp. Well 220 feet deep. Analyzed by J. D. Boreman.
27. Metuchen. Costa Ice Cream Co. Well 239 feet deep. Analyzed by J. D. Boreman.
28. New Brunswick. Arctic Ice Co. Well 300 feet deep. Analyzed by J. D. Boreman.
29. New Brunswick. New Brunswick Bottling Co. Well 175 feet deep. Analyzed by J. D. Boreman.
30. New Brunswick. Thodes Inc. Well 520 feet deep. Analyzed by J. D. Boreman.
31. Plainsboro. Walker Gordon Dairy. Well 506 feet deep. Flourides 0.1 p.p.m. Analyzed by Margaret D. Foster.
32. South Plainfield. Cornell Dubilier Corp. Well 350 feet deep. Analyzed by J. D. Boreman.
33. Woodbridge Township. Maple Hills Dairy. Well 312 feet deep. Analyzed by J. D. Boreman.
34. Woodbridge Township. Uniform Chemical Products Co. Well 300 feet deep. Analyzed by J. D. Boreman.

Considerable attention has been paid in recent years to the fluoride content of drinking waters because of the effect of this element upon the development and decay of the teeth of those who drink water containing it. Brief mention should, therefore, be made of the fluoride content of the waters in Middlesex County, although the results of analyses seem to indicate that most ground waters in the county do not contain enough fluoride to be of any significance. The results of the research on this problem seem to indicate that quantities of fluoride in drinking water ranging from 0.3 to 0.6 part per million are necessary to obtain any measurable beneficial effect in the way of preventing tooth decay,[14] and it is fairly well established that about one part per million is the least amount that is likely to have any deleterious effect on the development of children's teeth.[15] Determinations of fluoride were

[14] Dean, H. Trendley, Arnold, Francis A., Jr., and Elvere, Elias, Domestic water and dental caries, V; Public Health Reports, Vol. 57, pp. 1155-1179, 1942.

[15] Dean, H. Trendley, Chronic endemic dental fluorosis: Jour. Amer. Med. Assoc., Vol. 107, pp. 1269-1272, 1936.

made only in the more recent complete analyses of water shown in the table. They seem to indicate, however, that all the ground waters in the county, with the possible exception of some water from the Magothy formation and possibly also some from the Newark group, contain too little fluoride to be of any significance. None of them contain enough fluoride to be harmful. Analyses of waters from other parts of New Jersey seem to confirm these conclusions.

## HYDROLOGY AND GEOLOGY OF THE ROCK FORMATIONS

The geologic formations occurring in Middlesex County are discussed in the following pages in the same order that they appear in the stratigraphic table on page 18. Maps showing their areal extent are given on figures 4, 5, and 6. A brief geologic description of each formation or member listed in the table is presented. In general the reader is referred to the stratigraphic table and to the text accompanying it for the geologic age and relationship of the formations discussed in this section. Discussions of the groups into which the various formations or members fall is presented only when common features may best be described in this way. The hydrology of the various aquifers is presented in more or less detail depending upon their importance. Detailed discussions of the development and safe yield of the more important aquifers are also presented.

### Cenozoic Sequence

### QUATERNARY SYSTEM

#### Recent Series

#### ALLUVIUM

A preponderance of evidence indicates that since the retreat of the last glacial ice sheet, southern New Jersey has remained relatively static, with little or no movement of the land, either up or down, in relation to the level of the sea. During this period the streams have worked ceaselessly to remove the blanket of sand and gravel which had been deposited in all the larger valleys in Pleistocene time, and some of it, together with mud and organic material, has been redeposited in tidal flats and along stretches of the streams where the gradients are low. Such recently deposited material is known as alluvium and it covers several square miles in Middlesex County. It is relatively impermeable and of no importance as a source of water supply. Upstream from tidal limits the deposits are small, and so far as known, everywhere less than 10 feet thick; but bordering Cheesequake Creek, the South, and the Raritan Rivers they are broad and very much thicker. In fact, test boreholes have shown that nearly two miles southwest of the mouth of Cheesequake Creek the alluvium—here a soft mud filling—is more than 50 feet thick. Of greater importance from a water-supply standpoint is the deposit of silt and mud which has accumulated in the channel of the Raritan River north and west of Sayreville and which blankets the underlying Farrington sand member of the Raritan formation and tends to prevent the contamination of that sand by salt water from the river. Test boreholes drilled prior to the construction of the Eastern New Jersey Power Company plant at Sayreville disclosed the fact that south of Crab Island the mud extends down 53 to 55 feet, within 2 feet of the underlying bedrock.

## EOLIAN DEPOSITS

At present a large percentage of the southern half of Middlesex County is forested and winds have little effect in shifting the sand and soil of the region. That it was not so during some period since the deposition of the Cape May formation may be surmised from the sand dunes about one mile south of Spotswood and the rather widespread occurrence of typical Cape May material on the hilltops and higher slopes southeast of the South River between Matchaponix, Texas and Browntown. Similar material does not mantle the slopes northwest of the South River and it would therefore seem reasonable to suppose that the strong winds which accomplished this work came from the north or northwest. Because the wind-blown material is continuous with the undisturbed Cape May deposits it is impossible to separate them in mapping except on an arbitrary basis; and since elevation 40 is about the upper limit of the Cape May formation along the shore and in the valley of the South River, that elevation was made the dividing line in mapping these deposits.

In a few small areas the Eolian deposits overlie impermeable materials, and are sufficiently thick to yield satisfactory water supplies for domestic or farmstead purposes. In such places they provide the only water supplies available for such purposes without the construction of fairly deep drilled wells. Otherwise they have relatively little hydrologic importance.

**Pleistocene Series**

## WISCONSIN DRIFT

The Wisconsin drift was deposited by the last of four huge continental ice sheets of Pleistocene age which covered portions of northern United States. It forms a nearly continuous mantle over the underlying Triassic and Cretaceous rocks in the northeast part of the county. The southern limit reached by the Wisconsin ice sheet in Middlesex County is roughly along a curved line from Plainfield to Metuchen and the mouth of the Raritan River at Perth Amboy. The glacier advanced from the north approximately to this line, then climatic conditions became such that the rate of movement southward just equalled the rate of melting with the result that the front of the glacier oscillated back and forth along this line. The ice dropped and piled up a huge mass of debris on its margin which forms the terminal moraine and the waters from the melting glacier deposited large amounts of gravel, sand and silt to the southwest forming an outwash plain. Later, as the climate became warmer, the ice front melted back leaving a blanket of till covering all of the county northeast of the moraine. The drift is of importance from a water-supply standpoint primarily because some parts of it are permeable enough to absorb water from precipitation and transmit it readily into the underlying beds.

The *outwash plain,* found between Metuchen, Plainfield and East Bound Brook, covers an area of about 16 square miles. It consists of layers of sand and gravel which together are called stratified drift and are so mapped on figure 4 on page 19. The stratified drift is about 10 to 60 feet thick on the eastern edge near the moraine. The material becomes finer and the deposit thins to the west so that at its irregular western border it is largely sand. In general the stratified drift is quite permeable, but it is too thin and covers too small an area to be in itself an important source of water. However, it holds water which percolates into the underlying Triassic rocks and this has increased the yield of a good many wells in that formation over and above the average yield of wells drawing from uncovered Triassic shale.

The *terminal moraine* is composed of a mixture of red clay, sand, gravel and a few boulders. In most places the material is fairly impermeable and does not yield much water, but in a few localities there are beds of stratified permeable material and the yield is higher. Because these areas are small, however, large supplies are not available.

The southwestern or outer margin of the terminal moraine is fairly well defined, as its surface rises fairly abruptly 100 to 150 feet above the outwash plain. The moraine is from one to one and one-half miles wide, and its inner border is less well defined because it grades into the till plain to the northeast. The surface of the moraine is a series of hummocks and depressions, many of which are undrained and because of the impervious nature of the material are filled by small lakes. The thickness of the moraine is variable but ranges between 80 and 150 feet.

A *till plain* of Wisconsin age covers the area from the terminal moraine to the northeastern edge of the county. The till is similar to the morainic material and consists of unassorted and relatively impermeable red clay, sand, gravel and boulders derived largely from the underlying Triassic rocks. Its average thickness is only 20 to 30 feet with about 80 feet as a maximum. It is not an important source of ground water.

In some places the materials composing the terminal moraine and the till plain are so impermeable that they probably act as a roof over the underlying rocks and exclude from them much of the water from precipitation and from stream flow. This is indicated by the number of small ponds that have formed in depressions on these materials. On the whole it is probable that they do not increase but may decrease the amount of ground water that might otherwise be available from the underlying rocks.

## CAPE MAY FORMATION

The Cape May formation is typically a pinkish-yellow, fine to medium-grained quartz sand with occasional small pebbles of quartz and ironstone, but it sometimes departs considerably from this type. For example, just north of the railroad station at Morgan, it is well exposed in a small pit where the basal portion is approximately 50% gravel, whereas the upper 5 feet of the deposit is fully 75% sand. The pebbles are chiefly quartz, but ironstone and unaltered flint were also noted. Five hundred feet north the pebbly lower portion is lacking.

In the valley of the South River and along the south shore of the Raritan River the Cape May formation is rather consistently true to type and in general forms a rather thin mantle only three to ten feet thick over the underlying Cretaceous sediments except where it fills the pre-Cape May channels of these streams. North of the Raritan River, however, there is a marked change in the composition of the Cape May. There it contains numerous partly rounded pebbles and fragments of Triassic red sandstone and shale, as well as fairly numerous lumps of Cretaceous clay. Apparently in Cape May time there were even fewer outcrops of Triassic rocks south of the Raritan River than now, consequently only the northern tributaries of that river transported such material. The reason for the absence of clay lumps in the Cape May deposits south of the Raritan is not clear.

It has already been stated that the Cape May formation where it is exposed in the valley of the South River is only 3 to 10 feet thick *except where it fills pre-Cape May stream channels.* The many borings made for the proposed Intracoastal Ship Canal across New Jersey threw new light on the recent physiographic history of this region as well as affording a splendid opportunity to study the character of the formations below the surface to a depth of 50 feet below mean low tide. Through the courtesy of the War Department, opportunity was afforded to examine all the samples from the test borings and from these it was learned that in pre-Cape May time, the channels of the Raritan River, the South River and Cheesequake Creek were far deeper than at present. For example, near the mouth of Cheesequake Creek, typical Cape May material extends down to a level more than 52 feet below mean tide and half a mile northeast of Spotswood the pre-Cape May channel of the South River was 30 feet below mean tide. Where the present channel of the Raritan River narrows about a mile downstream from the Washington Canal, the pre-Cape May channel extended down to elevation –48 and beneath the new Edison Bridge connecting Perth Amboy with South Amboy the old channel at one point was 67 feet below mean tide. These examples are sufficient to demonstrate that prior to Cape May time the land must have stood at least 50 feet higher relative to sea-level than it does at the present time in order for the streams mentioned to have cut their pre-Cape May channels. In Cape May time—presumably a late interglacial epoch—the sea rose to a level 40 to 50 feet higher than at present, deposition occurred, and a few terraces, such as that at Morgan, were carved by wave action. That this epoch was of relatively short duration is evidenced by the lack of sea-cliffs and well-developed terraces.

Deposition of the Cape May sand and gravel was followed by a glacial epoch during which the sea stood at least 50 feet lower than at present and the stream channels were cut to levels within a few feet of their former positions. Then the ice melted, the sea rose, and for the last few thousand years the rivers have been busily filling their channels with the deposits of soft mud already discussed under the heading of "Alluvium".

The principal hydrologic importance of the Cape May is that it overlies some of the other aquifers and increases their intake capacity. This is especially true of the Old Bridge sand, which it overlies in the vicinity of the Perth Amboy Water Works and the Duhernal well field. There the Cape May not only overlies the aquifer, but also covers some of the adjoining clay members and water falling on the Cape May above these clays probably can move laterally through it into the aquifer, thus effectively increasing the size of its intake area. Like the Eolian deposits, the Cape May is also an important source of farmstead and domestic water supplies where it overlies thick impermeable clay layers.

Analyses of a considerable number of samples from the Cape May formation are given in the table on pages 40 to 44. It will be noted that some of them contained fairly high percentages of coarse sand and fine gravel, and that the percentage of very fine material is relatively low in all samples. The porosity ranges from 30 to 49 percent and averages about 43 percent, and the moisture equivalent by volume ranges from 2.5 percent to 10.8 percent. The average difference between the porosity and the moisture equivalent by volume for the samples collected volumetrically is 38 percent. If it is assumed that the specific yield is equal to the difference between the porosity and the moisture equivalent, then a block of the Cape May sand one square mile in area and one foot thick is capable of storing about 80 million gallons of available water. The coefficient of permeability ranges from 180 to 900 and a weighted average is about 450.

## PENSAUKEN FORMATION

In the southern half of Middlesex County most of the hills and upland above 60 feet in altitude are covered with a veneer of yellow to brown, clayey sand and gravel called the Pensauken formation. At the time of deposition the formation was probably continuous over the area, but subsequent erosion, particularly in stream valleys, has left it in patches and discontinuous areas ranging from a foot or less to as much as 70 feet thick.

The largest area is between Lawrence Brook and the South River west of the Borough of South River and extending southwest to Cranbury. The Pensauken formation in this area is quite important because it blankets the truncated sand members of the Raritan formation. Other important areas of the Pensauken are north of the Raritan River and in the area bounded by the Raritan Bay, the Raritan River, the South River and north of a line from Old Bridge to Cheesequake. Several hills south of the South River are also capped by the Pensauken formation. In this area the formation was deposited on an irregular surface of eroded Cretaceous sand and clay. This surface probably did not have as much relief as the present land surface as over most of the region the altitude of the base of the Pensauken ranges between 80 and 130 feet. The formation tends to slope with the present land surface towards the South River and Lawrence Brook. This indicates that before the deposition of the Pensauken, drainage lines in the northern part of the region were similar to those existing today, and that the larger streams were deeply trenched below a broad flat upland. The formation north and northeast of the South River differs from that south of that river in having much material of pre-Cretaceous origin derived from the north, whereas to the south the relatively small area covered by this formation in Middlesex County contains a large amount of Cretaceous material.

North of the South River a generalized section of the Pensauken, where not eroded, would be

*Generalized section of the Pensauken formation for the area north of the South River*

| | Feet |
|---|---|
| Loamy yellow sand and gravel | 1–3 |
| Yellow clayey sand, somewhat crossbedded and containing a few layers of gravel | 10–20 |
| Yellow gravel, sand and boulders | 1–3 |

The boulders in the lower part consist of quartzite, Triassic shale, trap, and ironstone. Some of the larger boulders are 3 feet or more in diameter and it is difficult to conceive how they could have been transported to their present positions except by ice rafting.

The middle part consists largely of clay and quartz sand stained brown or yellow with iron oxide. A few layers are sometimes stained black with limonite. Nearly every section has a few fairly well sorted gravel layers up to 6 inches thick consisting of well rounded quartz pebbles, and one-half mile northwest of Jamesburg this part consists largely of well sorted, cross-bedded, fine gravel. The bedding shows the material was transported from the northeast and east. In the large area north and west of the South River, the Pensauken is clayey so that the permeability is considerably reduced. In some places there is enough clay either mixed with the sand or in lenses to make the formation quite impermeable. However, these places are limited in extent and do not greatly affect the formation over a large area.

Near the Raritan and South Rivers, the lower part of the Pensauken formation is often arkosic. For example, a section at South Amboy along the Raritan River Railroad shows:

*Section of the Pensauken formation at South Amboy, New Jersey*

| | Feet |
|---|---|
| Loamy sand | 2 |
| Brown clayey sand and gravel | 6 |
| Crossbedded yellow arkosic sand | 15 |
| Brown arkosic sand with few pebbles | 6 |
| Coarse gravel with granite and shale pebbles | 4 |
| | 33 |

Arkosic sand is dug about a quarter of a mile north of Old Bridge, but a few hundred feet farther uphill to the north the Pensauken is a yellow sand with disseminated gravel but no arkosic material. In the southern part of the county, arkosic material has seldom been observed.

On uneroded upland surfaces the Pensauken has been modified by soil formation and cultivation so that it is not nearly so permeable as the original material.

No large water supplies have been developed from the Pensauken. It does, however, yield small supplies of water to many wells for domestic or farm uses. Like the Cape May, its principal importance from a hydrologic standpoint is the fact that it readily absorbs water from precipitation and transmits it to the underlying aquifers tending to increase their effective intake area. Much of the intake area of the Farrington sand and some of the intake area of the Old Bridge sand is overlain by this formation. It also overlies the rocks of the Newark group in part of the area south of the terminal moraine.

An indication of the permeable nature of the Pensauken may be found in the many dry but undrained depressions that occur in its surface in some localities. These depressions have no surface drainage and all water that falls into or drains into them must sink into the soil. Many of these depressions occur in land that is now under cultivation, and in some instances it seems probable that the cultivation of the soil and the resultant accelerated silting of the bottoms of the depressions is tending to make them less permeable so that they are becoming swampy or even accumulating small ponds.

The results of laboratory examinations of three samples collected from the Pensauken formation are shown in the table of physical properties of water-bearing material on page 41. The porosity and moisture equivalent of one of these samples were not determined. For the other two the porosity averaged 40 percent, and the moisture equivalent by volume averaged 10 percent. On the basis of these figures, the specific yield of the Pensauken is probably about 30 percent, and a block of this formation one square mile in area and one foot thick could store about 63 million gallons of available water. The coefficient of permeability of the Pensauken formation is considerably less than that of the Cape May. It ranged from 120 to 200 in the three samples examined and averaged 172.

## Mesozoic Sequence

### CRETACEOUS SYSTEM

#### Upper Cretaceous Series

Rocks of Upper Cretaceous age are exposed in the southeastern half of Middlesex County. In early Cretaceous times, part of southern New Jersey was submerged and sediments of early Cretaceous age were deposited there. Middlesex County was above sea level at that time and the Triassic and Wissahickon rocks which were at the surface were being eroded. Later, in Upper Cretaceous times, Middlesex County was also submerged and sediments were deposited on the previously exposed hard rocks. At that time the Upper Cretaceous rocks extended inland a considerable distance northwest of the county, but erosion has since removed nearly half these deposits and all trace of any younger marine sediments that may have been deposited in Tertiary time.

The Cretaceous sediments consist largely of sand and clay, deposited in fairly well sorted layers. Some of the layers are recognizable over wide areas while others are variable and of small extent. Such rapid changes in the types of material indicate near-shore deposition where any deposit may grade laterally into material of different type. The uniform, widespread formations imply deposition in deep water where shore currents do not operate. Fossils also show that there were fluctuations in depth of water while the Cretaceous sediments were being deposited.

The Cretaceous deposits have been divided into formations which are distinctive units that can be recognized and mapped over wide areas. Most of them are layers composed largely of one lithologic type of material, such as sand or clay. Other formations have been named because the contained fossils are distinctly different from those in the strata above and beneath.

The Cretaceous deposits have a regional dip to the southeast and also thicken in that direction. The lowest layers dip at rates of 50 to

70 feet or more per mile and are nearly parallel with the underlying rock surface which dips to the southeast at rates of 60 to 85 feet per mile. The thickening of the deposits to the southeast reduces the dip of the overlying beds so that the uppermost Cretaceous formation in Middlesex County dips at a rate of only 35 feet per mile.

The southeastward dipping Cretaceous formations are beveled by the present relatively horizontal land surface and so are exposed in bands having a northeast-southwest extension. The oldest formation is exposed at the northwest border of the Cretaceous deposits and the successively younger formations crop out in order to the southeast. Little was known about the seaward extension of the Cretaceous formations until recent years when deep dredging and cores of the sea bottom obtained with special apparatus proved conclusively that these extend eastward to the continental shelf.

Since the formations having a sandy facies in their shoreward extension probably grade into clay some distance from shore, it seems unlikely that these aquifers have permeable submarine outcrops. If this be true, however, there probably were breaks in the overlying sediments through which ground water escaped at some time in the past and the fresh water displaced the sea water originally present in the aquifers. Immediately before the drilling of the first wells tapping the Cretaceous aquifers it is probable that there was no flow through them to any deep submarine outlet, because the fresh-water head was not high enough to cause flow against the heavier sea water. There was, however, some circulation of fresh water from the higher parts of their intake areas to outlets at or near sea level.

## MOUNT LAUREL AND WENONAH SANDS UNDIFFERENTIATED

The undifferentiated Mount Laurel and Wenonah sands are the youngest of the Cretaceous formations in Middlesex County. At its outcrop this unit is composed of reddish brown micaceous sand and is about 50 feet thick. Only the lower portion crops out in Middlesex County and that occurs in a small area in the extreme southeastern part of the county. The unit is not an important aquifer here but yields moderate supplies of water in areas farther down the dip, notably in the vicinity of Asbury Park.[16]

[16] Thompson, D. G., Ground Water Supplies in the Vicinity of Asbury Park, N. J. Dept. Conservation and Development Bulletin 35; 1930.

One sample of sand was examined in the Water Resources Laboratory. The results as published by Stearns[17] indicate a coefficient of permeability of 1,095 and a difference between porosity and moisture equivalent of 39 percent. On this basis the sand compares favorably with the Farrington and Old Bridge sand members of the Raritan formation. This single sample may not, however, be truly representative. Observations made in the vicinity of Asbury Park seem to indicate that this sand probably is not as good an aquifer as the Englishtown sand or the sand members of the Raritan formation.

Analyses of samples of water collected farther down the dip in Monmouth County are included in the table on page 48 to indicate the probable nature of the water in this unit. Attention is called to the fact that the water from this unit in the small area where it occurs in this county, might be somewhat different from that indicated by the analyses. On the whole, however, it is probably very good water and entirely satisfactory for all purposes.

## MARSHALLTOWN FORMATION

The Marshalltown formation is about 40 feet thick and is composed of laminated micaceous clay which is sometimes glauconitic or sandy. It underlies the Mount Laurel and Wenonah sands and overlies the Englishtown sand.

## ENGLISHTOWN SAND

The Englishtown sand occurs in Middlesex County near the southeastern border of the county. It is a crossbedded, micaceous, fine to medium-grained white or yellow sand, which is occasionally lignitic and which sometimes is cemented by limonite into hard blocks of ironstone. The latter is often conglomeratic and contains pebbles an inch or more in diameter. On all the high hills southeast of Morristown, east of Browntown, and just north of Moerls Corner, it forms a protective cover for the underlying unconsolidated sand. The base of the sand is frequently gravelly and sometimes contains pebbles as much as two to three inches in diameter. In Middlesex County the Englishtown sand is approximately 100 feet thick. Lenses of clay in the Englishtown sand are known mostly from wells passing through it. One such lens of black clay about 20 feet thick was uncovered in a hill half a mile east of Browntown when the sand was removed for use in road construction.

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[17] Stearns, Norah Dowell, Laboratory tests on physical properties of water-bearing materials; U. S. Geol. Surv. Water Supply Paper 596-F, 1927, pp. 166-167.

The clay lenses are not extensive so they are only of minor importance in hydrologic studies.

In the extreme southeastern part of the county, the Englishtown sand is overlain by the relatively impermeable Marshalltown formation so that it probably contains water under artesian pressure. In this area it is probable that at least three or four million gallons of water daily could be developed from carefully placed wells. At present no large supplies of water have been developed from the Englishtown sand in Middlesex County because the locality in which it is available is remote from any center of population or industry. It yields good water to a few shallow wells for domestic use. Further to the east and south this sand yields substantial quantities of water to deep wells for municipal and industrial supplies. A few wells to this sand yield more than one-half million gallons daily and the total consumption of water from it is probably several million gallons daily.

Seven samples of sand were collected from the Englishtown sand at different points along its outcrop in Middlesex County and analyzed in the Water Resources Laboratory. The results of the laboratory tests are shown in the table on page 41. It will be noted that there is a fairly wide variation between the different samples. A weighted average difference between the porosity and the moisture equivalent by volume is about 39 percent. A weighted average of the coefficients of permeability is about 525. On the basis of the laboratory determination, as well as on the basis of the performance of wells farther down the dip, the Englishtown sand is probably the third best aquifer occurring in Middlesex County, being exceeded only by the Farrington sand member, and Old Bridge sand member of the Raritan formation. In the county, and probably in the State as a whole, much more water is drawn from the rocks of the Newark group than from the Englishtown sand, but as an aquifer these rocks are not as uniformly reliable as the Englishtown.

The water from the Englishtown sand is of very good quality, although it is somewhat more highly mineralized than that from the Old Bridge sand member and Farrington sand member of the Raritan formation. Samples collected from wells near Asbury Park had 109 to 124 parts per million of total solids and 86 to 87 parts per million of hardness. The iron content ranged from 0.69 to 1.7 parts per million and the chloride from 2 to 3 parts per million. It is probable that in wells in Middlesex County, which are nearer the intake area, the water may be less highly mineralized. The removal of iron may sometimes be necessary. Otherwise, the water is suitable for all ordinary purposes.

## WOODBURY CLAY

The Woodbury clay is a black non-glauconitic, micaceous clay about 50 feet thick. In some places it is quite sandy, consisting of thin alternating layers of light brown clay and fine white sand. The weathered clay is a light chocolate in color and tends to break into small blocks with conchoidal fracture. The Woodbury is conformable with the overlying Englishtown sand.

## MERCHANTVILLE CLAY

The Merchantville clay is a micaceous black clay 50 to 60 feet thick with variable amounts of glauconite. It weathers to rusty-brown, indurated masses. The clay is quite fossiliferous and in some places is fairly sandy. It is conformable with the Woodbury clay above but is uncomformable with the underlying Magothy formation.

From a hydrologic standpoint the Woodbury and Merchantville clays are most important when considered together since they form a nearly impermeable layer about 100 feet thick between the Englishtown sand and the Magothy formation.

## MAGOTHY FORMATION

The Magothy formation crops out along the Raritan Bay from Cliffwood to Morgan and southwestward in the valleys of Cheesequake Creek and the South River as far as Jamesburg. Farther to the west it is identified largely from wells.

Along Raritan Bay it is 130 feet thick and the upper portion consists of black lignitic clay interbedded with fine lignitic sand. The black clay contains many plant remains and nodules of fossiliferous pyrite. There is considerable lateral gradation from black clay to material dominantly sand. The lower portion consists of fine sericitic white sand with black lignitic clay layers, many of which contain small particles of amber. Several black clay layers in the lower part of the Magothy have been uncovered in road cuts between the head of Cheesequake Creek and Tennent Brook. Near Jamesburg the upper portion of the Magothy consists largely of fine sericitic white sand and the formation is only about 90 feet thick.

Although the formation is composed largely of sand, it is not of much importance as an aquifer because the sand is uniformly fine grained and the yield of wells tapping it is not large. No large supplies are drawn from this formation in Middlesex County, although numerous wells for domestic or farmstead supplies take their water from it.

The Magothy formation lies immediately above the Raritan formation and is separated from the Old Bridge sand member by the Amboy stoneware clay, which was eroded away in some places before the Magothy was deposited. It is probable, therefore, that water can be transmitted from the Magothy formation through holes in the Amboy stoneware clay to the Old Bridge sand member of the Raritan formation, thus increasing to some extent the effective intake area of the Old Bridge sand. The extent to which this occurs cannot be determined because there are not enough wells to indicate how large or how numerous the openings in the Amboy stoneware clay may be. It is probable, however, that only a relatively small percentage of the water entering the Old Bridge sand can be accounted for in this way.

Five samples of sand from the Magothy formation were analyzed in the Water Resources Laboratory. The results of these analyses are shown in the table on page 41. Four samples were volumetric samples taken from various parts of the outcrop of the formation, and one was collected from a well. It will be noted that the sand is fairly well sorted and moderately fine grained. The porosity of the five samples ranged from 42 percent to 52 percent and averaged 46 percent. The moisture equivalent by volume ranged from 1.2 percent to 8.6 percent and averaged 4.4 percent. On the basis of these figures the specific yield of the sand would probably be about 41 percent, and it would appear that a block of sand of the Magothy formation one foot thick and one square mile in area would be capable of storing about 85 million gallons of available water. The coefficient of permeability of the five samples ranged from 60 to 925 and averaged 296. It is apparent, therefore, that while the Magothy formation is capable of storing large quantities of water it does not generally transmit it very freely, and the development of large-capacity wells in the Magothy formation in Middlesex County would probably be difficult if not impossible.

The most striking feature of the water from the Magothy formation in Middlesex County is that it usually contains very large amounts of iron. A sample from one well tapping this formation contained 34 parts per million of iron, and a total of only 27 parts per million for all the other constituents. The hardness expressed as calcium carbonate was only 13 parts per million and the chloride 6 parts per million. In view of the fact that the sand of the Magothy formation is fine-grained and does not usually yield much water to wells, the total pumpage from it is small and the head of the water has probably not been drawn down anywhere enough to cause salt-water intrusion.

## RARITAN FORMATION

The Raritan formation is composed of alternating and irregular beds of clay, sand and gravel. The sands are predominantly white or light-colored, but gray and yellow beds are not uncommon, particularly in the region west of Jamesburg, and sometimes they are colored pink or orange by small percentages of iron oxides. The clay beds range in color from white through cream and light gray to dark gray and brick red. In composition they range from dark, sandy and lignitic beds, usually containing many nodules of pyrite or marcasite, to white-burning, highly refractory clays of great value. Many of the sandy beds are relatively clean or free of clay, but all gradations occur from nearly pure quartz sand to beds containing a high percentage of clay, muscovite, limonite, feldspar or other minerals. Lignite is a fairly common constituent of both the sands and the dark impure clays.

Most of the Raritan formation is believed to have been formed in shallow, brackish water and in estuaries and lagoons rather than in the open sea. This belief is based not only upon the variable character of the formation and the lignite, but also upon fossil evidence; numerous remains of land plants having been found in an excellent state of preservation near the middle of the formation in the Woodbridge region.

Although the horizontal extent of any one bed in the Raritan formation is not very great, it is nevertheless possible to divide it into several fairly distinct and mappable units in most of Middlesex County. These units are alternating layers of sand and clay. The clays of the Raritan formation have been extensively used in the ceramic industry and have been the subject of several reports by the Geological Survey of New Jersey. In them the clays received informal names because of their economic importance. The other members, composed dominantly of sand, were not given names but received numbers. In this report, where attention is focused on the sand members, it is proposed to give these members names. Thus, the units in the Raritan formation are from top to bottom:

Amboy stoneware clay
Old Bridge sand member (No. 3 sand of previous reports)
South Amboy fire-clay
Sayreville sand member (No. 2 sand of previous reports)
Woodbridge clay
Farrington sand member (No. 1 sand of previous reports)
Raritan fire-clay

A description of these units follows.

### AMBOY STONEWARE CLAY

The Amboy stoneware clay varies in color from a light gray through darker grays to a nearly black clay with considerable carbonaceous material. Rarely it has a red mottled appearance. In some places it consists of a gray, more or less sandy clay resting on the white Old Bridge sand, but in other places the gray clay is underlain by as much as 10 feet of black carbonaceous clay. In turn the gray clay may be overlain with as much as 15 feet of black sandy clay. The black clay is lignitic and very similar to black clay in the Magothy formation, except that as a rule the black lignitic clays of the Magothy contain small rounded grains of amber. These are not common in the Raritan formation.

The Amboy stoneware clay was deposited on an uneven surface and was partly eroded before the deposition of the overlying Magothy formation. Its thickness ranges from 0 to 30 feet. Where present it forms an impermeable layer between the Magothy formation and the Old Bridge sand member of the Raritan formation.

### OLD BRIDGE SAND MEMBER

#### GEOLOGY

The most productive aquifer in Middlesex County is the Old Bridge sand, a member of the Raritan formation. This sand has not been identified in outcrop very far south of Jamesburg, or anywhere north of the Raritan River or the Raritan Bay. It crops out or is exposed beneath permeable Pleistocene deposits in an irregular band that extends from the Raritan Bay near South Amboy to and probably beyond Jamesburg. Along this band which is shown on figure 6 and which has an area of about 25 square miles, the sand is exposed to the direct infiltration of meteoric waters. As is the case with the major coastal plain formations it dips gently to the southeast and has been identified in wells several miles from its outcrop in that direction.

The Old Bridge sand is the No. 3 sand member of previous reports containing descriptions of the Raritan formation. The name Old Bridge was selected because the sand crops out at several places in and near that village. One of the best exposures is at the pit of the South River Sand Company about half a mile northeast of Old Bridge. Furthermore, Old Bridge is the center of the greatest ground water development in this sand, with the Perth Amboy Water Works at Runyon to the northeast and the Duhernal Water Supply less than a mile to the southwest. The Old Bridge sand is well exposed in the slopes of the hills bordering the South River and underlies much of the Pleistocene deposits both in the valley of that river and in the high ground to the northwest.

Usually the Old Bridge sand is fine to medium-grained, but occasionally portions of it are quite coarse. It is cross-bedded, slightly micaceous, and locally contains small beds of clay. At its outcrop it is practically free of pyrite and lignite, but samples from boreholes show that down the dip these substances are fairly common. Though the dry sand is white or light yellow, samples from below the ground-water table are sometimes highly colored by coatings of hydrated iron-oxide on the sand grains. Because it is normally a white, clean sand, it is dug and sold by a number of companies for use in foundries, concrete work, stucco, sand-lime brick, as blast sand, as a filler in asphalt, and to a lesser extent for other purposes.

In the investigations on which this report is based the thickness of the Old Bridge sand was determined in a number of localities both from surface exposures and from wells, and it was found to range from 80 to 110 feet. The dip of the sand is variable but it averages approximately 40 to 45 feet per mile to the southeast.

### PHYSICAL PROPERTIES

The Old Bridge sand is well sorted and ranges in size from a fairly fine sand to a coarse sand or fine gravel. The results of laboratory tests made upon 14 samples from this sand both at its outcrop and from wells are given in the table on page 42. A discussion of the significance of the various factors given in the table may be found on pages 45 to 46. The samples from wells are not considered as reliable as those from the outcrop area, because of the probable inclusion of clay from other layers or from drilling mud in the samples as collected. They are not included in the averages discussed in the next few paragraphs.

The coefficient of permeability of the Old Bridge sand as determined from the sand samples collected volumetrically at the outcrop and analyzed in the laboratory ranges from 230 to 2,150 and averages about 665. The coefficient of permeability as determined from pumping tests on 3 groups of wells ranged from 340 to 2,540 and averaged 1,490. Obviously all of these determinations are strictly applicable only to the points at which the samples were taken or to the areas immediately surrounding the wells used in the pumping tests. Nevertheless the points were scattered widely enough to be reasonably representative and the combined results are considered reliable. In the pumping tests, the variations from one layer to another are given their proper weight by nature and are integrated to give a true average for the section around the wells. For this reason they should be given somewhat more weight than the volumetric samples in arriving at a figure for the sand as a whole. It seems probable, therefore, that the average coefficient of permeability for the Old Bridge sand is between 1,000 and 1,500. On this basis the Old Bridge sand is capable of transmitting water more freely than any other aquifer in the county except the Farrington sand, and it compares favorably in this respect with most other productive aquifers in the state.

On the basis of the laboratory tests of samples taken at its outcrop the average porosity of the Old Bridge sand is about 42 percent and its average specific yield as determined by subtracting its moisture equivalent by volume from its porosity appears to be about 40 percent. The storage capacity of the sand is thus relatively high. On the basis of a specific yield of 40 percent, a block of this sand one square mile in area and 1 foot thick would contain about 84 million gallons of available water. In other words, if there were no recharge, about 84 million gallons of water would have to be removed from the sand in order to lower the water level 1 foot over an area of 1 square mile. It is evident therefore, that in this sand the water level normally fluctuates slowly where water-table conditions exist.

## QUALITY OF WATER

The water from the Old Bridge sand is excellent for most uses. Its quality varies somewhat from place to place, probably because most of the water used from this sand is pumped from, or very near its intake area, and the water is affected by local conditions. The total solids found in samples of water from this sand ranged from 19 to 65 parts per million and the hardness from 6 to 40 parts. The iron content of the different samples ranged from .02 to 5.8 parts per million. Iron removal plants have been installed by a number of the larger users of water from this sand. The chloride content of the samples in the table varied from 3 to 7 parts per million. Incipient salt-water intrusion into the Old Bridge sand has been observed near Old Bridge where the chlorides in samples from one test well were more than 100 parts per million. Apparently, however, this contamination has not yet reached very serious proportions.

### DEVELOPMENT AND PUMPAGE

The Old Bridge sand has been extensively developed for both public and industrial water supplies. In the course of the investigation on which this report is based, detailed records of pumpage from the Old Bridge sand extending over a period of years were collected. The record of pumpage is shown in table 5 below. It covers the period from 1917 to 1942 inclusive. The figures given are the average daily rate of withdrawals for each year. A breakdown of the total has been made so that withdrawals by public and by industrial supplies are listed separately. The greatest draft on the sand for any one year occurred during 1942 when it amounted to 23 million gallons a day. The least amount withdrawn from this sand for any one year for the period 1917 through 1942 was for the year 1932 when it amounted to slightly over 5 million gallons a day.

TABLE 5

QUANTITY OF WATER PUMPED FROM THE OLD BRIDGE SAND MEMBER OF THE RARITAN FORMATION IN MIDDLESEX COUNTY FOR INDUSTRIAL AND PUBLIC WATER SUPPLIES, 1917-1942

*In thousands of gallons daily*

| Year | Public | Industrial[a] | Total |
|---|---|---|---|
| 1917 | 9,600 | 30 | 9,630 |
| 1918 | 10,740 | 30 | 10,770 |
| 1919 | 9,630 | 30 | 9,660 |
| 1920 | 9,930 | 30 | 9,960 |
| 1921 | 8,210 | 30 | 8,240 |
| 1922 | 9,060 | 80 | 9,140 |
| 1923 | 9,490 | 80 | 9,570 |
| 1924 | 8,240 | 80 | 8,320 |
| 1925 | 8,500 | 80 | 8,580 |
| 1926 | 8,270 | 80 | 8,350 |
| 1927 | 6,690 | 80 | 6,770 |
| 1928 | 6,910 | 80 | 6,990 |
| 1929 | 7,200 | 80 | 7,280 |
| 1930 | 6,470 | 80 | 6,550 |
| 1931 | 5,560 | 150 | 5,710 |
| 1932 | 4,920 | 360 | 5,280 |
| 1933 | 5,710 | 450 | 6,160 |
| 1934 | 6,580 | 470 | 7,050 |
| 1935 | 7,220 | 450 | 7,670 |
| 1936 | 6,860 | 450 | 7,310 |
| 1937 | 7,400 | 590 | 7,990 |
| 1938 | 7,200 | 1,650 | 8,850 |
| 1939 | 7,340 | 2,610 | 9,950 |
| 1940 | 7,370 | 6,350 | 13,720 |
| 1941 | 8,160 | 10,870 | 19,030 |
| 1942 | 7,630 | 15,430 | 23,060 |

a. Partly estimated.

By far the largest part of the water drawn from the sand is pumped from or very near its intake area, where it contains water that is not confined by an overlying clay layer and is therefore under water-table conditions. From north to south, the more important water supplies drawing from this sand within the county are the South Amboy Water Works; part of the supply of the E. I. duPont deNemours & Company near Parlin; the Perth Amboy Water Works at Runyon; the Anheuser-Busch Company at Old Bridge; the Peter J. Schweitzer Company at East Spotswood and the Duhernal water supply development near Spotswood. Smaller quantities of water are taken from this sand at South River, Helmetta and Jamesburg and by a considerable number of wells for individual domestic and farmstead supplies. Down the dip in Monmouth County, it yields water to other wells or well fields.

The South Amboy Water Works is located along the shore of the Raritan Bay about a mile southeast of the center of the city of South Amboy. There are four wells in service at this plant, ranging in depth from 44 to 55 feet and all tapping the Old Bridge sand. Each well is pumped by an individual deep well pump, which discharges into a low level reservoir, whence the water is pumped into the mains. In 1918 and 1919 five deeper wells were drilled at this plant into the Farrington sand. However, the water from these wells contained from 2 to 6 parts per million of iron. They have not been in use since 1927 when the first wells tapping the Old Bridge sand were drilled. The water from the Old Bridge sand at this locality contains only from 0.7 to 0.9 parts per million of iron. The change was made to wells tapping this sand in order to obtain water containing less iron.

The wells now in use at this plant tap the Old Bridge sand in or near its intake area, where the water is under water-table conditions. A short distance northeast of the wells, the sand extends beneath the Raritan Bay which contains water almost as salty as sea water. The well field is near the northeastern tip of the intake area of the sand, as shown on the map on page 21 and is at a point of natural discharge for that part of the sand lying beneath the high ground southwest of the station. In March, 1919, the natural discharge from a swampy area near the station was observed to be about 200 gallons a minute from an apparent drainage area of only 0.15 square mile, or a yield of almost 2 million gallons a day per square mile. Prior to the date of the observation there had been several days of clear weather and the precipitation had not been unusually heavy for several weeks. It seems probable, therefore, that a substantial part of this high rate of discharge was not of local origin but represented water transmitted through the Old Bridge sand from higher parts of its outcrop.

The average consumption of water in South Amboy has increased gradually from about 700,000 gallons daily in 1928 to about 900,000 gallons daily in 1941. During most of this time the Old Bridge sand was used exclusively, and the pumpage at this station was apparently less than the natural recharge in the vicinity plus the natural discharge from the area to the southwest. Recently, however, there have been indications that the rate of pumping may have increased enough to create a serious danger of salt-water intrusion. This problem is discussed on pages 92 to 100.

Until development of the Duhernal well field southwest of Old Bridge in 1939, the Perth Amboy Water Department was the largest user of water from the Old Bridge sand. Pumpage from wells in the Perth Amboy well field at Runyon reached a maximum in the war year 1918, when it averaged 10.5 million gallons a day. From 1917 through 1942 the smallest annual average rate of pumpage at the Perth Amboy Water Works was 3.5 million gallons a day in 1932.

The first wells tapping this sand at this station were drilled about 1902 and they were first used in June, 1904. For several years prior to that time the city had been supplied by the natural flow from deep wells that tapped the Farrington sand. Some of these wells are still in existence and they have been used from time to time in the past to supplement the supply from the Old Bridge sand. At present, however, only one well at this station, a large-capacity well drilled in 1929-30, is in condition to draw from the Farrington sand. This well is used only to supplement the supply in periods of drought or high demand. By far the greater part of the water pumped at this station at present, as well as for many years in the past, comes from the Old Bridge sand.

There are more than 100 wells that tap the Old Bridge sand at the Perth Amboy Water Works, but the number in use varies from time to time as old wells fail or are repaired, and as new wells are drilled. At the end of 1941, only about 50 wells were in use. The wells are arranged in a series of lines that converge at a central pumping station. They are all pumped by direct suction from a central station. The most remote wells on some of the lines are approximately a mile from the station along the pipe line. The location of supply wells in this field and of observation wells driven to determine the shape of the water table are shown on Figure 9. This figure also shows by contours the shape of the water table at a time of heavy pumping and low water levels.

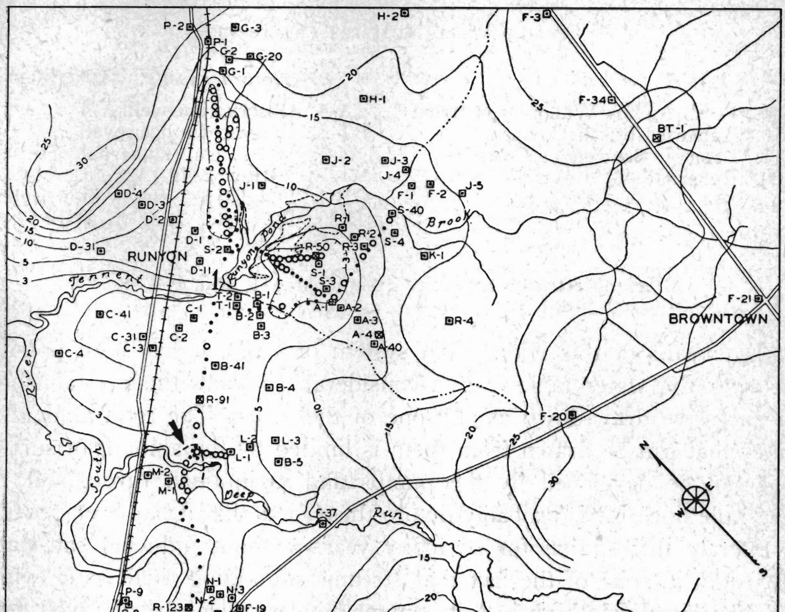


FIGURE 9.—Map showing well fields tapping the Old Bridge sand member of the Raritan formation near Old Bridge, N. J., the area of salt-water intrusion, wells and, by contours, the shape of the water table in a part of the area.

*(Key to Well Numbers on page 74)*

KEY TO WELL NUMBERS (figure 9)

*Well fields:*

1. Perth Amboy Water Department
10. Anheuser-Busch Company
11. Peter J. Schweitzer Company
100. Duhernal

*Recorder wells:*

A-4. Observation well A-4
BT-1. Browntown deep well
DH-1, DH-2, etc. Duhernal observation wells 1, 2, etc.
OB-1. Old Bridge observation well
R-50, R-91, etc. Runyon wells 50, 91, etc.

*Other observation wells* are designated A-1, B-5, P-8, etc.

By means of this widespread system of wells, it has been possible to lower the water table over a considerable area without establishing an excessive draw-down at any one of the wells. The total amount of water that can be drawn from them is limited by the amount of suction that can be developed by the pumps and maintained throughout the long pipe lines. It is probably due to these facts that it has been possible to operate this station for so many years without inducing salt-water intrusion, in spite of the fact that streams containing tidal water which is sometimes fairly high in salt content flow very close to the well field. Although the danger of salt-water intrusion was probably not considered when the system was planned, it is in many respects ideally designed to take water from a water-table sand that is exposed to salt water. There is, however, a definite possibility that salt water may be drawn into this sand in or near this well field. This problem is discussed in detail on pages 92 to 100.

During the last few years, the amount of water drawn from the Old Bridge sand has been greatly increased by the development of the Duhernal supply between Old Bridge and Spotswood, and also by the construction of two wells tapping this sand at the duPont plant near Parlin, and two new wells at the Schweitzer plant in Spotswood. Two of these developments were made in order to supply industrial water to replace that formerly taken from the Farrington sand, which is now seriously threatened by salt-water contamination. (See pp. 115-133.) The plants of the E. I. duPont deNemours & Company and of the Hercules Powder Company at Parlin, and also that of the National Lead Company at South Amboy, formerly took their water supplies exclusively from the Farrington sand. When it became apparent that the water supply from this sand was in danger of destruction by salt-water intrusion, the companies sought another source of supply. The duPont Company was able to obtain some water on its property near Parlin from wells in the Old Bridge sand, but not enough to supply its full requirements. The other companies were unable to obtain any satisfactory supplementary supplies at their plant sites. The three companies then entered into a cooperative arrangement to build and operate the Duhernal system, which takes water from the Old Bridge sand between Old Bridge and Spotswood. The pumpage by this system from the Old Bridge sand has increased from 2 million gallons a day in 1939 to nearly 12 million gallons a day in 1942.

The two wells that tap the Old Bridge sand at the duPont plant at Parlin are gravel-walled wells with a combined capacity of about 2 million gallons daily. At this plant the Old Bridge sand is exposed to direct percolation from the surface and industrial wastes have percolated into the sand so that the water from one of these wells is slightly contaminated and cannot be used for some purposes, but it is used where requirements are less rigid. In one of these wells the South Amboy fire clay appeared to be missing, and consequently the well passed directly from the Old Bridge sand into the Sayreville sand and is probably drawing from both. Samples from this well that are believed to be from the Sayreville sand appeared, on visual examination, to be fairly good water-bearing materials.

The Duhernal well field extends along the southeast side of the South River, from a point less than a mile southwest of Old Bridge into the edge of the town of Spotswood and thence up the Matchaponix Brook for about half a mile. All the water pumped in this field is used for industrial purposes in the plants of the three companies several miles away. In the field are 11 wells of large diameter and large capacity. A few of them have a capacity of more than two million gallons daily, and the combined capacity of all the wells is about fifteen million gallons daily. One of the wells is of the new water-collector type. It is 13 feet in diameter and has horizontal screens extending radially from the central well for as much as 200 feet. The others are gravel-walled, vertical wells of the most modern type. Each one is equipped with an individual deep well pump, which delivers the water under sufficient pressure to force it through the mains to the plants at which it is used. The need for a central pumping station is thus eliminated. Meters are installed at each well and a master meter measures the combined yield. Excellent and detailed records are kept of the operations in this well field.

In connection with the construction of the Duhernal well field, a dam was built across the South River, creating a reservoir known as the Duhernal Lake. This lake has an area at the normal overflow level of about 178 acres. It was built to provide a means of recharging the sands from the flow of the South River and thus improve the yield of the well field. The lake may also be used as a source of supply if the combined yield of the several well fields should become less than the needs of the industries.

The Old Bridge sand is tapped in the vicinity of Old Bridge and East Spotswood by one well at the plant of the Anheuser-Busch Company and by five wells at the plant of the Peter J. Schweitzer Company. These are gravel-walled wells with an aggregate capacity of at least four or five million gallons daily. All are situated near the northwest shore of the Duhernal Lake and derive a part of their water by recharge from it. The well at the Anheuser-Busch Company and three wells at the Schweitzer plant were drilled about 1929 or 1930. The two additional wells at the Schweitzer plant have been drilled since the middle of 1941. The well at the Anheuser-Busch Company has been in constant use since its construction. No large amount of water was pumped from the wells at the Schweitzer plant from the time of their construction until the middle of 1941, when the present owners began operations. The present daily pumpage is now about two million gallons. Each company has one well tapping the Farrington sand in addition to those that tap the Old Bridge sand, but they are used little because of the relatively high iron content of the water.

The Public Water supplies at Jamesburg and Helmetta are derived from the Old Bridge sand. At Helmetta there are two wells, 26 and 36 feet deep, respectively, and the consumption is only about 17,000 gallons daily. At the Jamesburg Water Company's pumping station there are five wells, ranging in depth from 70 to 126 feet. These wells are pumped by direct suction from a central pumping station. The consumption averages about 60,000 gallons daily.

The amount of water drawn from the Old Bridge sand within the county is shown in the tables on pages 33 and 70. In 1941 the average pumpage from this sand was slightly over 9 million gallons daily for the Duhernal supply, 6 million gallons daily for the Perth Amboy Water Works, and 3.9 million gallons daily for all other purposes, making an average of 19 million gallons daily pumped from the sand within the county. In 1942 the average was 23 million gallons daily, and in 1943 the average will apparently be still higher.

In addition to the water taken from this sand in Middlesex County, about 1.5 million gallons daily is taken in the communities along the shore in Monmouth County between Matawan and Keansburg. Another two or three million gallons daily is taken from the Raritan sands still farther down the dip where the members of this formation have not been traced and differentiated. It is estimated that about one-half of this pumpage comes from the Old Bridge sand either directly or indirectly. The total consumption of water from the Old Bridge sand in 1942, therefore, averaged about 25 or 26 million gallons daily.

### FACTORS AFFECTING SAFE YIELD

The safe yield of an aquifer or of any part of it is the amount of water it will yield indefinitely without impairing the quantity or quality of the supply. In order that the safe yield may not be exceeded, the withdrawal of water from an aquifer must not exceed the rate at which it can be recharged nor the rate at which it can transmit water. Likewise the rate of withdrawal must not be so great that it will lower the head or the level of the water in the formation sufficiently to draw contaminated water into it. The various factors relating to the safe yield of an aquifer are discussed by Meinzer,[18] and the intrusion of salt water as a factor in determining the safe yield of water-bearing formations is also discussed by Brown,[19] and Barksdale.[20]

In practice these limitations do not generally mean that the rate of withdrawal may not exceed the safe yield for brief periods provided the average rate does not exceed the safe yield. Most productive aquifers are capable of storing large quantities of water, and subsequently yielding it to wells. The storage capacity of the Old Bridge sand is high enough to permit large seasonal fluctuations of intake and withdrawal.

The areal extent of an aquifer is of obvious importance in that it limits the amount of recharge that may enter it, the amount of water stored in it, and the distance from which water may be drawn to any given well or well field tapping it. Furthermore, the greater the extent of an aquifer the larger is the number of sites at which it is feasible to draw water from it. This introduces the necessity of considering the aquifer as a whole. It is obviously impossible to determine the safe yield of a single well or well field, either existing or proposed, without considering all other existing or proposed developments that tap the same aquifer. It might lead to grossly erroneous conclusions to try to estimate the safe yield of the aquifer and the pumpage from it in small units.

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[18] Meinzer, O. E., Outline of methods for estimating ground-water supplies. U. S. Geological Survey, Water Supply Paper 638-C, 1932.

[19] Brown, J. S., Relation of sea water to ground water along coasts; Am. Jour. Sci., 5th ser., Vol. 4, pp. 274-294, 1922. A study of coastal ground water with special reference to Connecticut: U. S. Geol. Survey Water Supply Paper 537, 1925. This paper contains also a bibliography of publications on the subject.

[20] Barksdale, H. C., Sundstrom, R. W., and Brunstein, M. S., Supplementary Report on the ground-water supplies of the Atlantic City Region, New Jersey, State Water Policy Comm., Sp. Rept. 6, 1936, pp. 25 to 37.

In this report it is assumed that the intake areas of the Old Bridge and Farrington sands in Middlesex County must supply the water drawn from them in this county and also down the dip in Monmouth County. This is believed to be a fairly safe assumption because there is a lightly developed band up and down the dip of the Raritan formation from northeastern Mercer County to the ocean. This fact should not be considered as a safety factor that would permit overdevelopment in Middlesex and Monmouth Counties, however, because the intake areas of the sand members of the Raritan formation do not appear to be as productive in Mercer County as in Middlesex County and also because this band may be developed at any time.

The intake capacity of an aquifer depends upon the structure and condition of the soil, the slope of the surface, and nature of the vegetal cover. The amount of water actually entering the soil and passing down to recharge the water table depends upon the intensity and distribution of precipitation and upon the state of growth or dormancy of vegetation. Furthermore, an aquifer may either discharge water naturally into a stream or other body of surface water, or may receive recharge from it depending upon the level of the water table in the vicinity. It is evident, therefore, that it is not a simple matter to estimate the probable recharge of an aquifer. In fact it is generally not possible to estimate it directly. It can be estimated by observing the natural recharge that is not affected by pumping or by observing the effect of pumping upon the natural discharge, or perhaps by a comparison with a similar aquifer for which the rate of intake has been estimated. It is evident, therefore, that observations of water levels and records of pumpage or other artificial withdrawal and of natural discharge such as the flow of springs or the dry weather flow of streams originating on the aquifer, are very important in estimating the safe yield of the aquifer. If the relation of these factors to each other can be studied over a period of years, they may furnish a satisfactory indication of the safe yield of the aquifer. Furthermore, if the rate of pumping is increased with the passage of time, a continuous record and study of these various factors may indicate the approach of time when no further increases in pumpage should be made.

The capacity of an aquifer to transmit water depends upon the permeability of the material and the area of its cross section at right angles to the movement of the water. It also depends upon the slope of the water table, or of the hydraulic gradient. All these factors may be determined with a fair degree of accuracy by a combination of field and laboratory methods, or entirely by field methods if suitable wells are available for pumping tests and if adequate well logs are available.

There follows an analysis of the various factors affecting the safe yield of the Old Bridge sand. The natural recharge and the facilities for artificial recharge are probably the most important of these factors. Its transmissibility is high and therefore of relatively less importance. The danger of salt-water intrusion and of contamination by industrial wastes must also be considered.

### *Available Recharge*

Part of the water from precipitation runs off directly into the streams. Part of it is returned to the atmosphere and the remainder goes into the soil. Of the water that enters the soil a part finds its way into the streams very promptly, a part is retained in the soil, and the remainder goes to recharge the ground water below the water table. Part of the water that becomes ground-water recharge is subsequently returned to the atmosphere by transpiration and evaporation from the soil, and the remainder is later discharged gradually, either directly into the ocean or, more generally, into the streams. This water maintains the flow of streams when there is no storm runoff.

Under favorable circumstances it is possible to withdraw from productive aquifers much of the ground-water recharge and even some of the water that would naturally be lost to evaporation from the soil and to transpiration. The degree to which this may be accomplished depends largely upon how much the ground-water levels can be lowered. When pumping is begun the water levels are lowered at the point of diversion in order to produce a flow to it. At the same time the slope of the water table toward the points of natural discharge is decreased and the flow to them is diminished. If the lowering is great enough the flow to the natural outlets may be stopped altogether and if surface water is present at them, it may even be drawn into the aquifer, thus reversing the direction of flow and creating a condition that artificially recharges the aquifer.

The lower ground-water levels leave more storage space for water in the ground. In areas where the water table is normally near the surface and hence all the water available for recharge cannot be stored in the ground, the lower ground-water levels will result in more recharge. The use of ground-water storage by lowering the water table also permits pumping at a higher rate by carrying the load over dry seasons or even over a series of dry years when the quantity of water in storage is large. Where the water table is close to the surface the plant roots may draw water directly from the water table or from the capillary fringe, or capillary action may lift water to the surface of the soil where it can be evaporated. Hence, a further advantage to be gained by lowering the water table by pumping is that some of the ground water that is normally consumed by plants or discharged into the atmosphere by evaporation from the soil will be saved.

*Intake area.* On the whole, the intake area of the Old Bridge sand is exceptionally well suited for absorbing water from precipitation and stream flow and transmitting it to the water table. Where the sand itself is not exposed at the surface, it is overlain by the Cape May formation or, in some localities, by the Pensauken formation, both of which are quite porous and absorb water readily.

Over much of the intake area, as shown on the map on page 21, the land surface is relatively flat, and hence water from precipitation does not run off rapidly and has an opportunity to percolate into the soil. The soil over some parts of the intake area is not very productive and the vegetation there is not very rank so that the losses by transpiration are only moderate. The sandy nature of the soil also reduces the losses by direct evaporation from the soil, because capillary action will not lift water as high in a coarse material as in a finer one. This area is also traversed by a number of streams into which ground water is naturally discharged but which are capable of supplying a substantial quantity of water to the sand wherever the water table is lowered sufficiently.

The intake area of this sand is not well defined south of Jamesburg because it is deeply covered by the Cape May and Pensauken formations, which have not been penetrated by enough wells to make an accurate definition of the intake area possible. This is indicated by the shading of the lower end of the intake area as shown on the map. Where it has been defined and mapped, the intake area of this sand is about 25 square miles. The effective intake area is probably larger. Near Old Bridge there is shown on the map an island of clay, approximately two square miles in area, that is entirely surrounded by the intake area of the Old Bridge sand. It is probable that much of the water falling on this island eventually flows over the edge of the clay and percolates into the Old Bridge sand. Some of the water that falls on the Cape May and Pensauken formations where they overlie both the intake area and the adjacent clay beds probably finds its way laterally into the Old Bridge sand. In some localities there are holes in the Amboy stoneware clay which overlies the Old Bridge sand. There is very little information about the number or size of these holes, but if their total area is considerable, they may permit a good deal of water from the sands of the Magothy formation to percolate down into the Old Bridge sand. All of these factors combined may increase the effective intake area of the Old Bridge sand by as much as 30 percent.

*Recharge as indicated by water-level fluctuations.* Whenever there is ground-water recharge from any source, the water table will rise. Conversely a drop in water levels no matter what its cause, indicates ground-water discharge. It is of interest, therefore, to study the fluctuations of the water table with a view to determining the amount of the recharge.

A comparison of the water levels in several observation wells with the annual rate of pumping and with the monthly precipitation is shown in figure 10. At the top of this diagram are shown the hydrographs of six wells, the Hulsart well, the Browntown well, Runyon wells 50 and 91, and Duhernal wells 2 and 4. Of these wells, only two (Runyon well 50 and Duhernal well 4) are very near any heavy pumping. Runyon well 91 was outside the immediate effect of pumping most of the time and the other three are at considerable distances from any pumping. The pumpage at the Perth Amboy Water Works and at the Duhernal development and the total pumpage from the Old Bridge sand are shown as yearly averages below the hydrographs. At the base of the diagram, the monthly precipitation at Runyon is shown and compared with the normal monthly precipitation. Records from Runyon well 50 and precipitation records are available from 1923 to 1929 and records of pumpage are available from 1917 to date, but a study of these records does not seem to reveal anything not shown on the diagram.

A study of the water levels shown on the diagram reveals that they all respond in varying degrees to changes in the rate of recharge as indicated by the precipitation records and especially by the departures from normal precipitation. They also show a seasonal fluctuation caused by the greater losses to evaporation and transpiration in the growing season. Duhernal well 4, which is near the middle of the Duhernal well field, also shows a substantial decline after the beginning of pumping in the Duhernal field and in response to increased rates of pumping there. Runyon well 50 responds primarily to the combined effects of pumping and recharge from the Runyon pond. It is believed to be significant that the water levels in this area have rather consistently risen to about the same level during each winter. This indicates that any deficiency of recharge that may have occurred during the summer season, when most of the precipitation is used by plants and when the flow of Tennent Brook is not sufficient to maintain the level in the

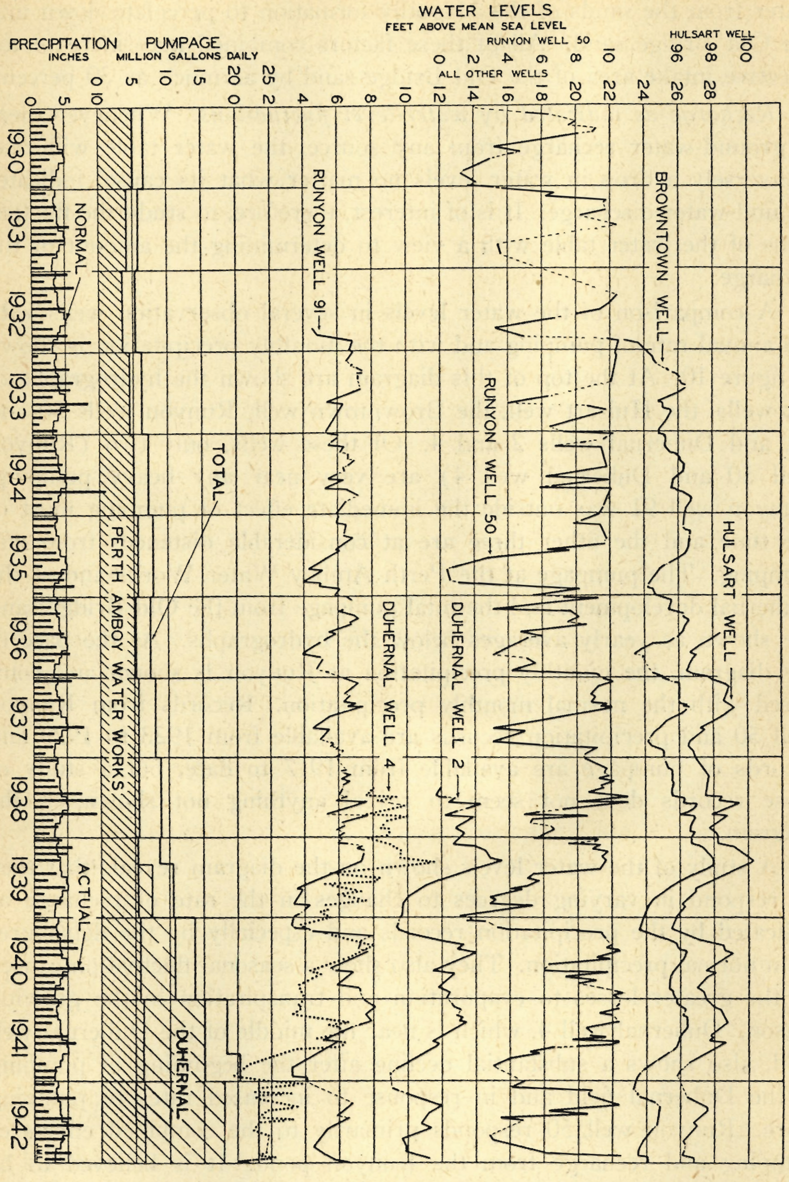


FIGURE 10.—Diagram showing relation between pumpage, precipitation and water levels in the Old Bridge sand member of the Raritan formation, 1930 to 1942. For locations of wells see Figs. 2 and 9.

Runyon pond, is usually made up during the following winter. The other wells appear to be influenced primarily if not wholly by the natural causes referred to above.

In addition to the usual seasonal fluctuations, there appears to be a declining trend in most of the wells beginning in 1939. The rate of pumping at the Perth Amboy Water Works does not fluctuate very much seasonally and has remained fairly constant from year to year. However, the pumping from the Duhernal development began in 1939 and was increased from time to time until 1942. At first it would appear that this decline was probably due to the pumpage at the Duhernal development. A further study of the diagram indicates that this was not true to any considerable extent except in the case of Duhernal well 4. The year 1938 was an unusually wet one so that the water levels were high at its close. The year 1939 was one of the driest years during the period. The deficiency in precipitation lasted from the beginning of the growing season in 1939 to the end of January 1940. There was, therefore, a marked decline of water levels from the unusually high levels in the winter of 1938-39 to the unusually low levels early in 1940. Dry weather also occurred during the growing season in 1941 and produced an accentuated lowering of water level at that time. The apparent downward trend from the beginning of 1939 into 1942 in the case of several of the wells is believed to be primarily due to these peculiarities in the distribution of precipitation.

The Hulsart well was added to the diagram in order to support this conclusion. This well is 5 or 6 miles from the centers of pumping at Runyon and Old Bridge, and taps the Englishtown formation where the water in it is under water-table conditions. It is, of course, entirely independent of any pumpage from the Old Bridge sand, and since there is no pumpage from the Englishtown sand within several miles, this well probably fluctuates entirely in response to variations in recharge and natural discharge. It will be noted that the Hulsart well almost exactly parallels the Browntown well and is comparable to Duhernal well 2 and Runyon well 91 if allowances are made for the differences in the ranges of fluctuations in these wells.

Certain quantitative inferences may be drawn from the study of figure 10. If, for example, the Browntown well be assumed to be representative of the conditions in the whole intake area of the sand, there was a decline of about 4.4 feet from the spring of 1939 to midwinter 1940. On the basis of a 40 percent specific yield and 25 square miles of intake area, this would represent a loss of about 9,000,000,000 gallons of ground water from storage. On the same assumptions a similar gain in recharge occurred from the fall of 1937 to the spring of 1939. These figures are given merely to indicate the magnitude of the quantities involved in the natural recharge or depletion of an aquifer such as the Old Bridge sand.

By another application of this same method it is possible from the hydrographs of wells such as those shown on figure 10 to estimate the total recharge for a period by a summation of all the rises of the water table during the period. For a ten-year period from 1933 to 1942, the average annual rise of the water table for the Browntown well and Runyon well 91 combined was 5.6 feet. On the basis of a specific yield of 40 percent this represents a recharge of about 27 inches a year or a theoretically possible yield of 1,300,000 gallons a day per square mile. It should be borne in mind that this figure does not take into account any of the losses from the water table. It would not be the amount of water available to wells unless it were possible to stop all losses completely. It does, however, furnish a basis for judging the reasonableness of estimates of available recharge made by other methods.

*Estimates of natural recharge.* In the case of the Farrington sand it was estimated[21] that about 20 inches of the annual precipitation was available for recharging the sand. This estimate should apply reasonably well to the Old Bridge sand. On this basis the natural recharge from the 25 square mile intake area referred to above would be about 24 million gallons daily. If the effective intake area is 30 percent greater, the available natural recharge of the sand would be about 31 million gallons daily.

In recent years great advances have been made in the analysis of stream flow. By studying the hydrograph obtained at a gaging station it is now possible to estimate with a fair degree of accuracy the amount of water flowing past the station that was derived from ground-water infiltration. The ground-water flow into a stream is water that percolated into the soil and was stored temporarily below the water table. This water gradually seeps into the streams and maintains the stream flow between periods of precipitation. In Middlesex County the streams all drain a wide variety of formations, ranging from highly permeable materials to materials that are quite impermeable. However, there are several streams in southern New Jersey that have drainage areas entirely on the Cohansey formation. This formation is composed almost entirely of sand and is roughly comparable to the sandy aquifers occurring in Middlesex County. The records of stream flow at gaging

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21 Barksdale, H. C., Op. Cit. Special Report 7, page 16.

stations on several of these streams have been analyzed and their average ground-water flow appears to be equivalent to about 12 inches of runoff per year. This figure would give about 14 million gallons daily from the 25 square miles of intake area of the Old Bridge sand, or about 19 million gallons daily if the effective intake area is 30 percent larger. The ground-water flow of the South Jersey streams results from the water that their sandy drainage areas can absorb under natural conditions. If the water table were lowered by pumping, the amount of ground-water intake would be increased because additional ground-water storage space would be provided and because the losses to evaporation and transpiration would be reduced in areas where the water table is near the surface. It is probable, therefore, that the natural recharge of the Old Bridge sand is considerably more than 12 inches.

A better way of estimating the maximum rate of recharge of the sand is to estimate the intake in a locality of heavy pumping, where the shape of the water table can be determined and hence the area tributary to the wells and the changes in ground-water storage can be estimated. In such a locality the losses to transpiration and evaporation would be at a minimum and the available ground-water storage would be used to good advantage to maintain the rate of withdrawal during periods of deficient recharge. The best locality for this purpose within the intake area of the Old Bridge sand is that around the Perth Amboy Water Works, because most of the data required for such a study are available. In this area, however, the problem is complicated by recharge from the Runyon pond and from Deep Run.

A group of test wells was constructed in the area around the Perth Amboy Water Works and the results of water level measurements in them form the basis of contour maps of the water table in that vicinity (see figure 9). From these maps it has been possible to determine approximately the area tributary to the wells at the water works and the volume of sand recharged or unwatered from time to time. When this volume is multiplied by the specific yield of the sand the product is the quantity of water added to or removed from storage. A stream-gaging station was maintained on Tennent Brook above the pond for several years, so that it has been possible to determine the inflow to the pond with a reasonable degree of accuracy by making adjustments for the tributary area between the gaging station and the dam. Unfortunately it has been impossible to measure the discharge from the pond at all times because of the varying rate of flow through the flood gates. However, the rate of recharge from the pond is such that for considerable periods of time there is no flow over the dam or through the gates. The evaporation station at Runyon provides a means of estimating the loss from the surface of the pond. Good records of pumpage are available at the water works. Estimates of the artificial recharge from the pond and of the natural recharge available to the wells at this station have been made on the basis of these data.

The calendar year 1941 included a longer period than usual when there was no flow over the dam or through the flood gates. It is, therefore, one of the best periods for computing the artificial recharge from the pond and the natural recharge in the surrounding area for a full year. The results for this year have been checked against shorter periods in other years and are believed to be fairly representative. To avoid the complications arising from recharge from Deep Run the pumpage from the wells along this stream and the area tributary to them were eliminated from the following computations.

During 1941 the total water pumped from the wells in the area studied amounted to 2,055,000,000 gallons or 275,000,000 cubic feet. It was derived partly from artificial recharge, partly from water removed from storage in the ground, and partly from natural recharge over the area tributary to the wells. It was estimated that the total quantity of artificial recharge from the pond for the year was about 115,000,000 cubic feet of water. In arriving at this figure reasonably satisfactory estimates were made of the flow into the pond and over and through the dam. Allowance was also made for evaporation from the pond and for precipitation on the pond. From contour maps of the water table at the beginning and end of the year, it was determined that about 183,000,000 cubic feet of the sand were unwatered and, on the basis of a specific yield of 40 percent, about 73,000,000 cubic feet of water were removed from storage in the ground. The quantities of water obtained from artificial recharge and from ground-water storage were subtracted from the total quantity pumped and the remainder, about 87,000,000 cubic feet of water, must have been derived from natural recharge during the year. It was estimated that this amount of water came from about 1.8 square miles. The recharge during the period was therefore about 20.8 inches over the area or at a rate of about 990,000 gallons daily per square mile.

On the basis of these figures the natural recharge into the intake area of the Old Bridge sand would be about the same as that computed above for 20 inches of recharge. It will be noted that the estimated rate of recharge in the vicinity of the Perth Amboy Water Works as computed above is very much greater than the 12 inches of ground-water flow based upon the South Jersey streams. The increase is believed to be due mainly to the more efficient use of the ground-water storage space and also to some extent to a reduction of the losses to transpiration and to evaporation from the soil brought about by the lowered water table during the growing season.

The precipitation at Runyon for 1941 was 37.74 inches or 6.63 inches less than normal. This fact seems to indicate that the recharge in a normal year might be somewhat larger. However, it would not be safe to draw more heavily upon the sand unless it were possible to draw more heavily upon ground-water storage in a still drier year or in a possible series of dry years. The quantity of water stored beneath the water table was 73,000,000 cubic feet less at the end of the year than it was at the beginning. This is equivalent to about 17 inches of water over the area. From May to December, 1941, the stream flow was not enough to keep the pond filled, and the artificial recharge was much below normal. The deficiency of 17 inches in the ground-water storage at the Perth Amboy Water Works in this year would normally be made up largely by artificial recharge from the pond.

*Artificial recharge.* Artificial recharge of the Old Bridge sand has been practiced at the Perth Amboy Water Works ever since the sand was first used as a source of supply. The oldest development serving to recharge the sand is the Runyon pond which antedated the use of wells to this sand. The importance of the recharge from the pond was soon appreciated by those in charge of the operation of this plant. When the demand began to approach the capacity of the wells, various steps were taken to increase the effectiveness of the artificial recharge. A shallow area of the pond was dredged to a depth of about two feet below the spillway level, and control works were set up to admit water only when the water in the main part of the pond was clear. A steady flow through the control works indicated the effectiveness of this development. Large ditches were constructed beside some of the lines of wells and were connected with the pond or, in one instance, with Deep Run so that water could flow into them and recharge the sand near the wells. During the first World War several large basins were excavated near the pumping station and water was pumped into them from Deep Run to supplement the recharge obtained from the flow of Tennent Brook. Within recent years the system of large ditches has been extended and arranged to intercept the flow of an intermittent tributary of Tennent Brook that would normally enter the brook below the dam and be lost. The efficiency of the recharge development is now such that water seldom flows over the spillway of the dam except when the runoff is unusually high.

Further evidence of the effectiveness of the Runyon Pond in recharging the Old Bridge sand and maintaining the level of ground water in the well field was obtained during the hurricane storm of September, 1938. Heavy precipitation occurred over a period of two or three days and there was a sharp general rise of the water table. The rains produced a flood on Tennent Brook that washed out the dam at Runyon and drained the pond. The water level in the wells in the vicinity of the pond dropped two or three feet in spite of the general rise in the water table, and the head against which the pumps had to operate was increased materially. Obviously the lowering of the water table in the vicinity of the Perth Amboy Water Works was contrary to the general trend and could be explained only by the lowering of the level of the pond.

For a time after the iron-removal plant was installed at the Perth Amboy Water Works, the filter wash water which was heavily laden with precipitated iron, was discharged into the pond. It built up a thick and relatively impervious deposit over a part of the pond bottom. This practice has been discontinued, but the deposit has not been removed. It undoubtedly decreases to some extent the effectiveness of the pond as a means of recharging the Old Bridge sand.

The drainage area of Tennent Brook above the dam at Runyon is approximately 9 square miles. At the gaging station above the pond it is 5.25 square miles. At the spillway level at altitude 12.1 feet above mean sea level, the pond has an area of about 63 acres. Its storage capacity when full is about 35 million gallons. Plane table maps were made of the pond at several different altitudes of the water surface. They have been used as the basis for determining the area of the pond at different levels as well as its capacity.

Occasionally during the period of record the data obtained were suitable for estimating the rate of artificial recharge per acre of pond bottom. For short periods when there was no precipitation and when the pond level was essentially constant at an elevation below the spillway, the area of the pond, the flow into it and the loss to evaporation were determined. Adjustments for changes in the amount of water stored in the pond were made if necessary and the inflow to the pond, not otherwise accounted for, was considered to be artificial recharge and reduced to a per acre per day basis. For example, from May 5 to 8, 1941, the average level of the pond was 11.10 feet or about 1 foot below the spillway. The flow into the pond for the whole period was estimated to be 1,380,000 cubic feet. The loss to evaporation was estimated to be 41,000 cubic feet on the assumption that the evaporation from the pond surface was 70 percent of the evaporation from the land pan at the Runyon station. The gain in storage in the pond was 45,000 cubic feet. The total ground-water recharge for the four days was, therefore, 1,294,000 cubic feet. The area of the pond at this level was 31.6 acres, so that the average rate of recharge from the pond during the four days was 76,000 gallons per day per acre.

Similar computations were made for a number of other periods when the pond level and the water table were at different altitudes. A wide range of results were obtained. One important factor affecting the rate of recharge from the pond appeared to be the difference between the pond level and the level of the water table in the surrounding area. In addition to this there was a very marked tendency toward a higher rate of recharge when the pond was full than when it was nearly empty. This seems to indicate that the condition of the pond bottom along the edges where the crust of sediments is broken each year by vegetation, is better suited for artificial recharge than is that part of the bottom which is generally too deeply submerged to permit the growth of plants. The lowest rate of recharge determined was only 4,000 gallons per day per acre in October, 1941, when the level of the pond was 8.55 feet and much of the submerged part of the pond bottom was underlain by the deposits from the filter wash water. The maximum rate of recharge from the pond is probably 80,000 or 90,000 gallons per day per acre. On this basis the maximum rate of recharge from the pond would be more than 5,000,000 gallons daily.

Studies by the engineers of the Duhernal water supply based upon the relative temperatures of the water in the Duhernal lake and in the wells, upon the chemical composition of the waters and upon variations in the rate of the discharge over the dam have indicated that there is substantial recharge from the lake. No such studies have been made on the northwest side of the pond at the wells of the Anheuser-Busch Company and the Peter J. Schweitzer Company, but it is probable that part of the water taken from these wells is also derived from the lake. A conservative estimate of the amount of recharge from the lake during 1941 is about 4,000,000 or 5,000,000 gallons daily.

It is probable that the artificial recharge from this lake is now much larger, because the ground-water levels around it have been drawn down still more. Further decreases in the ground-water levels around the pond will probably cause still higher rates of artificial recharge from the pond until the level is reached at which there is a break in the continuity of the saturated sand between the pond bottom and the water table. Initially the bottom of the lake appeared to be as suitable for artificial recharge as that of the Runyon pond. There has been no opportunity to inspect it since the lake was filled. However if the rate of recharge should be comparable to the maximum rate determined for the Runyon pond, the total recharge from the lake might be in the order of 14,000,000 or 15,000,000 gallons daily.

New developments for artificially recharging the Old Bridge sand should by all means accompany any increased pumping from it. Numerous possibilities for artificial recharge exist. For example, the sand is exposed along Deep Run for almost a mile upstream from the present wells of the Perth Amboy Water Department. If additional wells should be constructed in this area, it would be easily possible to induce a substantial amount of artificial recharge either by damming the stream or by conducting the water from it through a series of ditches or canals in the vicinity of the wells. Deep Run is affected by the tide at least as far upstream as the bridge near well F-37 (see figure 9). Probably the salt water does not advance that far up the stream, but suitable precautions should be taken to avoid recharging the sand with anything except fresh water.

In the vicinity of the Duhernal Lake it may be possible to increase the recharge by spreading fresh water through ditches or canals extending into the well field from the pond or, perhaps at higher levels, from the streams tributary to the pond. After a deposit of silt has accumulated in the lake dredging the bottom of the lake especially near its shores should be considered. Recharge developments similar to those suggested along Deep Run might also be constructed along Iresick Brook above the point where it enters the Duhernal Lake. Opportunities for additional artificial recharge doubtless exist in still other parts of the intake area of the sand. The examples given above are intended to be illustrative rather than exhaustive.

The probability that the recharge can be increased by a greater lowering of the water table over the part of the intake area remote from the present centers of pumping, should not be overlooked. This would make a larger amount of ground-water storage space available and decrease the probability that some recharge may be lost in these areas, especially during the winter season, because the ground storage is already full. It is advisable, therefore, to spread wells more widely over the intake area in order not to concentrate the lowering of head in a few small parts of it.

*Capacity to Transmit Water*

As indicated on page 69 the average coefficient of permeability of the Old Bridge sand is probably between 1,000 and 1,500. For the purpose of estimating its capacity to transmit water the lower and more conservative figure will be used. In an area where there is relatively little effect of pumping the natural slope of the water table was observed to be about 14 feet per mile. The thickness of the sand in this area was about 60 feet. On the basis of these data it would appear that the natural flow through the sand was about 840,000 gallons a day (1,000 x 14 x 60) for each mile of width of the aquifer. From South Amboy to the end of the intake area as it is defined on figure 6 (see page 21) the distance on a straight line is about 15 miles. If the area selected were typical, the natural discharge into streams would be about 12,600,000 gallons a day. The slopes toward the various centers of pumping are probably much greater than 14 feet per mile, and there is, therefore, little doubt that the sand can transmit very large quantities of water. In the intake area, however, the lowering of the water table decreases the effective thickness of the aquifer. It is desirable, therefore, not to pump too much water from any small part of this area but rather to spread the pumping more or less evenly over it. This would have the further advantage that the water table could be lowered more uniformly and better use could thus be made of ground-water storage.

If the rate of pumping at any of the well fields were so great that it exceeded the capacity of the sand to transmit water from a distance, there would be a progressive lowering of the water levels in the field even though the rate of pumping remained constant. A study of figure 10 (see page 82) does not indicate any such condition. The water levels in the Runyon well field, where the rate of pumping has been essentially stabilized for many years, return to about the same level each winter and there is certainly no evidence of any long-term decline. It is also apparent from the diagram and from the map on page 73 that a substantial depression in the water table has been created in the area around the Duhernal well field since 1939. This depression does not seem to be out of proportion to the amount of water pumped. It would probably become stabilized at a safe level if a constant rate of pumping from the well field were maintained. In a general way, therefore, the study of figure 10 seems to confirm the conclusion that the capacity of the Old Bridge sand to transmit water is so high that it probably does not limit its safe yield.

### *Danger of Salt-Water Intrusion*

There appears to be danger of salt-water intrusion into the Old Bridge sand at two points. At the South Amboy Water Works where the sand is exposed to salt water in the Raritan Bay, and in the vicinity of Old Bridge where salt or brackish water in the South River comes in contact with its intake area. In both localities test wells should be maintained and samples of the water in them taken regularly in order to detect any possible advance of salt water. If it appears necessary, the rate of pumping in either locality should be decreased in order to stop the advance of salt water.

At the South Amboy Water Works the wells draw from this sand near the Raritan Bay and near the area in which the sand is probably exposed beneath the bay. There may possibly be a protective blanket of fine silt on the bottom of the bay, but along the shore where wave action stirs the materials on the bottom of the bay such a cover would probably not be continuous. Prior to the development of the wells that tap the Old Bridge sand, a considerable amount of water was discharged from the sand into a pond and swampy area between the pumping station and the bay. It is reported that the pond was maintained until about 1939, but it has been dry most of the time since. The fact that the pond has not been maintained indicates that the cone of depression around the wells has extended beyond the site of the pond. If the rate of pumping is such that the cone of depression extends out beneath the bay, salt water will almost surely advance into the sand and ultimately reach the wells, rendering the water from them unfit for use.

As long as the pond was maintained it provided an assured fresh-water barrier between the wells and the bay. Without the pond it is imperative that test wells be constructed to observe the level of the water in the sand and permit the collection of samples of water for analysis.

The South River at Old Bridge frequently contains water of a fairly high chloride content. On the other hand, when the stream flow is high the water in the river is quite fresh. Since June, 1939, samples of water have been taken from the bottom of South River at Old Bridge at high tide, once a month. The results of analyses of these and other samples from points along the South River and the Washington Canal are shown in table 6 on page 93. The chloride content of the water from the river at Old Bridge has varied from 2.5 parts per million in July, 1941, to 4,550 parts per million in October, 1941.

TABLE 6.—CHLORIDE CONTENT OF MONTHLY SAMPLES FROM TIDAL STREAMS IN MIDDLESEX COUNTY, NEW JERSEY

Parts per Million

Analyzed in Water Resources Laboratory, Geological Survey, U. S. Department of The Interior (Except as Noted)

| Date | Location 1 | Location 2 | Location 3 | Location 4 |
|---|---|---|---|---|
| *1933* | | | | |
| May 9 | .... | 7.0[a] | .... | .... |
| *1938* | | | | |
| Apr. 29 | .... | 8.3[b] | .... | .... |
| Oct. 3 | .... | 7.5 | 2,425 | 3,700 |
| *1939* | | | | |
| June 9-12 | .... | 2,438 | 6,425 | 7,988 |
| July 5 | .... | 9.0 | 5,450 | 7,950 |
| Aug. 4 | .... | 1,500 | 6,350 | 8,675 |
| Sept. 6 | .... | 775 | 6,950 | 9,425 |
| Oct. 7 | .... | 1,175 | 6,700 | 8,775 |
| Nov. 8 | .... | 13 | 578 | 4,475 |
| Dec. 9 | .... | 1,000 | 8,550 | 10,100 |
| *1940* | | | | |
| Jan. 13 | .... | 2,250 | 8,625 | 12,000 |
| Feb. 10 | .... | 925 | 7,450 | 9,250 |
| Mar. 9 | .... | 8 | 4,875 | 6,875 |
| Apr. 6 | .... | 9 | 47 | 775 |
| May 3 | .... | 9 | 2,150 | 2,900 |
| June 15 | .... | 10 | 3,750 | 6,900 |
| July 13 | .... | 11 | 1,100 | 6,850 |
| Aug. 10 | .... | 134 | 3,650 | 7,450 |
| Sept. 9 | .... | 10 | 2,650 | 6,450 |
| Oct. 7 | .... | 10 | 4,800 | 7,512 |
| Nov. 11 | .... | 2,175 | 6,600 | 8,850 |
| Dec. 9 | .... | 15 | 5,775 | 9,450 |
| *1941* | | | | |
| Jan. 12 | .... | 10 | 5,450 | 8,725 |
| Feb. 12 | .... | 6 | 1,700 | 3,175 |
| Mar. 7 | .... | 6 | 6,275 | 5,900 |
| Apr. 7 | .... | 5.0 | 17 | 44 |
| May 6 | .... | 194 | 4,575 | 7,350 |
| June 5 | .... | 975 | 7,125 | 8,800 |
| July 10 | .... | 2.5 | 1,425 | 6,200 |
| Aug. 22 | 24 | 3,775 | 10,250 | 11,000 |
| Sept. 6 | 7.0 | 2,375 | 9,650 | 10,550 |
| Oct. 23 | 42 | 4,550 | 10,725 | 11,925 |
| Nov. 5 | 13 | 2,150 | 10,425 | 10,800 |
| Dec. 5 | 8 | 4,100 | 10,650 | 11,150 |

| Date | Location 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| *1942* | | | | |
| Feb. 10 | 8 | 14 | 825 | 6,800 |
| Mar. 7 | 8 | 14 | 127 | 4,800 |
| Apr. 6 | 12 | 15 | 2,005 | 4,875 |
| May 6 | 8.0 | 179 | 6,700 | 7,875 |
| June 6 | 24 | 1,370 | 1,150 | 8,275 |
| July 6 | 14 | 26 | 6,960 | 10,200 |
| Aug. 4 | 8.5 | 372 | 7,450 | 10,250 |
| Sept. 2 | 12 | 197 | 6,450 | 9,500 |
| Oct. 12 | 7.8 | 448 | 6,400 | 7,200 |
| Nov. 4 | 12 | 92 | 4,100 | 7,600 |
| *1943* | | | | |
| Jan. 7 | 7.0 | 15 | 2,200 | 3,400 |
| Feb. 8 | 5.5 | 6.0 | 34 | 1,950 |
| Mar. 9 | 8.2 | 8.0 | 457 | 2,150 |
| Apr. 5 | 7.0 | 13 | 3,200 | 4.800 |
| May 4 | 7.5 | 18 | 4,900 | 6,400 |
| June 8 | 12 | 16 | 860 | 4,100 |

1. South River, 0.2 mile downstream from Duhernal dam.
2. South River, at Old Bridge from highway bridge near railroad bridge.
3. South River, from Washington Street bridge at South River.
4. Washington Canal, at junction with Raritan River.
a. Maximum of fourteen hourly samples. The maximum chloride content of hourly samples from Deep Run at bridge ¾ mile NE of Old Bridge on this date was 9.0 p.p.m.
b. duPont Laboratory. Maximum of six samples, 3 at high tide and 3 at low tide. On this date the maximum chloride content of six samples taken from bridge on State highway route S28 about ½ mile upstream and analyzed in the duPont laboratory was 11 p.p.m.

The South River flows across the intake area of the Old Bridge sand for a distance of more than two miles. The point at which the samples are taken is about in the middle of this reach. At times of very low stream flow, samples of water containing as high as 42 parts per million have been obtained from a point a short distance below the Duhernal dam. It is apparent, therefore, that if the water table adjacent to and beneath the South River is lowered sufficiently, salty water will be drawn into the sand in this area and will contaminate the wells nearby. There is danger of contamination not only from the main channel of South River, but also from tributaries such as Deep Run and Tennent Brook which cross the intake area of the sand and undoubtedly contain salt water at the same times that the main stream is highest in salt.

The part of Tennent Brook into which tide water ordinarily advances is more than one-quarter of a mile from the Runyon well field. The tidal part of Deep Run, on the other hand, passes very close to one group of wells. Since January, 1942, a group of the active wells at the Perth Amboy Water Works near Deep Run has been sampled each month. The results of the analyses of these samples are shown in table 7 on page 95, along with records of the chloride content of several

TABLE 7.—CHLORIDE CONTENT OF MONTHLY SAMPLES FROM WELLS TAPPING THE OLD BRIDGE SAND MEMBER OF THE RARITAN FORMATION IN MIDDLESEX COUNTY, NEW JERSEY

Parts per Million

Analyzed in Water Resources Laboratory, Geological Survey, U. S. Department of The Interior

| | Well No. | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Date | P-8 | P-9 | 10-B | 87 | 93 | 96 | 99 | 109 |
| *1933* | | | | | | | | |
| May 10 | .... | 17[a] | .... | .... | .... | .... | .... | .... |
| *1938* | | | | | | | | |
| Mar. 23 | .... | .... | 5.0 | .... | .... | .... | .... | .... |
| Apr. 4 | 3.4[b] | .... | 4.1 | .... | .... | .... | .... | .... |
| May 9 | 3.1[b] | .... | 4.5 | .... | .... | .... | .... | .... |
| June 4 | .... | .... | 4.9 | .... | .... | .... | .... | .... |
| June 7 | 3.1[b] | .... | .... | .... | .... | .... | .... | .... |
| July 7 | .... | .... | 4.8 | .... | .... | .... | .... | .... |
| Aug. 9 | .... | .... | 5.2 | .... | .... | .... | .... | .... |
| Sept. 8 | .... | .... | 5.0 | .... | .... | .... | .... | .... |
| Oct. 8 | .... | .... | 4.8 | .... | .... | .... | .... | .... |
| Nov. 7 | .... | .... | 4.5 | .... | .... | .... | .... | .... |
| Dec. 10 | .... | .... | 4.8 | .... | .... | .... | .... | .... |
| *1939* | | | | | | | | |
| Jan. 7 | .... | .... | 5.1 | .... | .... | .... | .... | .... |
| Feb. 4 | .... | .... | 4.0 | .... | .... | .... | .... | .... |
| Mar. 4 | .... | .... | 4.8 | .... | .... | .... | .... | .... |
| Apr. 7 | .... | .... | 4.2 | .... | .... | .... | .... | .... |
| May 6 | .... | .... | 5.0 | .... | .... | .... | .... | .... |
| June 3 | .... | .... | 5.1 | .... | .... | .... | .... | .... |
| July 8 | .... | .... | 4.6 | .... | .... | .... | .... | .... |
| Aug. 5 | .... | .... | 4.9 | .... | .... | .... | .... | .... |
| Sept. 9 | .... | .... | 4.8 | .... | .... | .... | .... | .... |
| Oct. 9 | .... | .... | 4.8 | .... | .... | .... | .... | .... |
| Nov. 8 | .... | .... | 4.0 | .... | .... | .... | .... | .... |
| Dec. 9 | .... | .... | 4.8 | .... | .... | .... | .... | .... |
| *1940* | | | | | | | | |
| Jan. 13 | .... | .... | 4.9 | .... | .... | .... | .... | .... |
| Feb. 10 | .... | .... | 4.8 | .... | .... | .... | .... | .... |
| Mar. 9 | .... | .... | 4.4 | .... | .... | .... | .... | .... |
| Apr. 6 | .... | .... | 4.6 | .... | .... | .... | .... | .... |
| May 4 | .... | .... | 5.0 | .... | .... | .... | .... | .... |
| June 8 | .... | .... | 4.5 | .... | .... | .... | .... | .... |
| July 6 | .... | .... | 4.9 | .... | .... | .... | .... | .... |
| Aug. 3 | .... | .... | 4.9 | .... | .... | .... | .... | .... |
| Sept. 7 | .... | .... | 5.1 | .... | .... | .... | .... | .... |
| Oct. 7 | .... | .... | 4.9 | .... | .... | .... | .... | .... |
| Nov. 11 | .... | .... | 4.8 | .... | .... | .... | .... | .... |
| Dec. 7 | .... | .... | 5.0 | .... | .... | .... | .... | .... |

| Date | Well No. P-8 | P-9 | 10-B | 87 | 93 | 96 | 99 | 109 |
|---|---|---|---|---|---|---|---|---|
| *1941* | | | | | | | | |
| Jan. 4 ...... | .... | .... | 4.6 | .... | .... | .... | .... | .... |
| Feb. 8 ...... | .... | .... | 4.4 | .... | .... | .... | .... | .... |
| Mar. 5 ...... | .... | .... | 4.5 | .... | .... | .... | .... | .... |
| Apr. 3 ...... | .... | .... | 4.5 | .... | .... | .... | .... | .... |
| May 5 ...... | .... | .... | 4.8 | .... | .... | .... | .... | .... |
| June 5 ...... | .... | .... | 4.6 | .... | .... | .... | .... | .... |
| July 8 ...... | .... | .... | 4.8 | .... | .... | .... | .... | .... |
| July 9 ...... | 4.9 | 13 | .... | .... | .... | .... | .... | .... |
| Aug. 21 ...... | 4.8 | 24 | 4.2 | .... | .... | .... | .... | .... |
| Sept. 5 ...... | 4.6 | 28 | 4.6 | .... | .... | .... | .... | .... |
| Oct. 24 ...... | 4.8 | 27 | 4.8 | .... | .... | .... | .... | .... |
| Nov. 5 ...... | .... | .... | 4.6 | .... | .... | .... | .... | .... |
| Nov. 6 ...... | 4.8 | 26 | .... | .... | .... | .... | .... | .... |
| Nov. 19 ...... | .... | .... | .... | .... | .... | .... | 9 | .... |
| Dec. 5 ...... | 4.5 | 23 | 4.2 | .... | .... | .... | .... | .... |
| *1942* | | | | | | | | |
| Jan. 27 ...... | .... | .... | .... | 3.8 | 3.4 | 32 | .... | 5.2 |
| Feb. 5 ...... | 4.9 | 25 | 4.6 | .... | .... | .... | .... | .... |
| Feb. 16 ...... | .... | .... | .... | 3.4 | 3.4 | 35 | .... | 4.8 |
| Mar. 4 ...... | 4.9 | 23 | 4.4 | .... | .... | .... | .... | .... |
| Mar. 5 ...... | .... | .... | .... | 3.4 | 3.4 | 37 | .... | 5.0 |
| Apr. 2 ...... | 4.5 | 23 | 4.5 | .... | .... | .... | .... | .... |
| Apr. 6 ...... | .... | .... | .... | 2.6 | 3.4 | 32 | .... | 3.2 |
| May 5 ...... | 4.8 | 21 | 4.8 | .... | .... | .... | .... | .... |
| May 6 ...... | .... | .... | .... | 3.1 | 3.1 | 26 | .... | 4.2 |
| June 6 ...... | 4.9 | 20 | 4.2 | 3.1 | 3.1 | 24 | .... | 24 |
| July 3 ...... | 4.9 | 21 | 4.8 | 3.5 | 3.5 | 28 | .... | 25 |
| Aug. 3 ...... | 4.9 | 21 | 4.6 | .... | .... | .... | .... | .... |
| Aug. 4 ...... | .... | .... | .... | 3.5 | 3.5 | 28 | .... | 28 |
| Sept. 1 ...... | 4.8 | 20 | 5.0 | 3.5 | 3.5 | 26 | .... | 24 |
| Oct. 7 ...... | .... | .... | .... | 3.6 | 3.5 | 40 | .... | 4.0 |
| Oct. 12 ...... | 5.8 | 21 | 4.8 | .... | .... | .... | .... | .... |
| Nov. 2 ...... | 4.9 | 20 | 4.6 | .... | .... | .... | .... | .... |
| Nov. 4 ...... | .... | .... | .... | 3.8 | 4.9 | 20 | .... | 11 |
| *1943* | | | | | | | | |
| Jan. 6 ...... | 5.2 | 24 | 4.9 | .... | .... | .... | .... | .... |
| Jan. 7 ...... | .... | .... | .... | 4.5 | 3.5 | 42 | .... | 5.0 |
| Feb. 3 ...... | 4.9 | 22 | 4.9 | .... | .... | .... | .... | .... |
| Feb. 4 ...... | .... | .... | .... | 3.8 | 3.5 | 40 | .... | 6.0 |
| Mar. 8 ...... | 5.0 | 22 | 4.9 | 3.5 | 3.5 | 36 | .... | 12 |
| Apr. 5 ...... | 5.0 | 22 | 4.8 | 3.5 | 3.5 | 28 | .... | 30 |
| May 4 ...... | 5.0 | 22 | 5.0 | .... | .... | .... | .... | .... |
| May 7 ...... | .... | .... | .... | 3.5 | 3.5 | 26 | .... | 87 |
| June 8 ...... | 4.9 | 24 | 4.9 | .... | 3.5 | 30 | .... | 30 |
| June 9 ...... | .... | .... | .... | 3.2 | .... | .... | .... | .... |

P-8 and P-9 Test wells at Old Bridge
10-B Anheuser-Busch, Inc., well
87, 93, 96, 99 and 109 Perth Amboy Water Department wells

a. From well near the site of well P-9, now abandoned.
b. From Runyon well 124 about 0.3 mile south of well P-8.

other wells tapping the Old Bridge sand in this area. It is believed to be significant that two of the wells nearest Deep Run have shown chloride contents as high as 42 and 87 parts per million, respectively. The chloride content of these wells varies from time to time, apparently in response to variations in the salinity of the water in Deep Run. The normal chloride content of the wells at the Perth Amboy Water Works ordinarily ranges between 2.5 and 5.0 parts per million and averages about 3.5 parts per million. It is evident therefore that there is some salt-water intrusion in this area. However, if it does not increase beyond the range already observed it will not have any serious consequences. Water containing higher chlorides than any of the samples is used in many places and furthermore the water from this group of wells is mixed with that from many others and the chloride content of the mixed water is probably not changed appreciably.

The situation in this area should, however, be watched very carefully. The regular collection of samples from the selected key wells should be continued and occasionally samples from every available well in that area should be taken in order to define the extent of the contamination. If there should be an appreciable increase in the salinity of the water from these wells, or if the area of salt-water contamination shows a tendency to expand, the advance of salt water can be checked by reducing the pumpage from this group of wells or by constructing a dam across Deep Run some distance below the wells. It is believed to be feasible to construct such a dam just above the Camden and Amboy Division of the Pennsylvania Railroad. It should be high enough to prevent overtopping by the highest storm tides. If it is not feasible to construct a dam that high, tide gates should be constructed to prevent high tides from overtopping the dam and filling the pool above it with salt water. The construction of such a dam and the maintenance of a fresh-water pond above it would undoubtedly increase the amount of recharge into the Old Bridge sand and increase the amount of water that can be taken from wells in its vicinity. If Deep Run should ever be developed for a surface-water supply and the amount of fresh water flowing past the Perth Amboy wells thereby reduced, the construction of a dam near the railroad to prevent salt water backing up into the well field would be almost imperative because the salinity of the water in the tidal reaches of Deep Run would then be much higher.

During the first World War eight wells were drilled along the edge of the marsh bordering the South River and extending almost to Old Bridge. These wells and an auxiliary pumping station to pump from them were completed just before the end of the war but were not used.

For a short period after the war an attempt was made to pump them by direct suction from the main station at Runyon. Because of the length of pipe line involved and the necessity of crossing some relatively high ground, it is probable that only a small amount of water was pumped from these wells at that time. It is fortunate that these wells were not pumped much, otherwise salt water would have been drawn into the sand around them.

The increased draft by the Duhernal development upon the Old Bridge sand southwest of Old Bridge, and the realization that water high in chloride content sometimes advances well above Old Bridge, caused some concern lest salt water might be drawn into the sand and contaminate both the Perth Amboy wells and the Duhernal wells. Three samples of water were, therefore, collected in April, May and June of 1938, from the well at the end of the South River line of wells belonging to the city of Perth Amboy. These samples all contained less than 3.5 parts per million of chloride. Because of the difficulty of pumping this large well and because it was more than half a mile upstream from the railroad bridge at Old Bridge, a test well, P-8, was constructed farther downstream.

Test well P-8 (see map on page 73) was constructed near the point where the South River is crossed by the railroad. This well was drilled 55 feet deep to the bottom of the Old Bridge sand. A thin layer of clay was observed just below the 18-foot depth. It was considered desirable to sample the water both above and below this clay so well P-9 was constructed at the same location to a depth of 18 feet. These two wells have been sampled regularly since July, 1941 (see table 7 on page 96). The chloride content of the water from well P-8 has been consistently between 4.5 and 6.0 parts per million. The chloride content of the samples from the shallower well has varied from 13 to 28 parts per million and averaged about 22 parts per million. It is apparent, therefore, that some salt water has entered the shallow sand above the clay bed but in the vicinity of these wells it has not penetrated below this bed.

In May, 1933, a sample of water was collected from a shallow well driven near the site of wells P-8 and P-9 and found to contain 17 parts per million of chloride. At the same time a sample collected from test well M-2 in the tidal marshes near Deep Run and upstream from the railroad bridge, was found to contain 190 parts per million of chloride, and a sample from test well C-4 contained 11 parts per million. It is evident, therefore, that the contamination of the shallow part of the sand in the vicinity of Old Bridge was not caused by the pumping at the Duhernal development and probably was not caused by any pumping at the Perth Amboy Water Works. The contamination is due rather to the fact that salt water frequently backs up into the streams and submerges parts of the lowland adjacent to them. Along Deep Run the contamination has probably extended all the way to the bottom of the sand, as is indicated by the contamination of the two wells at the Perth Amboy Water Works.

In connection with the construction of the Duhernal project, four test wells were drilled between that project and the well field of the Perth Amboy Water Department. It was originally intended to use these wells for observing ground-water levels between the two well fields and thus avoid interference with the Perth Amboy wells. All four wells were equipped with water stage recorders.

One of these wells, known as Duhernal observation well No. 3, was a short distance downstream from the Duhernal dam and within 50 feet of the bank of the South River. After maintaining a water stage recorder on this well for more than a year it was evident that the water level in it fluctuated almost entirely in accordance with the level of the water in the South River, responding not only to the levels during flood period but also to tidal fluctuations. It was decided, therefore, that it might be more profitable to use this well as a sampling point, and the recorder was removed so that a pump could be installed. This well has been sampled regularly by the engineers of the Duhernal water supply and the samples analyzed in their laboratory. The chloride content of the water from it has normally ranged from 3 to 5 parts per million, but in the summer of 1941, when chlorides as high as 42 parts per million were observed in the stream near this well at high tide, the chloride content of the water from the well rose as high as 8 parts per million. Subsequently, when the chlorides in the river were again low the chloride content of the samples from this well dropped to about 5 parts per million. The results of sampling this well suggest that the Old Bridge sand in this vicinity is open to contamination from the river. If the flow of the river should be materially reduced by the withdrawal of water from it above the Duhernal dam so that more saline water could reach this area, and if the pumping in the area should lower the water table substantially, a serious problem might be created.

If the salinity of the water from the various test wells around Old Bridge should show a tendency to increase or if the city of Perth Amboy plans to use its wells along the South River, it would probably be desirable to construct a dam across the river above the railroad bridge so that fresh water may be impounded in the channel and on the low ground above this point and salt water prevented from advancing farther upstream. Like the dam suggested for Deep Run, it should be either high enough to prevent overtopping by extreme high tides or protected by tide gates that would prevent it from being overtopped. The fresh water pond above the dam would also provide additional artificial recharge for the sand and would permit the pumping of more water from it than would otherwise be possible. It would also maintain the head of the fresh water in the sand upstream from the railroad at a level high enough to prevent the advance of salt water through the sand from the exposed area downstream.

The effect of the danger of salt-water intrusion upon the safe yield of the Old Bridge sand is indefinite. It probably will not be very great provided the principal users of water from the sand are prepared to take remedial measures as they become necessary. Salt-water intrusion might affect the safe yield most seriously in the vicinity of Old Bridge, because of the large amount of pumpage in that area. The construction of dams on the tidal streams appears to offer a satisfactory remedial measure in this area. At the South Amboy Water Works the rate of pumpage may have to be reduced until a fresh-water barrier can be reestablished or the entire supply may be destroyed. In either area the maintenance of the present rate of withdrawal appears doubtful and any increased pumpage might be disastrous unless suitable precautionary and remedial measures are taken.

### *Contamination by Industrial Wastes*

In the vicinity of Parlin there are areas in which the Old Bridge sand has been contaminated by industrial wastes. In the early history of the industrial development in this locality considerable quantities of waste materials, many of which were acid in nature, were dumped on the ground or discharged into a drainage system flowing across the sand and into the South River. This practice has been discontinued in recent years and any wastes now discharged are of a relatively harmless nature. Nevertheless there are areas in which the sand contains highly acid water or water contaminated with other undesirable chemical materials. Some of this contaminated water has been drawn into the wells at Parlin. Any additional wells in this area should be located as far as possible from known sources of contamination of this nature. This condition is not as serious as the danger of salt-water contamination, however, because it is not a continuing one. It will probably be possible to remove entirely the undesirable materials from the sand by pumping over a long enough period.

### SOUTH AMBOY FIRE-CLAY

Typically, the South Amboy fire-clay is a light gray or white, tough, refractory clay; but it may be colored brick red or gray and in some places it is sandy and of no economic value. It is well exposed in several pits in or near the Borough of Sayreville and in all these the clay is practically free of lignite, a circumstance which distinguishes it sharply from the upper part of the Woodbridge member and from the overlying clays. Unfortunately this characteristic does not prevail everywhere, for reliable observers have noted the presence of lignite in pits opened many years ago, and it has been found in a few samples from boreholes near Jamesburg.

The clay ranges from 0 to 25 feet thick along its outcrop, and down the dip attains a thickness of 35 feet half a mile southeast of Parlin. A brief period of erosion is believed to have followed the deposition of the South Amboy fire-clay for its upper surface is sometimes undulatory or even sharply irregular in places where it is overlain in normal sequence by the Old Bridge sand. Where overlain by deposits of Cape May age it is markedly irregular, but in such places the irregularity can be attributed largely, if not entirely, to post-Cretaceous erosion.

All the reliable records of deep wells in and near the Runyon well field have reported striking the South Amboy fire-clay at depths ranging from 57 to 86 feet. Since it is a tough, impervious stratum in that area, it must therefore act as a barrier to the downward movement of the ground water in the Old Bridge sand. The records of many wells and test boreholes show that southwest of Old Bridge, however, the clay is quite irregular in its occurrence, and in that direction, therefore, the clay is of negligible importance from a hydrologic standpoint.

### SAYREVILLE SAND MEMBER

Near the Raritan River the South Amboy fire-clay is underlain by a bed of variable composition which is dominantly composed of fine to medium grained, white, micaceous sand. This is the Sayreville sand, or the No. 2 sand of previous reports dealing with the Raritan formation. The name Sayreville sand is proposed for this member because it has been well exposed at several places in the northern part of the Borough of Sayreville and the location name will not easily be confused with the names of the formations or with other members of the Raritan formation.

North of the Raritan River, the Sayreville sand consists of layers of fine, white, micaceous sand, cross-bedded fine to coarse-grained white sand, with or without layers of white clay, and beds of arkosic sand. The general thickness is about 35 to 40 feet. The beds are so variable that there is no order of stratigraphic sequence over more than a small area. The lenses of arkosic sand, which may be as much as 12 feet thick were once used in the manufacture of fire brick near Perth Amboy.

Though a conspicuous member of the Raritan formation in the vicinity of Woodbridge and Perth Amboy, the Sayreville sand is thin or lacking in the vicinity of Runyon. In the prominent hill half a mile southwest of the southern approach to the Victory Bridge over the Raritan River it is a fine to coarse-grained white sand, arkosic towards the base, and about 40 feet thick. A mile to the southwest it is markedly cross-bedded, contains thick beds of ironstone and is only 15 feet thick. In a good exposure in Sayreville, due south of Crab Island, it is only 6 to 7 feet thick; and though the sand is fairly coarse, it contains lumps and thin lenses of white clay. Just 1,400 feet farther southwest, in the large pit of the Sayre & Fisher Brick Company, the sand is lacking and the South Amboy fire-clay can be seen directly overlying the laminated clays of the upper part of the Woodbridge clay. This same relationship can be observed in the pit of the New Jersey Clay Products Company, one and a quarter miles to the south-southwest. This "pinching out" of the Sayreville sand is the chief reason why not one well southeast of the Camden and Amboy Railroad is yielding water from this stratum. Carefully kept logs of wells and test boreholes show that even though it is sometimes present in the Runyon area, it is thin and clayey and not therefore an important aquifer.

No important water supplies have been developed from the Sayreville sand. In fact, not a single well is known to draw its water entirely from it and it was, therefore, impossible to obtain a sample of water for analysis. However, the South Amboy fire-clay which separates the Sayreville sand from the overlying Old Bridge sand, is irregular and sometimes absent so that in one or two wells there has apparently been no separation between these two sands, and at least one well probably draws water from both the Old Bridge and the Sayreville sands.

One sample of sand was collected from this member for analysis in the Water Resources Laboratory during the present investigation. The analysis in the table on page 42 indicates that the sample contained a considerable amount of clay and other fine materials. Its porosity was

44 percent, and its moisture equivalent was 12 percent. It would appear, therefore, that the specific yield of the sand is only about 32 percent and that its ability to store water is not as great as most of the other sands in the county. Analyses of two other samples from this sand are reported by Stearns,[22] and they indicate a probable specific yield of about 39 percent, which is more in line with the other sands in the area. The analysis on page — shows that the coefficient of permeability of the recent sample from the Sayreville sand was only 30, indicating that water would move through it very slowly under ordinary conditions. The two samples reported by Stearns indicate an average coefficient of permeability of about 500 which again is more in line with the other sands in this area. Samples of this sand subsequently obtained from wells, although not analyzed in the laboratory, appeared to contain a smaller percentage of fine or clayey material than the sample sent to the laboratory. A recent examination of this sand where exposed in another pit tends to confirm this conclusion. It seems probable, therefore, that the capacity of the Sayreville sand to store and transmit water is fairly high in some places. Nevertheless its thinness and lack of continuity make it most unlikely that any substantial water supply can ever be developed from it.

### WOODBRIDGE CLAY

The Woodbridge clay underlies the Sayreville sand and ranges from 50 to 90 feet in thickness where uneroded. The upper portion consists of well stratified, dark-gray clays containing a sufficient amount of fine-grained sand to make an ideal material for the manufacture of common brick, and it is widely used for that purpose. The middle portion of the member commonly consists of gray clay, though sandy clays or clayey sands may occur. Both the upper and middle portions of the Woodbridge clay are extensively used in the manufacture of hollow tile. The basal portion of the member contains beds of compact, tough, and highly refractory fire-clay which are white, light-gray or brick red in color.

Nodular masses of impure siderite are common in the upper portion of the Woodbridge clay near Sayreville and the South River and when present they aid in its identification. These nodules contain marine fossils thus showing that marine conditions probably prevailed for at least a part of Raritan time. The upper part of the clay also contains lignite and pyrite. Dinosaur footprints have been found in the Wood-

[22] Stearns, Norah Dowell, Laboratory tests on physical properties of water-bearing materials; U. S. Geol. Surv. Water Supply Paper 596-F, 1927, pp. 166-167, Samples 71 and 72.

bridge clay and these, together with the lignite, indicate that a marine environment may not have existed throughout all of Woodbridge time.

Quite apart from its economic importance as a source of clay, this thick and widespread unit in the Raritan formation is of great hydrologic importance because it forms an impervious cover over the prolific Farrington sand. It limits the intake area of that sand to the area of its outcrop and farther down the dip, confines the water in the sand so that it occurs under artesian conditions.

### FARRINGTON SAND MEMBER

A report describing the water supplies of the Farrington sand or No. 1 sand of previous reports dealing with the Raritan formation, was published in 1937.[23] The description of the sand and of the water supplies from it in this report are, therefore, somewhat abbreviated and emphasis is placed upon new data collected since the preparation of the earlier report. This sand occurs both north and south of the Raritan River and probably across the Arthur Kill on Staten Island. Not much water is pumped from its intake area, but it is tapped by wells in many places down the dip from the intake area where the water is encountered under artesian pressure.

#### *Geology*

The Farrington sand lies beneath the Woodbridge clay. As indicated on figure 6 on page 21, it crops out in a conspicuous band nearly a mile wide along the southeast edge of Farrington Lake where several sand pits give a good opportunity to examine it. A large amount of water enters the sand in this area which makes it very important from a hydrologic standpoint. For the above reasons, this member is called the Farrington sand in this report.

The upper part of the Farrington sand is generally medium to fine-grained. The lower portion, 10 feet to 20 feet thick, is a coarse, arkosic, light-gray or light-yellow sand usually containing a considerable sprinkling of small pebbles. The arkosic material, as seen in outcrop, is always partly kaolinized, the white kernels of the partly decomposed feldspar standing out sharply in contrast with the gray and yellow colors of the sand and gravel. The latter is composed chiefly of well rounded quartz pebbles, but also contains numerous pebbles of flint ranging in diameter from a quarter of an inch to a maximum of two

[23] Barksdale, Henry C., Water Supplies from the No. 1 Sand in the Vicinity of Parlin, New Jersey, Special Report 7.

inches. Occasionally the gravelly beds contain rather numerous small chunks of red or white clay, quite obviously derived from the underlying Raritan fire-clay and evidently redeposited close to their source. Lenses of clay, usually only a few feet thick, also occur within the limits of this member and thin clay seams are fairly common.

As recorded in well logs, the sand is often divided by clay lenses into two or more parts, but since the static levels of the water from all parts of the member are about the same for any one location, the dividing clay beds are evidently of very local extent. The following log was compiled from samples obtained from a test well drilled for the Borough of Sayreville about a mile and a quarter northwest of the Runyon pumping station.

*Partial log of test well at Sayreville, New Jersey*

| *Sample depth* | *Description* | *Formation* |
|---|---|---|
| 118–120 | Clean, fine to coarse-grained, light gray sand with a little lignite and pyrite. | Farrington sand member of the Raritan formation. |
| 120–137 | Clean, coarse-grained sand and small gravel (including unweathered flint). Some grains cemented by pyrite. A little fine-grained sand and some lignite at 132 feet. | |
| 137–163 | Light gray clay with a little sand. | |
| 163–180 | Coarse gray sand and small pebbles. | |
| 180–198 | Coarse, light gray sand and gravel. | |

It will be noted that the full thickness of the member is 80 feet. Half a mile southwest at the pumping station of the Borough of South River, the reported thickness in a deep well was only 44 feet; but at the Anheuser-Busch plant half a mile southwest of Old Bridge it is 78 feet 8 inches thick, at the Peter J. Schweitzer Company plant in East Spotswood it is 56 feet thick, at Runyon it is 91 feet thick and near Parlin it ranges from 50 to 104 feet thick. It is known to be continuous to the southwest at least as far as Jamesburg as it was found (83 to 129 feet thick) in the wells at the New Jersey State Home for Boys two and a quarter miles to the east-southeast and in a test borehole 0.85 mile east of Dayton and 3 miles west-northwest of Jamesburg. The Farrington sand dips to the southeast at the rate of about 55 feet per mile.

Northeast of Parlin the member thins, the sand becomes finer grained and sometimes quite clayey, and in South Amboy wells drilled to this horizon have been only moderately successful. In the district between Parlin and Jamesburg, however, the Farrington sand is one of the best aquifers in the State. Wells of large diameter and modern construction have yielded as much as two million gallons daily, and nearly all of them are rated in excess of half a million gallons daily.

The Farrington sand is thin or lacking above the buried trap ridge between the Borough of South River and Perth Amboy as shown in figure 3 on page 17. A great many wells have been drilled in this area, but those over the trap ridge with the exception of a few within a mile or so northeast of the Borough of South River have not been as successful as wells to the northwest or southwest. Hydrologically this is important because the thinning of the Farrington sand on the ridge tends to prevent the movement of salt water from the intake under the Raritan River to the centers of pumpage to the southeast.

*Physical Properties*

The results of laboratory tests on seven samples of this sand taken at different exposures along its outcrop are given in the table on page 42. The coefficient of permeability of the sand as determined by these tests ranges from 210 to 3,500, and a weighted average would probably be between 1,200 and 1,500. Pumping tests at the Perth Amboy Water Works gave figures for the coefficient of permeability which were in this same order of magnitude. The specific yield of the sand, as indicated by the average difference between its porosity and its moisture equivalent, is about 32 percent. With a specific yield of 32 percent, a block of the Farrington sand one foot thick and one square mile in area, would be capable of storing about 67 million gallons of available water.

*Quality of Water*

The uncontaminated water from the Farrington sand is exceptionally good for most purposes. Its quality varies slightly from place to place, but the total solids are usually less than 40 parts per million. The hardness is usually less than 15 parts per million. The only feature of this water that is sometimes objectionable is its iron content, which ranges from 2 to 6 parts per million in some localities.

The chloride content of the water from the Farrington sand is normally only 2 to 4 parts per million, but the sand has been contaminated by the intrusion of sea water in several places in the county.

Where this has occurred, the water has become highly mineralized and unfit for any ordinary use except cooling. Samples collected from wells in the contaminated areas have been found to contain from 10 to 7,675 parts per million of chloride. The other minerals contained in sea water, notably the hardness-forming minerals, calcium and magnesium, have, of course, increased in proportion to the increase in chlorides so that the water rapidly becomes less desirable, even before the concentration of salts renders it useless. The degree and extent of the contamination has tended to increase with continued pumping. The area, extent, and probable significance of the very serious problem created by the salt-water intrusion into this sand is discussed on pages 115 to 139.

### *Development and Pumpage*

The first water supply developed from the Farrington sand south of the Raritan River was at the Perth Amboy Water Works at Runyon where a well tapping it was drilled in 1897. About the same time industrial wells drawing from this sand were drilled in the city of Perth Amboy. For several years after 1897 the Farrington sand at Runyon was the principal source of water supply for the city of Perth Amboy. Later this supply was augmented by pumping from the Old Bridge sand, and water from both sands was used. In Middlesex County the water from the Farrington sand is now used almost exclusively for industrial purposes.

Before the beginning of the World War of 1914, only a few industrial plants in Perth Amboy, South Amboy, and Sayreville were using water from the Farrington sand. The total pumpage from the sand within the county probably did not exceed one or two million gallons daily at that time. The favorable location of the region for export trade produced a sudden increase in industrial activity during the war and a corresponding increase in the use of water from the Farrington sand. Unfortunately there are practically no records of pumpage during these years, but from the information available about the capacity of the wells then in use it seems probable that the total rate of pumpage from the sand within the county did not exceed 7 million gallons daily.

Many of the industrial plants established in this area during the war were adapted to peace-time operations and continued or increased their use of water. New industries were attracted to the area and the pumpage increased still more. A table showing withdrawals from the Farrington sand for the years 1929 through 1935 was included in the earlier report on this sand.[24] This table has been revised and extended through 1942 and is given as table 8 below. It covers the period 1929 through 1942, and gives separately the pumpage from the sand by the Perth Amboy Water Works and by the wells of the Duhernal companies, as well as a summary of other pumpage both north and south of the Raritan River.

TABLE 8.—QUANTITY OF WATER PUMPED FROM THE FARRINGTON SAND MEMBER OF THE RARITAN FORMATION IN MIDDLESEX COUNTY, NEW JERSEY, 1929-1942

| Year | North of Raritan River | Duhernal Companies | Perth Amboy Water Dept. | Other Pumpage South of Raritan | Total |
|---|---|---|---|---|---|
| | | *In thousands of gallons daily* | | | |
| 1929 ...... | 2,080 | 6,202 | 92 | 203 | 8,577 |
| 1930 ...... | 1,970 | 5,964 | 877 | 309 | 9,120 |
| 1931 ...... | 1,583 | 5,053 | 1,173 | 342 | 8,151 |
| 1932 ...... | 1,240 | 4,352 | 1,198 | 398 | 7,188 |
| 1933 ...... | 1,221 | 5,442 | 187 | 377 | 7,227 |
| 1934 ...... | 1,315 | 6,570 | 135 | 369 | 8,389 |
| 1935 ...... | 1,331 | 8,129 | 585 | 407 | 10,452 |
| 1936 ...... | 1,879 | 9,094 | 655 | 408 | 12,036 |
| 1937 ...... | 2,066 | 8,434 | 650 | 404 | 11,554 |
| 1938 ...... | 1,874 | 5,495 | 0 | 408 | 7,777 |
| 1939 ...... | 1,895 | 6,358 | 546 | 424 | 9,223 |
| 1940 ...... | 1,975 | 4,785 | 301 | 402 | 7,463 |
| 1941 ...... | 1,922 | 4,898 | 772 | 996 | 8,588 |
| 1942 ...... | 1,875 | 4,015 | 620 | 556 | 7,066 |

The pumpage from the Farrington sand reached a peak in 1936 when it amounted to slightly over 12 million gallons a day. Approximately 9 million gallons a day of this amount was pumped by the industries in Sayreville Township. Intrusion of salt water into this sand at the Washington Canal caused the development of the Duhernal well field which derives its supply from the Old Bridge sand and made possible a substantial reduction in the pumpage from the Farrington sand by these industries. In 1942 the pumpage was only 4 million gallons a day, a drop of 5 million gallons a day from 1936. The decrease would probably have been even greater had it not been for the increased industrial activity due to the present war.

Pumpage from the Farrington sand by the Perth Amboy Water Department at Runyon during the period 1929-1942, inclusive, has varied from an average rate of 92,000 gallons a day in 1929 to a maximum rate of 1,198,000 gallons a day in 1932. Only one large capacity well tapping the Farrington sand is used. It is now pumped only to supplement the supply from the wells tapping the Old Bridge sand when the yield of those wells is low due to drought or when the demand for water is exceptionally great.

[24] Barksdale, H. C., Op. Cit., Special Report 7, p. 14.

Consumption of water from the Farrington sand north of the Raritan River has varied between 1,200,000 gallons a day and 2,100,000 gallons a day since 1929. This water has been used entirely by industries in Woodbridge and Raritan Townships and in the City of Perth Amboy. Until recently a great deal of the pumpage in this area was concentrated in and near Perth Amboy. Because of contamination of the sand by salt water, however, most of the industries within the city now obtain water from the Perth Amboy Water Department. The total pumpage from the Farrington sand north of the Raritan River has not varied greatly, however, because increases in Woodbridge and Raritan Townships have offset the reductions in Perth Amboy.

### *Factors Affecting Safe Yield*

In general, there are three factors that may limit the safe yield of an artesian aquifer such as the Farrington sand: its available recharge, its capacity to transmit water from the intake area to the well fields, and the possibility that some form of contamination may be induced or accelerated by the pumping. The true safe yield of the sand is that rate of pumping which does not exceed any of these three factors. Whichever factor permits the smallest quantity of water to be removed from the sand is the limiting factor and determines the safe yield.

### *Available Recharge*

The recharge in the intake area of the Farrington sand was estimated in the previous report to be about 950,000 gallons daily per square mile, or 20 inches of the water from precipitation each year. The intake area of the sand as far as it has been defined is about 17 square miles, as is shown in figure 6 on page 21, and the recharge in this area is accordingly estimated to be about 16 million gallons daily. The sand is separated into two parts by the estuary of the Raritan River and by the underlying trap ridge. Recharge occurring north of the Raritan River is believed not to be available to wells south of the river and vice versa. The intake area north of the river is approximately 6.8 square miles, and its recharge is estimated to be about 6.5 million gallons daily. The intake area south of the river, so far as it has been defined, is about 10.2 square miles, and its recharge is estimated to be about 9.7 million gallons daily. The area at its southeastern end shown by shading in figure 6, is not very well defined, because of the depth of the overlying Quaternary deposits. The sand probably extends still farther south, because it is believed to have been encountered in the deep well of the Cranbury Water Company. Any additional intake area in this direction, however, is so far from the present centers of pumping that it would probably not supply any appreciable amount of water to them.

*Artificial Recharge.* The natural intake capacity of the Farrington sand could, no doubt, be increased by artificial recharge. However, there has as yet been no attempt to recharge this sand artificially. The easiest and most obvious method of inducing artificial recharge would be the location of ponds on some of the smaller streams that cross its intake area, both north and south of the Raritan River.

Another possible means of recharging the sand would be to introduce water into it through wells. This method is expensive, however, and the techniques involved have not been developed to an extent that makes it thoroughly reliable. In order to successfully recharge the sand through wells, the water used should be absolutely free from any material that would be deposited in the sand outside the recharge well and thus reduce its capacity. If surface water were used for this purpose, it should be filtered and preferably sterilized as well to prevent the clogging of the sand by solid particles or by the growth of microorganisms. Recharge wells may, of course, be redeveloped from time to time to restore their capacity, but it is difficult to maintain the original capacity of such a well even with the best of care, especially if the recharge water is not carefully prepared. Recharge of the Farrington sand through wells might be considered in the vicinity of Parlin and South Amboy, in order to retard the advance of salt water and possibly force it out of the sand. Elsewhere in the county it is not believed to be economically justifiable.

If the fullest possible use were made of all opportunities for artificially recharging the Farrington sand, it might be possible to increase its total recharge by several million gallons daily. It must be borne in mind, however, that the surface water diverted into this sand would not be available for use elsewhere. For example, the principal streams south of the Raritan River that flow across its intake area discharge into Lawrence Brook, which is being used by the city of New Brunswick as a source of public water supply.

### *Capacity to Transmit Water*

The capacity of the Farrington sand to transmit water from the intake areas to the various wells as indicated by the coefficient of permeability of the samples analyzed in the laboratory is relatively high. It appears improbable that this factor would limit the safe yield of the sand. For the purposes of estimating, the average coefficient of permeability may be assumed to be 1,350, and 80 feet may be used as the average thickness of the sand. In June, 1936, when the rate of pumping from the Farrington sand in the Parlin area was near its maximum (9.4 million gallons a day), water levels in the vicinity of Parlin, as determined from the duPont and Hercules observation wells averaged about 57 feet below sea level. At the same time the water level in the intake area of the sand, as determined from the Fischer well, was about 60 feet above sea level, making a total difference in head of 117 feet between the intake area and the area of pumping. The average distance from the intake area to the approximate center of pumping at Parlin is about 5 miles. The average gradient was, therefore, about 23.4 feet per mile. With this hydraulic gradient the sand would transmit 1,350 x 80 x 23.4 or about 2.5 million gallons a day for each mile of its width. South of the Raritan River the width of the aquifer is at least 10 miles so that it might transmit 25 million gallons daily under the assumed conditions. In the immediate vicinity of the individual pumped wells, where the gradients are much steeper, the rate of flow was, of course, much greater.

The capacity of the sand to transmit water may also be judged by a study of the effect of pumping different quantities of water upon the head of the water in the sand at various points. The relation between pumpage from the Farrington sand and the water levels in various observation wells tapping this sand is shown on figure 11 on page 112. The location of all the wells on this diagram except the Fischer well are shown on figure 12. The location of the Fischer well is shown on figure 2, on page 6, because it is outside the limits of figure 12.

This diagram shows the pumpage by months and the fluctuations of water level in several observation wells tapping this sand. The pumpage is subdivided to show the amount taken from the wells of the Duhernal companies and the amount taken from the well at the Perth Amboy Water Works. Water level fluctuations are shown in five wells. Two of these are at Parlin: an observation well at the duPont plant, and an observation well at the plant of the Hercules Powder Company. The other three are an old deep well at Runyon, a test well at the site of the proposed Sayreville Water Works, and the Fischer well, which is an observation well in the intake area of the sand several miles from any center of pumping.

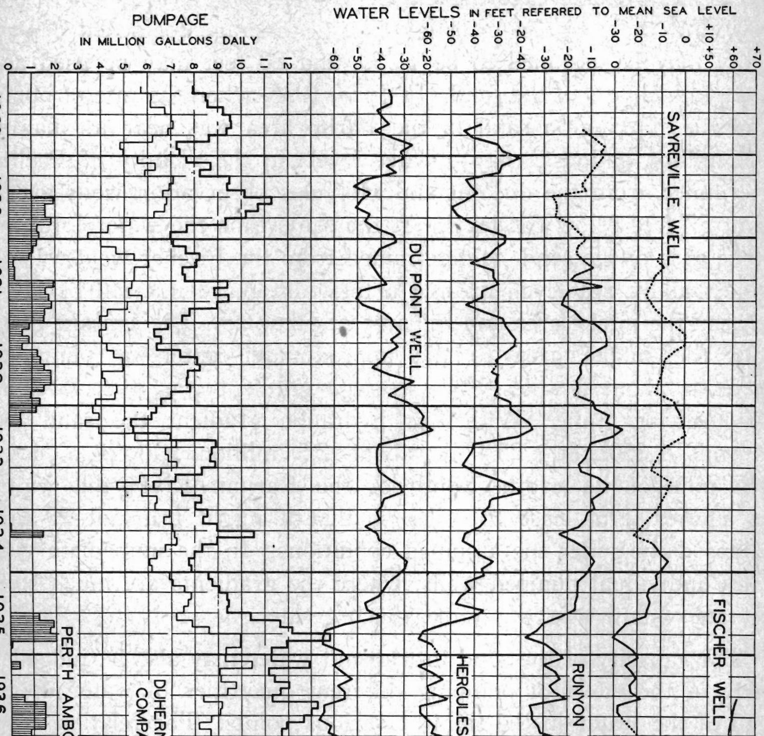


FIGURE 11.—Diagram showing the relation between water levels and pumpage in the Farrington sand member of the Raritan formation, 1929 to 1942. For locations of wells see Figs. 2 and 12.

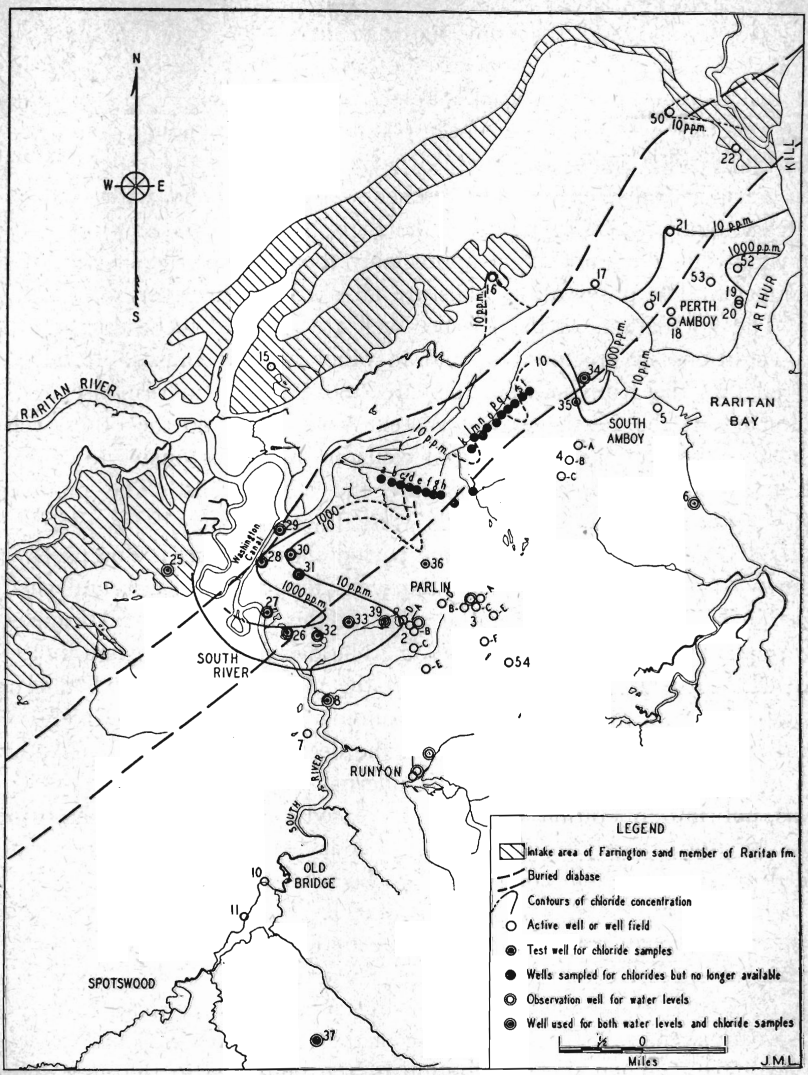


FIGURE 12.—Map of the area between Perth Amboy and Spotswood showing the location of wells tapping the Farrington sand, the intake area of this sand, and the approximate extent of the salt-water intrusion into this sand

KEY TO WELL NUMBERS

1. Perth Amboy Water Department
2. Hercules Powder Company (5 wells)
3. E. I. duPont deNemours & Company (6 wells)
4. National Lead Company (3 wells)
5. Jersey Central Power & Light Company (2 wells)
6. South Amboy Water Department (3 wells not used)
7. South River Water Department (2 wells)
8. Sayreville Borough (5 test wells)
10. Anheuser-Busch Company
11. Peter J. Schweitzer Company
15. Nixon Nitration Works (13 wells)
16. Heyden Chemical Company (2 wells)
17. Carborundum Company (2 wells)
18. Raritan Copper Works (2 wells)
19. Roessler & Hasslacher Chemical Company
20. General Cable Company
21. Puritan Dairy
22. Bona Fide Mills
25. National Fireproofing Company
26. Furman observation well
27 to 37 (inclusive) and 39. Observation wells
50. Clover Green Dairies
51. Chesebrough Manufacturing Company
52. Atlantic Terra Cotta Company
53. Amboy Ice Company
54. Monteath Lumber Company

It will be noted that the pumpage from the wells of the three Duhernal companies accounts for the major part of the total pumpage. In recent years the well at the Perth Amboy Water Works has been operated only when it has not been possible to obtain enough water from the Old Bridge sand. In general, the fluctuations of the water level in the various wells, except the Fischer well, correspond with the total rate of pumping. The pumpage north of the Raritan River is fairly constant and does not affect appreciably the trend of the line for total pumpage. The observation wells are all south of the river.

The fluctuations of the Fischer well are believed to be due entirely to variations in precipitation and to other natural causes. It will be noted that the Runyon well fluctuates more widely in response to the pumpage at the Perth Amboy Water Works than do the other wells, and that the Hercules and duPont wells are more responsive to changes in the Duhernal pumpage than are the other wells. The pumpage was higher and the water levels were lower during 1935, 1936 and 1937 than at any other time in the period shown. This is due partly to increased demand from most of the wells tapping the sand, and partly to the fact that the wells at the plant of the National Lead Company were put into operation during 1935. The decrease in pumpage in 1938 was due to conservation measures at the plants of the three Duhernal companies, and to the fact that the summer of 1938 was relatively wet and it was not necessary to operate the deep well at the Perth Amboy Water Works. In 1939 the new Duhernal supply south of Old Bridge was put into operation and the decreased pumpage since that time has been due largely to the fact that a considerable portion of the water used by the Duhernal companies has been taken from this source.

In general, the effect on the water levels in the wells of a given rate of pumpage was about the same both before and after the three years of excessively high pumping. There have, of course, been some changes due to the fact that the construction of the National Lead Company wells in 1935 and the use of the Schweitzer well in 1941 and 1942 have changed the distribution of the pumpage in the area somewhat, but on the whole comparable rates of pumpage in the early 1930's and in the early 1940's have produced comparable water levels in the wells. There is no indication from this diagram that the rates at which the water has been pumped from the Farrington sand have produced any excessive drawdowns in the observation wells. If the rate of pumping had been greater than the capacity of the sand to transmit water from the intake area, a progressive lowering of the water level would have occurred. Even in 1935, 1936 and 1937, when the rate of pumping was about 13 million gallons daily for several months and approached

14 million gallons daily for a few months, the lowering of the water level does not appear to have been out of proportion to the rate of pumping. It may be concluded, therefore, from the study of this diagram, that the capacity of the Farrington sand to transmit water is greater than any rate at which it has been pumped up to the present time.

### *Salt-Water Intrusion*

The factor that appears most likely to limit the safe yield of the Farrington sand, at least in the area within a few miles of the Raritan River, the South River, and the Arthur Kill, appears to be the danger of salt-water intrusion. In fact salt water has already entered the sand both north and south of the Raritan River and advanced for some distance. A considerable number of wells have been more or less severely contaminated.

The areas in which salt-water contamination of the Farrington sand has occurred, a part of the intake area of the sand, and the locations of most of the wells tapping it within the county are shown on figure 12 on page 113. An attempt has been made to indicate the degree of contamination by means of contours enclosing areas in which the salinity of the water is believed to be 10 parts per million or more, and 1,000 parts per million or more. Solid contours are used to indicate fairly well-defined areas of contamination while those less well-defined are indicated by dashed contours. It will be noted that the two largest areas in which contamination has occurred are in the city of Perth Amboy and in the area between the Washington Canal and the well fields at Parlin. Apparently, however, tongues of salt water are reaching out toward the active wells from a number of other points along the tidal streams.

*North of Raritan River.* A majority of the wells in Perth Amboy and along the north shore of the Raritan River have been contaminated by salt water, apparently drawn in from the river or from the Arthur Kill. In this area it appears probable that most of the wells within a mile or two of these bodies of salt water will ultimately be contaminated by salt water. They may have to be abandoned except as sources of water for cooling or similar purposes.

In most places north of the Raritan River the sand is not as thick as it is south of the river. Nevertheless, very substantial quantities of water have been withdrawn from it in the past, especially in the city of Perth Amboy. Some wells in the city have already been abandoned because of salt water contamination and it is probable that others may soon have to be abandoned. The chloride contents of the water from most of these wells are given in table 9 on page 116. Samples have

TABLE 9.—CHLORIDE CONTENT OF SAMPLES OF WATER FROM WELLS TAPPING THE FARRINGTON SAND MEMBER OF THE RARITAN FORMATION IN MIDDLESEX COUNTY, NEW JERSEY

Parts per Million

Analyzed in Water Resources Laboratory, Geological Survey, U. S. Department of The Interior (Except as Noted)

| Owner | Owner's No. | Map No. | Date: 1937 July to Aug. | Date: 1938 May | Date: 1942 July to Oct. |
|---|---|---|---|---|---|
| Perth Amboy Water Dept. | Deep Well | 1-A | 2.0 | 1.9 | 2.2 |
| Hercules Powder Co. | Well 1 | 2-A | 2.6 | 2.8 | 3.4 |
| do | Well 2 | 2-B | 2.6 | 2.8 | 3.2 |
| do | Well 3 | 2-C | 3.1 | 3.2 | .... |
| do | Well 4 | 2-D | 3.0 | 3.0 | 13 |
| do | Well 5 | 2-E | 4.0 | 3.8 | 3.5 |
| E. I. duPont deNemours & Co. | Well 1 | 3-A | 2.1 | 2.2 | 2.1 |
| do | Well 2 | 3-B | .... | .... | .... |
| do | Well 3 | 3-C | 2.5 | 2.4 | 2.0 |
| do | Well 4 | 3-D | 2.5 | 2.1 | 2.5 |
| do | Well 5 | 3-E | 2.0 | 4.0 | 2.1 |
| do | Well 6 | 3-F | 2.1 | 2.2 | 2.1 |
| National Lead Co. | Well 1 | 4-A | 2.1 | 2.1 | 2.2 |
| do | Well 2 | 4-B | 2.1 | 2.0 | 2.2 |
| do | Well 3 | 4-C | 2.1 | 2.1 | 2.2 |
| Jersey Central Power & Light Co. | Well 1 | 5-A | 2.1 | 2.2 | 3.1 |
| do | Well 2 | 5-B | 3.1 | 2.1 | 7.0 |
| South River Water Dept. | Well 1 | 7-A | .... | .... | 2.4 |
| do | Well 2 | 7-B | 2.5 | 2.4 | 3.0 |
| Sayreville Borough | Test Well 3 | 8-C | 3.2[a] | .... | .... |
| Anheuser-Busch Co. | Deep Well | 10-A | 4.2 | 4.2 | .... |
| Nixon Nitration Co. | .... | 15 | .... | 5.2[b] | 5.5[b] |
| International Smelting & Refining Co. | Well 1 | 18-A | 600 | 10 | 210 |
| do | Well 2 | 18-B | 81 | 158 | 298 |
| do | Well 3 | 18-C | .... | 92 | 85 |

| | | | | | |
|---|---|---|---|---|---|
| Roessler & Hasslacher Chemical Co. | .... | 19 | 23 | .... | 220 |
| General Cable Co. | .... | 20 | 77 | 84 | 139 |
| Puritan Dairy Co. | .... | 21 | 4.8 | 4.5 | 14 |
| Bonafide Mills[c] | .... | 22 | 7.1 | 7.1 | 6.5[d] |
| Rhoads Well | .... | 31 | 11.8[e] | .... | .... |
| Amboy Ice Co. | .... | 53 | .... | 4.5 | 20 |
| Carborundum Co. | .... | 17 | .... | .... | 5.2 |
| Heyden Chemical Co. | .... | 16-A | .... | .... | 23 |
| do | .... | 16-B | .... | .... | 128 |
| N. J. State Home for Boys | Well 2 | 13-B | .... | .... | 2.0 |
| do | Well 3 | 13-C | .... | .... | 2.0 |
| Atlantic Terra Cotta Co. | .... | 52 | .... | .... | 1,570 |
| Clover Green Dairies | .... | 50 | .... | .... | 15 |
| Monteath Lumber Co. | .... | 54 | .... | .... | 5.2 |
| Peter J. Schweitzer Co. | .... | 11-A | .... | .... | 6.0 |
| Cranbury Water Co. | Deep Well | 12-A | .... | .... | 3.0 |

a. Sample collected Sept. 24, 1937.
b. Mixed samples from several wells.
c. Formerly Barber Asphalt Co.
d. Sample collected June 25, 1942.
e. Sample collected Oct. 21, 1937. Analyzed by the Pease Laboratories, New York City.

been collected from some of the wells in three different years and the table shows the changes that have occurred from time to time. Apparently the only hope for the continued withdrawal of any substantial quantity of fresh water from the Farrington sand north of the Raritan River lies in the construction of relatively shallow wells near the intake area and as far as possible from the streams that contain salt water.

*South of Raritan River.* As indicated on figure 12 on page 113, salt water is believed to be advancing into the Farrington sand in several localities south of the Raritan River. The largest of these is an area lying between the Washington Canal, the South River, and the well fields at Parlin. This area has been studied in considerable detail, and the intensity and extent of the contamination is fairly well known. Another area that is fairly well delimited is just north of South Amboy. Three other probable areas of salt-water contamination extend from points along the Raritan River toward the well fields at Parlin and South Amboy. These areas have not been defined with the same degree of certainty as the other two, but the available records suggest they may exist.

The Farrington sand south of the Raritan River is protected from the salt water in the river and in the material beneath it by the buried trap ridge that underlies both the river and a strip of land south of it. This buried ridge is a part of the diabase dike that forms the Palisades along the Hudson River, and rises to the surface again to the southwest. In most of Middlesex County it is buried beneath the younger Cretaceous deposits. In pre-Cretaceous times the diabase dike stood as a ridge on the land surface. In the area between Perth Amboy and the town of South River it stood so high that the Farrington sand was not deposited on top of it, except perhaps in some gaps or low places. Numerous test wells have been drilled through the materials overlying the buried ridge and the great majority of them have gone directly from the Woodbridge clay, which overlies the Farrington sand, into the diabase. Unfortunately, however, the ridge was not high enough to furnish much, if any, protection to the Farrington sand in the vicinity of the Washington Canal and the salt water has easy access to the sand in this area. It seems probable, however, that in the other areas of salt-water contamination referred to above, the salt water is advancing across the trap ridge through relatively shallow gaps that do not permit a large flow.

The investigations that preceded the earlier report on the Farrington sand[25] in this area brought out the fact that it is possible for salt water

[25] Barksdale, H. C., Op. Cit., Special Report 7.

to enter the sand in the vicinity of the Washington Canal and probably in the meanders of the South River that extend near the intake area of the sand. It was pointed out that the deepening of the Washington Canal in 1929 provided a ready means of access, whereby the salt water could enter the Farrington sand, and that the heavy rate of pumping at Parlin and elsewhere in the area might have reduced the fresh water head near the canal to such an extent that the intrusion of salt water was possible.

In 1937 and 1938 a series of test wells (Nos. 27, 28, 29, 30, 32, and 33 on figure 12) were drilled, and the analysis of water from them showed that salt water had advanced into the sand in the direction of Parlin to an alarming extent. Chlorides ranging as high as 6,581 parts per million were found in samples from test well 29, and as high as 2,670 in samples from test well 27. Chlorides of almost 300 parts per million were found in samples from test well 32, and test well 33 yielded water containing about 20 parts per million of chloride. All the wells at Parlin were then yielding water containing only 2 to 4 parts per million. The test wells were sampled periodically in order to ascertain what fluctuations of the chloride content might occur and how fast the salt water might be advancing toward the well fields. The chloride contents of these samples are given in table 10 on page 124. The conditions in this area were discussed in a paper published in 1940.[26] They are discussed herein in somewhat more detail in the light of more recent information.

### *Salinity of Surface Waters*

It is probable that the water in the Raritan Bay is usually only a little less salt than normal sea water. Samples of water from the Raritan River estuary opposite Perth Amboy, collected by the New Jersey State Board of Health, were found to contain as much as 19,000 parts per million of chlorides. Up the Raritan River and its branches the chlorides decrease as more and more fresh water is mixed with the water from the bay. In times of flood the larger volume of fresh water entering the estuary of the river forces the salt water out toward the bay, but the continual movement of the tides brings the salt water back into the tidal reaches of these streams as soon as the floods subside. In times of very low flow the salt water probably advances almost to the head of tide in the Raritan River at New Brunswick and, as already noted, appreciably increased chlorides have been

[26] Barksdale, H. C., The Contamination of Ground Water by Salt Water near Parlin, New Jersey. Trans. Am. Geophysical Union, 1940.

observed along the South River almost up to the Duhernal Dam. Definitely salt or brackish water has been observed at Old Bridge on numerous occasions.

Usually the highest chlorides occur at the bottom of the stream at high tide, although this relation is by no means a constant one as indicated by the studies made on the Connecticut River.[27] For this reason the samples collected during the present investigation have consistently been bottom samples at high tide. The results of analyses of these samples are shown in table 6 on page 93. At the northern end of the Washington Canal where it joins the Raritan River, the chloride content of the samples taken has varied from 44 parts to 12,000 parts per million, and most of the samples contained more than 7,000 parts per million. At the Washington Street Bridge between South River and Sayreville, the bottom samples from the South River were found to contain from 17 parts to 10,725 parts per million of chlorides, and most of them contained more than 5,000 parts per million. Serious salt-water intrusion into the Farrington sand has occurred between these two points.

No samples have been collected from the Arthur Kill or its tributaries during the course of this investigation, but it seems probable that the water in it is at least as salt as that in the estuary of the Raritan River.

### *Theory of Movement of Salt Water*

The basic principles that govern the intrusion of salt water into sands yielding fresh water were first set forth by Badon Ghyben and Herzberg.[28] More recent discussions of the effect of these principles upon the safe yield of water-bearing sands have already been referred to in this report (p. 77). Salt water is heavier than the fresh water and tends to fill the bottom part of an exposed aquifer. It is normally drawn upwards into wells when the head of the fresh water is decreased. Where salt water and fresh water come in contact with each other in a water-bearing sand, there is usually only a narrow zone in which they are mixed so that the change from fresh water to very salt water may occur within a relatively short distance. Because of this fact the intrusion of salt water into a well field may seem to be very sudden even though it may have been moving toward the field for a long time.

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27 Works Progress Administration for Connecticut, The Salinity of the Connecticut River, Connecticut State Water Commission, Bulletin S-1, 1938.

28 Badon Ghyben, W., Nota in Verband met de voorgenomen put boring nabij Amsterdam: K. Inst. Ing. Tijdschr., 1888-89, p. 21, The Hague, 1889. Herzberg, Baurat, Die Wasserversorgung einiger Nordseebader: Jour. Gasbeleuchtung and Wasserversorgung, Jahrg. 44, Munich, 1901.

In the vicinity of the Washington Canal the salt water is entering the sand through openings in the overlying impermeable material. The Washington Canal, itself, and the channel of the South River near well 25, are no doubt the most important of these openings. Here the salt-water intrusion is occurring under rather unusual conditions, since it is entering the sand near its top and flowing down the dip toward the pumped wells, instead of being drawn upward toward them from some point down the dip as is usually expected. Furthermore in this area the salt water is confined beneath an overlying clay bed soon after it enters the sand, so that the only obvious means of escape for it is through the wells toward which it is being drawn, or back through the openings by which it first gained access to the sand. Inasmuch as these openings are above the bottom of the sand and, in some instances at least, up the dip from the pumped wells, it seems likely that it might be very difficult if not impossible to force the salt water out through them by increasing the head of the fresh water in the sand.

At any point where the salt or brackish surface water is in contact with a fresh-water aquifer, it will enter the aquifer if the head of the fresh water is low enough to permit it. On the other hand, if the fresh-water head is high enough there will be a flow of fresh water out into the salt water, and no salt water will enter the aquifer. At any given level there might conceivably be a balance between the head of the fresh water and that of the salt water, so that no flow occurred in either direction. Under ordinary circumstances, however, the salt water would be in contact with the aquifer throughout a range of depths and unless the fresh-water head were greater than the salt-water head throughout all the exposed area, some salt water would probably flow into the aquifer. In fact, it might be possible for fresh water to flow out of the aquifer near the top of the exposure at the same time that salt water was flowing into it near the bottom.

If the level of the salt water were to fluctuate with the tide and if the head of the fresh water in the aquifer were high enough to exclude salt water at high tide, obviously no salt-water intrusion would occur. If, however, the fresh-water head were only high enough to exclude the salt water at some intermediate tidal level, some salt water would enter the aquifer at every high tide. At every low tide the flow of fresh water out of the aquifer would be increased and at least a part of the salt water that entered the aquifer during the previous high tide would be expelled. How complete this expulsion might be would depend to some extent on the relative length of time that the flow was into or out of the aquifer, but it is doubtful if it would be essentially complete unless the fresh water flowed out most of the time. It would seem, therefore, that in order to exclude all salt water from the aquifer, it would be necessary to maintain the fresh-water head higher than the salt-water head at high tide. However relatively little salt water would enter the aquifer if the fresh-water head were kept high enough to cause flow out of it except during the highest part of the tidal cycle.

The original head of the fresh water in the Farrington sand when the first wells were drilled was about 40 feet above sea level. At that time the Washington Canal did not exist and if the sand were exposed in the South River, it is almost certain that fresh water flowed out into the stream at all times. Subsequently the head of the fresh water was lowered substantially by pumping, the Washington Canal was dredged and deepened, and the salt water entered the sand in considerable quantities. It is probably possible to raise the fresh-water head in the sand by reducing the rate of pumping until no more salt water can enter the sand from these channels. The Washington Canal is much nearer to the centers of pumping than that part of the South River where salt-water intrusion appears most likely. Therefore, a greater reduction in pumpage will be necessary to prevent further intrusion from the canal than from the river.

### *Description of Intrusion*

The advance of salt water into the Farrington sand from the vicinity of the Washington Canal has now been observed in some detail for more than five years. The fluctuations of the chloride content of the water from the various wells that tap this sand and have been sampled regularly are shown in figure 13. More detailed information is given in table 10 on page 124. If these fluctuations are studied in connection with the map on figure 12, it will be noted that the salt water has been advancing toward the well field. In a few instances the rate of movement may be estimated by a comparison of the chlorides in different wells. A discussion of some of the more significant records may be of value for the light that it throws on the behavior of the salt water.

An examination of the lines representing chloride content in the wells shown in figure 13 will show that while most of the wells have a fairly consistent trend, they also show rather wide variations from time to time. Each time the wells are sampled they are pumped long enough to be sure that the water taken is representative of the water in the sand around the well at that time. It is believed, therefore, that the variations in chloride represent true variations in the salinity of the

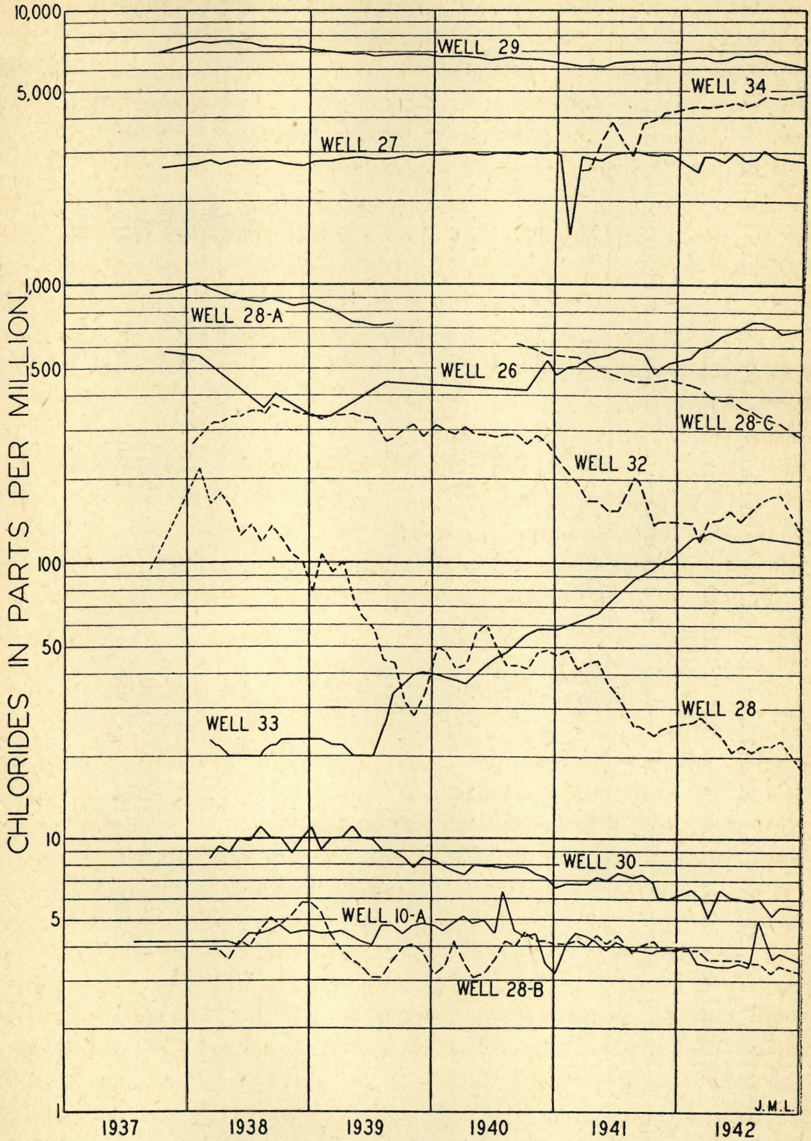


FIGURE 13.—Diagram showing the fluctuations in the chloride content of samples from wells tapping the Farrington sand member of the Raritan formation. Numbers refer to wells shown on figure 12.

TABLE 10.—CHLORIDE CONTENT OF MONTHLY SAMPLES FROM KEY WELLS TAPPING THE FARRINGTON SAND MEMBER OF THE RARITAN FORMATION IN MIDDLESEX COUNTY, NEW JERSEY

Parts per Million

Analyzed in Water Resources Laboratory, Geological Survey, U. S. Department of The Interior (Except as Noted)

| Date | Well No. | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 10-A | 26 | 27 | 28 | 28-A[c] | 28-B | 29 | 30 | 32 | 33 | 34 |
| *1937* | | | | | | | | | | | |
| July 28 | 4.2 | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... |
| Sept. 7 | .... | .... | .... | 95 | 620 | .... | 6,581 | .... | .... | .... | .... |
| 23 | .... | 525[a] | .... | .... | .... | .... | .... | .... | .... | .... | .... |
| Oct. 3 | .... | .... | .... | .... | .... | .... | 7,000[b] | .... | .... | .... | .... |
| 7 | .... | .... | .... | .... | .... | .... | .... | 11[b] | .... | .... | .... |
| 9 | .... | .... | .... | .... | .... | .... | .... | 10[b] | .... | .... | .... |
| 14 | .... | .... | .... | .... | .... | .... | .... | 9[b] | .... | .... | .... |
| 15 | .... | .... | 2,670[b] | .... | .... | .... | .... | .... | .... | .... | .... |
| 22 | .... | 575[b] | .... | .... | .... | .... | .... | .... | .... | .... | .... |
| Nov. 5 | .... | .... | .... | .... | 956[a] | .... | .... | .... | .... | .... | .... |
| *1938* | | | | | | | | | | | |
| Jan. 14 | .... | .... | .... | .... | .... | .... | .... | .... | 266[b] | .... | .... |
| 17 | .... | .... | .... | .... | .... | .... | .... | .... | 270 | .... | .... |
| 20 | .... | .... | .... | .... | .... | .... | .... | .... | 265[b] | .... | .... |
| 27 | .... | .... | .... | .... | .... | .... | .... | .... | 276[b] | .... | .... |
| 31 | .... | .... | .... | .... | .... | .... | .... | .... | 280[b] | .... | .... |
| Feb. 3 | .... | 558 | 2,750 | 218 | 1,010 | 10 | 7,612 | .... | 280 | .... | .... |
| Mar. 7 | .... | .... | 2,825 | 162 | 972 | 3.9 | 7,560 | 8.4 | 311 | .... | .... |
| 9 | .... | .... | .... | .... | .... | .... | .... | .... | .... | 23 | .... |
| 24 | .... | .... | .... | .... | .... | .... | .... | .... | 319[b] | 22[b] | .... |

| Date | Well No. 10-A | 26 | 27 | 28 | 28-A | 28-B | 29 | 30 | 32 | 33 | 34 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *1938* | | | | | | | | | | | |
| Apr. 5 | .... | .... | 2,738 | 178 | 940 | 3.9 | 7,612 | 9.4 | 318 | 22 | .... |
| May 7 | .... | .... | 2,788 | 158 | 910 | 3.6 | 7,675 | 8.9 | 332 | 20 | .... |
| 9 | 4.2 | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... |
| June 4 | 4.1 | .... | 2,800 | 125 | 892 | 4.2 | 7,600 | 10 | 335 | 20 | .... |
| July 6 | 4.5 | .... | 2,775 | 137 | 878 | 4.0 | 7,550 | 9.8 | .... | .... | .... |
| 7 | .... | .... | .... | .... | .... | .... | .... | .... | 352 | 20 | .... |
| Aug. 9 | 4.5 | .... | 2,800 | 118 | 870 | 4.6 | 7,362 | 11 | 350 | 20 | .... |
| 15 | .... | .... | .... | .... | .... | .... | .... | .... | .... | 21[b] | .... |
| Sept. 8 | 4.6 | .... | 2,800 | 135 | 890 | 5.1 | 7,350 | 10 | 370 | 22 | .... |
| 20 | .... | 403[b] | .... | .... | .... | .... | .... | .... | 364[b] | 22[b] | .... |
| Oct. 8 | 4.8 | .... | 2,750 | 121 | 870 | 4.8 | 7,350 | 10 | 355 | 23 | .... |
| Nov. 7 | 4.5 | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... |
| 12 | .... | .... | 2,725 | 106 | 845 | 5.2 | 7,250 | 8.8 | 350 | 23 | .... |
| Dec. 10 | 4.6 | .... | 2,700 | 100 | 855 | 5.8 | 7,250 | 9.9 | 340 | 23 | .... |
| *1939* | | | | | | | | | | | |
| Jan. 7 | 4.6 | .... | 2,775 | 79 | 860 | 5.8 | 7,150 | 11 | 340 | 23 | .... |
| Feb. 4 | 4.5 | .... | 2,800 | 106 | 830 | 5.4 | 7,100 | 9.1 | 330 | 23 | .... |
| Mar. 4 | 4.5 | 339[a] | 2,800 | 93 | 815 | 4.4 | .... | 10 | 340 | 22 | .... |
| Apr. 7 | 4.6 | .... | 2,850 | 101 | 770 | 3.9 | 6.900 | 10 | 340 | 22 | .... |
| May 6 | 4.4 | .... | 2,875 | 73 | 735 | 3.6 | 6,850 | 11 | 345 | 20 | .... |
| June 3 | 4.2 | .... | 2,875 | 64 | 730 | 3.4 | 6,925 | 10 | 335 | 20 | .... |
| July 8 | 4.1 | .... | 2,850 | 58 | 710 | 3.1 | 6,775 | 9.9 | 332 | 20 | .... |
| Aug. 5 | 4.8 | .... | 2,850 | 45 | 715 | 3.1 | 6,800 | 9.0 | 290 | 25 | .... |
| 16 | .... | 449[a] | .... | .... | .... | .... | .... | .... | 275[a] | 27[a] | .... |
| Sept. 9 | 4.8 | .... | 2,875 | 44 | 725 | 3.6 | 6,850 | 9.0 | 280 | 34 | .... |
| Oct. 7-9 | 4.5 | .... | 2,925 | 32 | .... | 4.0 | 6,875 | 8.5 | 300 | 37 | .... |
| Nov. 8 | 4.8 | .... | 2,875 | 28 | .... | 4.1 | 6,825 | 7.8 | 315 | 40 | .... |
| Dec. 9 | 4.9 | .... | 2,950 | 34 | .... | 3.8 | 6,825 | 8.5 | 285 | 41 | .... |

| Date | Well No. 10-A | 26 | 27 | 28 | 28-A | 28-B | 29 | 30 | 32 | 33 | 34 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *1940* | | | | | | | | | | | |
| Jan. 13 ........... | 4.8 | .... | 2,950 | 50 | .... | 3.2 | 6,750 | 8.2 | 315 | 40 | .... |
| Feb. 10 ........... | 4.6 | .... | 2,950 | 48 | .... | 3.4 | 6,750 | 7.9 | 300 | 39 | .... |
| Mar. 9 ........... | 4.9 | .... | 2,975 | 42 | .... | 4.2 | 6,750 | 7.6 | 290 | 38 | .... |
| Apr. 6 ........... | 5.2 | .... | 3,000 | 43 | .... | 3.5 | 6,750 | 7.4 | 310 | 37 | .... |
| May 4 ........... | 4.9 | .... | 2,950 | 56 | .... | 3.1 | 6,650 | 8.0 | 290 | 40 | .... |
| June 8 ........... | 5.0 | .... | 2,950 | 60 | .... | 3.2 | 6,550 | 7.9 | 290 | 43 | .... |
| July 6 ........... | 4.5 | .... | 3,000 | 50 | .... | 3.6 | 6,600 | 7.9 | 285 | 46 | .... |
| Aug. 3 ........... | 6.4 | .... | 3,000 | 43 | .... | 4.2 | 6,650 | 7.8 | 290 | 48 | .... |

| Date | Well No. 10-A | 26 | 27 | 28 | 28-B | 28-C | 29 | 30 | 32 | 33 | 34 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *1940* | | | | | | | | | | | |
| Sept. 7 ........... | 4.6 | .... | 2,975 | 43 | 4.0 | 615 | 6,600 | 7.9 | 290 | 52 | .... |
| Oct. 7 ........... | 4.4 | 420 | 3,025 | 42 | 4.5 | 600 | 6,600 | 7.8 | 268 | 56 | .... |
| Nov. 9 ........... | .... | 480 | 3,000 | 48 | 4.2 | 580 | 6,562 | 7.4 | 288 | 58 | .... |
| 11 ........... | 4.5 | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... |
| Dec. 7 ........... | 3.5 | .... | .... | 49 | 4.2 | 560 | 6,475 | 7.2 | 270 | 58 | .... |
| 9 ........... | .... | 540 | 3,025 | .... | .... | .... | .... | .... | .... | .... | .... |
| *1941* | | | | | | | | | | | |
| Jan. 4 ........... | 3.2 | 475 | 2,975 | 47 | 4.1 | 560 | 6,375 | 6.6 | 238 | 58 | .... |
| Feb. 8 ........... | 4.1 | 510 | 1,525[d] | 49 | 4.1 | 555 | 6,300 | 6.8 | 215 | .... | .... |
| Mar. 5 ........... | 4.5 | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... |
| 7 ........... | .... | 515 | 2,900 | 42 | 4.2 | 550 | 6,200 | 6.8 | 195 | .... | 2,600 |
| Apr. 3 ........... | 4.4 | .... | .... | .... | .... | .... | .... | .... | .... | .... | 2,620 |
| 8 ........... | .... | 545 | 2,850 | 44 | 4.0 | 520 | 6,200 | 6.8 | 169 | .... | .... |
| May 5 ........... | 4.2 | .... | .... | .... | .... | .... | .... | .... | .... | .... | 3,350 |
| 6 ........... | .... | 555 | 2,825 | 45 | 4.4 | 492 | 6,150 | 7.2 | 168 | 67 | .... |
| June 5 ........... | 3.9 | 565 | .... | .... | .... | .... | .... | .... | .... | .... | 3,875 |
| 8 ........... | .... | .... | 2,950 | 37 | 4.1 | 480 | 6,350 | 7.0 | 155 | 73 | .... |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| July | 8 | 4.2 | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... |
| | 9 | .... | 588 | .... | .... | .... | .... | .... | .... | .... | 79 | .... |
| | 10 | .... | .... | 3,000 | 33 | 4.4 | 465 | 6,425 | 7.5 | 155 | .... | .... |
| | 12 | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... | 3,250 |
| Aug. | 6 | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... | 2,925 |
| | 21 | 3.9 | .... | .... | 26 | 3.8 | 450 | 6,450 | 7.2 | 204 | 89 | .... |
| | 22 | .... | 580 | 3,025 | .... | .... | .... | .... | .... | .... | .... | .... |
| Sept. | 5 | 3.9 | .... | .... | .... | .... | .... | .... | .... | .... | .... | 3,825 |
| | 6 | .... | .... | .... | 26 | 4.0 | 450 | .... | .... | 197 | .... | .... |
| | 19 | .... | 570 | 2,975 | .... | .... | .... | 6,500 | 7.4 | .... | 92 | .... |
| Oct. | 14 | .... | .... | .... | .... | .... | .... | .... | .... | .... | 96 | .... |
| | 24 | 3.8 | 482 | 2,950 | 24 | 4.2 | 460 | 6,500 | 6.9 | .... | .... | .... |
| | 25 | .... | .... | .... | .... | .... | .... | .... | .... | 137 | .... | 4,050 |
| Nov. | 5 | 3.9 | 505 | 2,975 | 25 | 4.0 | 462 | 6,500 | 6.1 | 142 | .... | .... |
| | 6 | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... | 4,200 |
| | 11 | .... | .... | .... | .... | .... | .... | .... | .... | .... | 101 | .... |
| Dec. | 5 | 3.9 | .... | .... | 26 | 3.9 | 460 | 6,575 | 6.0 | .... | .... | 4,225 |
| | 6 | .... | 530 | 2,950 | .... | .... | .... | .... | .... | 142 | 104 | .... |

| Date | | Well No. | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 10-A | 26 | 27 | 28 | 28-B | 28-C | 29 | 30 | 32 | 33 | 34 |
| *1942* | | | | | | | | | | | | |
| Feb. | 5 | 4.0 | 550 | .... | .... | .... | .... | .... | .... | .... | .... | 4,400 |
| | 14 | .... | .... | .... | .... | .... | .... | 6,675 | 6.5 | 139 | 123 | .... |
| | 16 | .... | .... | 2,575 | 27 | 3.9 | 435 | .... | .... | .... | .... | .... |
| Mar. | 4 | 3.5 | 592 | 2,930 | 28 | 3.9 | 428 | .... | .... | 120 | 124 | .... |
| | 5 | .... | .... | .... | .... | .... | .... | 6,700 | 6.1 | .... | .... | 4,375 |
| Apr. | 2 | 3.4 | 612 | 2,910 | 26 | 3.6 | 398 | 6,500 | 5.1 | 142 | 129 | 4,400 |
| May | 5 | 3.4 | 662 | 2,980 | .... | .... | .... | .... | .... | 144 | 125 | .... |
| | 6 | .... | .... | .... | 24 | 3.6 | 388 | 6,520 | 6.5 | .... | .... | .... |
| | 7 | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... | 4,475 |
| June | 5 | .... | 682 | 3,000 | 21 | 3.6 | 390 | 6,750 | 6.1 | 154 | 121 | .... |
| | 6 | 3.4 | .... | .... | .... | .... | .... | .... | .... | .... | .... | 4,575 |
| July | 3 | 3.5 | .... | .... | .... | .... | .... | .... | .... | 142 | 120 | 4,420 |
| | 6 | .... | 705 | 2,810 | 22 | 3.6 | 365 | 6,740 | 6.0 | .... | .... | .... |
| Aug. | 3 | 3.4 | 740 | 2,840 | 21 | 3.5 | 355 | 6,800 | 5.9 | 155 | 121 | .... |
| | 4 | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... | 4,580 |
| Sept. | 1 | 5.0 | .... | .... | 22 | 3.5 | 338 | 6,700 | 6.0 | 166 | 124 | .... |
| | 2 | .... | 740 | 3,075 | .... | .... | .... | .... | .... | .... | .... | 4,800 |
| Oct. | 7 | .... | 710 | 2,880 | 22 | 3.2 | 325 | 6,400 | 5.2 | 174 | 122 | 4,700 |
| | 12 | 3.6 | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... |
| Nov. | 2 | 3.8 | 670 | 2,850 | 23 | 3.4 | 318 | 6.300 | 5.6 | 175 | 120 | 4,700 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *1943* | | | | | | | | | | | |
| Jan. 6 | 3.5 | 690 | 2,780 | .... | .... | .... | 6,100 | 5.5 | .... | .... | 4,850 |
| 7 | .... | .... | .... | 18 | 3.2 | 282 | .... | .... | 126 | 118 | .... |
| Feb. 1 | .... | 720 | 2,950 | 19 | 3.2 | 270 | 6,200 | 6.2 | .... | .... | .... |
| 3 | 3.6 | .... | .... | .... | .... | .... | .... | .... | 136 | .... | .... |
| 8 | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... | 4,350 |
| 10 | .... | .... | .... | .... | .... | .... | .... | .... | .... | 140 | .... |
| Mar. 1 | .... | .... | 2,950 | 16 | 4.0 | 240 | 5,900 | 5.4 | .... | .... | 4,200 |
| 2 | .... | 760 | .... | .... | .... | .... | .... | .... | .... | .... | .... |
| 7 | .... | .... | .... | .... | .... | .... | .... | .... | .... | 144 | .... |
| 8 | 3.9 | .... | .... | .... | .... | .... | .... | .... | 122 | .... | .... |
| Apr. 4 | .... | 760 | .... | .... | .... | .... | .... | .... | .... | 144 | .... |
| 5 | 3.6 | .... | 3,000 | .... | 3.8 | 225 | 5,600 | 5.6 | 103 | .... | 4,150 |
| May 3 | .... | 710 | 2,980 | .... | 4.1 | 222 | 5,800 | 5.2 | .... | 154 | 4,900 |
| 4 | 3.6 | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... |
| 11 | .... | .... | .... | .... | .... | .... | .... | .... | 113 | .... | .... |
| June 8 | .... | 535 | 2,950 | 16 | 3.8 | 215 | 5,900 | 5.2 | .... | .... | 4,850 |
| 11 | .... | .... | .... | .... | .... | .... | .... | .... | 65 | 149 | .... |

a. duPont laboratory.
b. Hercules laboratory.
c. Well 28-A failed in 1939 and was replaced with well 28-C in 1940.
d. Collected soon after repair of well.

water in the sand at the test wells. They are probably due to two principal causes, variations in the rate and distribution of pumping, and variations in the salinity of the water in the channels from which the salt-water intrusion originates.

Heavy pumping would lower the head of fresh water in the vicinity of the Washington Canal more than light pumping, and hence draw more salt water into the sand. Changes in the distribution of pumping may result in a greater lowering of the fresh-water head at the point of salt-water intake and hence in a higher rate of salt-water intake. On the other hand, however, they may merely change the direction of movement of the salt water already in the sand. The heaviest and steadiest pumping from the sand is at Parlin and beyond, and the piezometric surface slopes most steeply in that direction. The tongue of salt water (see figure 12) from the Washington Canal area, therefore, trends almost directly toward the wells at Parlin. However, when the deep well at the Perth Amboy Water Works is operated, the piezometric surface is warped toward it and the tongue of salt water is bent slightly off its course in the direction of this well. When this occurs, the chloride content of the water from wells 26 and 32, which are on the same side of the salt-water tongue as the Runyon well, tends to increase. When this well is not operated the salt water is again drawn more directly toward Parlin and the chloride content of the water at wells 26 and 32 tends to be somewhat less. These fluctuations would occur, regardless of whether the fresh-water head at the salt-water intake was changed by the operation of the Runyon well. Heavy pumping at wells 10 and 11 would have a similar effect to the operation of the Runyon well.

Obviously variations in the salinity of the water in the stream channels and the canal at the point of salt-water intake would affect the salinity of the water in the sand, even if the rate of intake were constant. It has already been pointed out that the salinity of the water in the streams does vary through wide limits depending upon fresh-water flow of the streams.

The combined effects of these varying factors would cause the salt water to advance toward the centers of pumping in irregular waves of high and low salinity. Unless the rate of salt-water intake can be permanently checked, however, it is probable that the salinity of the water moving toward the pumped wells will continue to increase until it approaches the average salinity of the water in the channels from which it enters the sand. The salinity of the water from the pumped wells would, however, be considerably less, because they draw water from all directions, and fresh water from other directions would be mixed with salt water from the contaminated area.

About 1930 a well operated by the Sayre and Fischer Company and located near test well 27 was abandoned because of the salinity of its water. At that time it was thought that the well casing had deteriorated and admitted salt water from the stream nearby. The log of test well 27, however, indicates that this was probably not the case. In 1932 a sample was collected from the Sayre and Fischer Company's well and when analyzed in the laboratory of the New Jersey State Board of Health, was found to contain 300 parts per million of chloride. In 1938 the salinity of the water from well 27 averaged almost 3,000 parts per million. In other words the salinity of the water in this vicinity had increased almost 1000 percent in about six years.

In 1938 the chloride content of the water from well 32 was about 350 parts per million or very roughly the same as the salinity of the Sayre and Fischer well in 1932. This would indicate that water containing 300 parts per million of chloride had advanced about a mile in six years. It should be borne in mind, however, that well 32 appears to be somewhat to one side of the main tongue of salt water. The advance may, therefore, have been more than is indicated by the chlorides in it. The decrease in the chloride content of well 32 in recent years was probably due to a change in the distribution of pumpage.

Until the middle of 1939 well 33 contained about 20 parts per million of chloride. Its chloride content then began rising rather rapidly and in May, 1943, a sample of water from this well contained 154 parts per million. Also in May, 1943, test well 39 was completed and a sample collected from it and analyzed in the laboratory of the Hercules Powder Company contained 19 parts per million of chlorides. This would indicate that water containing about 20 parts per million of chloride has advanced a little over 0.4 of a mile in about four years. It would normally be expected that the rate of movement would be more rapid as the salt water approached the pumped wells. However, the rate of pumping at Parlin during the last four years has been very substantially less than the rate during the years from 1932 to 1938. Had the high rate of pumping that was maintained during the two or three years before 1939 been continued, the salt water would unquestionably have advanced much faster.

A study of the test borings for the Edison and Victory Bridges across the Raritan River between Perth Amboy and South Amboy and of other borings made in connection with the proposals to deepen the channels for navigation in the vicinity of these bridges, indicated that salt water might be entering the sand beneath the river in this area. The test borings for the two bridges also indicated that there was some sand on the top of the trap ridge in this vicinity. In 1941 test well 34 was drilled to determine whether the salt water was moving across the ridge. The water in the sand in this location was found to be highly saline. The first samples of water contained about 2,600 parts per million of chlorides and the chloride content of the water from this well has increased steadily to almost 5,000 parts per million. It is apparent, therefore, that salt water is advancing across the trap ridge in this locality and as indicated on figure 12, it is probably being drawn toward the wells of the National Lead Company.

Test well 34 is situated above the trap ridge where the sand is not very thick. It is probable, therefore, that a relatively small amount of salt water is moving through the opening back of this well and advancing into the sand.

Test well 35 was drilled a few months after well 34 and the chlorides in the water from this well have not yet increased to 10 parts per million. The salt water is probably moving much more slowly through the entire thickness of the sand south of the trap ridge than it does through the thin layer of sand on the top of the ridge. Nevertheless the salinity of the water in well 35 is now about twice as high as that of the water from the National Lead Company's wells, and it seems fairly certain that salt water is advancing toward the National Lead Company's wells.

The increase in the chloride content of the water from the wells at the Jersey Central Power & Light Co. in South Amboy (see table 9 on page 116) tends to confirm the conclusion that salt water is being drawn across the ridge at this point. These wells were in operation long before the National Lead Company's wells were drilled, and although they are not pumped as heavily, the salt water crossing the ridge near well 34 has probably been drawn toward them for a considerable distance.

When the results from well 34 indicated that salt water was moving across the trap ridge and contaminating the water in the Farrington sand in the vicinity of South Amboy, the Duhernal companies were concerned lest other gaps might exist along the top of the ridge between South Amboy and Sayreville and might permit salt water to advance into their well fields before it was observed. They, therefore, drilled a series of twenty test wells (designated on figure 12 as wells a, b, c, d, and so forth) along the top of the trap ridge in order to determine, if possible, any localities in which salt water might advance across the ridge. Some of these wells encountered sand on the top of the ridge and samples of water from a few of them contained rather high concentrations of chloride. The casings and screens were removed after the samples were collected, and it has not been possible, therefore, to obtain subsequent samples that would indicate a possible change in the chloride content of the water in the sand in these localities.

The most threatening condition indicated by these test wells appeared to be northwest of Parlin. In order to check upon any advance from this area test well 36 was drilled and has been sampled regularly. The chloride content from the water of well 36 is now about twice the normal chloride content of the water in wells at Parlin. This fact suggests that a little salt water is advancing across the top of the ridge and moving toward Parlin. The quantity must be small, however, because the river and the trap ridge are relatively close to the center of pumping at this location, and had there been any easy means of access for the salt water, it would already have arrived at Parlin. The probable advance of salt water toward well 36 and Parlin in this area and in two other areas farther downstream toward South Amboy, are indicated by dotted chloride contours on the map. The last two are based entirely upon the results of the series of test wells along the river. It is entirely possible that at the sites of the contaminated wells, the buried trap ridge is sloping toward the river and that a short distance south there may be no passage for the salt water toward the well fields.

### *Suggested Remedial Measures*

The Farrington sand in the area south of the Raritan River appears to be threatened with salt-water contamination from several directions. The movements of the salt water across the trap ridge are perhaps of relatively small importance, because there is probably very little sand at the top of the ridge. The contamination from the vicinity of the Washington Canal is a very serious matter, and inasmuch as it has advanced all the way to the edge of the well field of the Hercules Powder Company, it is well to consider what measures can be taken to extend the usefulness of the well fields at Parlin.

The remedial measures suggested below are offered without any regard for their relative cost. It should be borne in mind, however, that a continued supply of good water from the Farrington sand is an extremely valuable asset, and its preservation would, therefore, justify a substantial expenditure. The Duhernal companies have recognized this fact, and are endeavoring to substitute water from the Old Bridge sand for water from the Farrington sand so far as possible.

The salt water that enters the Farrington sand in the vicinity of the Washington Canal passes beneath the Woodbridge clay within a very short distance of the canal. It is doubtful, therefore, if most of the salt water now in the sand in this area can be removed from this sand by any means except by pumping through wells. A complete cessation of pumpage might cause some of it to flow back into the Washington Canal, but in order to do so completely the heavier salt water would have to be forced to the surface. It seems more probable that if pumpage were stopped completely, the salt water would lie near the bottom of the sand and fresh water would flow across it and out into the canal.

On the other hand if heavy pumping should be continued, more and more salt water would be drawn into the sand and the situation would become steadily worse until it would probably be necessary to abandon all the wells tapping this sand in the area between the Raritan River and Bay, the South River and Cheesequake Creek. If this should occur, there would be left in the sand a vast quantity of salt water that would be a continual menace to any other water supplies from the sand.

Probably the best available solution of this problem would be to decrease the pumping from the sand to such an extent that no more salt water enters it, and then to remove the salt water already in the sand gradually by pumping. This could be done either through existing wells or through wells especially constructed for the purpose. As indicated in the theoretical discussion above, if the head of the fresh water in the sand near the canal and along the South River is maintained at a sufficiently high level, the salt water will not flow into the sand. Since the channels are not very deep, it is probable that no salt water could flow into the sand at any time if the fresh-water head in their vicinity were maintained a few tenths of a foot above highest tide level to allow for the greater specific gravity of the salt water. As a practical matter it would probably be safe if the head of the fresh water in the vicinity of the salt-water channels were maintained a foot or two above the mean tide level. In this case there might be some small additions to the volume of salt water in the sand, but this would probably not be a very serious matter in view of the very large amounts of salt water already there. Ultimately some provision must be made to remove the salt water from the sand, and any small additional quantity might be taken care of by the same means.

During the winter of 1942-43 the Duhernal companies conducted a test to determine the possibility of maintaining a satisfactorily high level along the Washington Canal. The Duhernal supply was used to its developed capacity and only such water was pumped from the Farrington sand as was necessary to make up any deficiency in the demand. The Perth Amboy Water Department was not using its deep well and the other wells tapping the sand were drawing rather lightly. It was possible for a period ending early in April to maintain an average rate of pumping of only 2,340,000 gallons daily from the Farrington sand. Water levels were observed at every available point, and a contour map of the piezometric surface was drawn. This map indicated that between the pumped wells and the canal there was a ridge of high pressure at least one foot above mean sea level at all points. It seems probable that at that time very little, if any, salt water was flowing into the Farrington sand.

Some idle wells were flowing to waste during the test and undoubtedly some fresh water was flowing out into the South River and the Washington Canal. One of the wells that was flowing was well 26, which yields water fairly high in chloride content. This could not, of course, be considered entirely a loss, because it was removing salt water from the sand. Possibly the other wells that flowed might be sealed in order to prevent the wasting of fresh water. Probably the major loss of fresh water was the amount that flowed into the salt-water channels. This water might properly be considered as the cost of excluding salt water rather than as a loss.

On the basis of this test, it appears probable that the Farrington sand might be pumped at a rate of 2 or 2½ million gallons daily continually without drawing in any substantial additional amount of salt water. In 1927 when the total pumpage from this sand south of the Raritan River was estimated at about 4 million gallons daily, an industrial well near the site of well 27 was observed to flow at a level of 3 or 4 feet above mean sea level. In April, 1943, the water levels in this vicinity were not that high, probably because of differences in the distribution of pumpage. The critical factor is the head of the water in the sand as indicated by the level of the water in the test wells between the canal and Parlin. It is reasonable to assume that a larger amount of water could be pumped from the sand without lowering the water level near the canal too much if the centers of pumping were located farther from the canal.

A high head of the water in the sand in the critical area between the canal and Parlin might be maintained by recharging the sand through wells. This should, of course, be done with fresh water and might have the effect of completely isolating the main body of salt water between the canal and Parlin, so that it could be gradually removed either by the existing wells or by wells especially drilled for the purpose nearer the canal. The maintenance of satisfactory recharge wells would require careful treatment of the water in order to avoid clogging the screens. Even so it would probably be necessary to re-develop the recharge wells occasionally. A program for maintaining the head in the Farrington sand by means of recharge wells would be expensive both on the basis of its first cost and on the basis of operating cost. Furthermore, it would not be practical unless a satisfactory supply of fresh water were available. It would, however, be one of the better means of definitely shutting off the salt water that is now entering the sand, so that the contaminated area could ultimately be cleaned up. If such a program should be underaken, it should be realized that it might be necessary to continue recharging after the salt water had been eliminated or to reduce the rate of pumping from the sand, in order that the natural head might be high enough to prevent another intrusion of salt water.

Regardless of what measures are taken to prevent salt water from entering the sand, it seems probable that most of the salt water now in the sand must be removed through wells. If recharge wells were constructed, it would be logical to install special wells between Parlin and the recharge wells in order to remove the salt water. Unless recharge wells were constructed, it would probably be best not to set up any pumping nearer the canal than the present wells, because the total rate of pumping would have to be reduced still further in order to prevent additional intrusion of salt water. Since this is the case the salt water in the sand will probably continue to advance until it reaches the most exposed wells at Parlin. The salinity of the water in Hercules well No. 4 (well 2-D on figure 12) has already increased to a little over 10 parts per million.

As the salt water in the sand is drawn closer and closer to the wells at Parlin, the salinity of the water in Hercules well 4 will undoubtedly increase. If this well should be abandoned when the water from it becomes too salt for ordinary use at the plant, the salt water will be drawn rather quickly into the next most exposed well. If this second well were then abandoned, it would be drawn on to the next well, and thus the entire well field would be contaminated in a relatively short time.

When the salinity of Hercules well 4 rises so high that the water from it cannot be used, this well should not be abandoned but should be continued in operation and the water from it used for cooling or even pumped to waste in order to remove the salt water from the sand before it reaches the other wells at Parlin. At that time it would probably be wise to shut down one or two of the wells nearest Hercules well 4 in order to prevent the salt water from being drawn around this well and into them. It is impossible at this time to estimate the rate at which this well should be pumped in order to remove the salt water and protect the other wells in the field. The well should probably be pumped some of the time each day, and the total amount of water taken from it should be roughly proportional to the total amount of water taken from all the other wells. Careful experimentation at the time when the protective pumping of this well becomes necessary should provide the best guide for operating it. There is a slight possibility that the salt water might advance at such a rate that all of it could not be removed through Hercules well 4. In that case it would be advisable to pump more than one well to remove the salt water and protect the other wells in the area. The operation of one or more wells to remove the salt water and protect the other wells at Parlin would involve some expense, but it is believed that the expense would be justified by the protection of the remaining wells not only in the Hercules Powder Company well field but also in the well field of the duPont Company, into which the salt water would soon be drawn if the Hercules wells were abandoned successively as they became salt.

If the measures designed to protect the Farrington sand from salt-water contamination in the vicinity of Parlin and Runyon should not be effective, and the water from the sand in this area should become so salt that it cannot be used for ordinary purposes, consideration might be given to the possibility of moving most of the pumpage from this sand to the higher ground along its intake area in the vicinity of wells 24, 38 and 23 (see figure 2). As long as the wells in the vicinity of Parlin can be operated, no pumpage should be undertaken near the intake area, because it would rob these wells of much of their fresh water and greatly increase the danger of their destruction by salt-water intrusion. The development of wells tapping the Farrington sand in this area should, therefore, be considered only as an alternative to pumping the existing wells if it proves impossible to protect them from salt-water intrusion. If the principal pumpage should be transferred to the vicinity of the intake area, it would be wise to continue to pump a relatively small amount of water (perhaps 1 or 2 million gallons daily) from wells in the vicinity of Parlin in order to protect the rest of the formation from contamination.

In the case of the Old Bridge sand and in the case of the 100-foot sand at the Atlantic City Water Works,[29] the construction of a dam to prevent the salt water from advancing up the stream channels from which it enters the sand has been recommended. In order to protect the Farrington sand such a dam would have to exclude salt water from practically the entire estuary of the Raritan River. It would permanently flood all of the land now covered by tidal marshes and might flood some additional land, especially at times of high flow in the Raritan River. The cost of such a dam and of the land that would be flooded and its interference with navigation would probably be prohibitive.

### *Estimate of Safe Yield*

*North of Raritan River.* The intake area of the Farrington sand north of the river is only 6.8 square miles and a considerable part of this area is near the streams containing salt water. It seems probable, therefore, that the safe yield of the sand in this area will be limited by the danger of salt-water intrusion, to the water that can be obtained from less than 5 square miles of intake area. No more than 3 million gallons daily should be withdrawn from this sand in this area. The construction and regular sampling of outpost wells in order to keep track of the movement of the salt water would be advisable in connection with any fresh-water development of the Farrington sand north of the river. Additional development should, of course, not be made even near the intake area unless the rate of pumping from the sand is materially decreased in the vicinity of Perth Amboy and elsewhere in areas exposed to salt-water contamination.

*South of Raritan River.* South of the Raritan River the safe yield of the Farrington sand as it is now developed is even more sharply limited by the danger of salt-water intrusion than is the yield north of the river. The test conducted by the Duhernal companies during the winter of 1942 to 1943 indicated that the safe yield of the formation with the pumpage distributed as it was at that time was only about 2.3 to 2.5 million gallons daily. An estimated pumpage of about 4 million gallons daily in 1927 appeared to have been safe, but the distribution of pumpage at that time, as well as its amount, has not been definitely established. It would seem, therefore, that the safe yield of the sand as now developed south of the river is somewhere between 2 and 4 million gallons daily, depending to a considerable extent upon the dis-

[29] Barksdale, Henry C., and others. Supplementary report on the ground-water supplies of the Atlantic City region. N. J. State Water Policy Comm. Sp. Rept. 6, 1936.

tribution of pumpage. The pumpage from this sand south of the river should be reduced and held within these limits. Obviously, pumpage near the Washington Canal or other sources of salt water would tend to draw in the salt water more rapidly than the same amount of pumpage farther away. If additional salt-water intrusion in the vicinity of the Washington Canal should be stopped by the operation of recharge wells, the safe yield of the existing wells might be increased considerably.

If it were possible to relocate most of the wells tapping this sand so that nearly all the water from it could be taken near its intake area, the safe yield would probably be 6 or 7 million gallons daily. The limiting factors then would be the available recharge of the sand, and the necessity of maintaining the fresh-water head near bodies of surface water containing salt. That part of the intake area near the Raritan River and the South River should not be drawn upon. The head of the water in the sand in this area should be maintained at as high a level as possible to prevent the intrusion of salt water. As already stated, no development should be attempted near the intake area of the Farrington sand while the present wells are in operation because the damage by salt-water intrusion would be very much increased.

### *Effect of Proposed New Jersey Ship Canal*

One of the plans for the proposed New Jersey Ship Canal contemplates a dam across the upper part of the estuary of the Raritan River, a short distance downstream from the end of the Washington Canal. If such a dam were constructed and if the pond above it were *constantly* filled with *fresh* water, it would remove the threat of salt-water intrusion from the vicinity of the Washington Canal and the South River but not from points farther downstream. It is very doubtful, however, if enough fresh water is available to flush the locks adequately and prevent the locking of salt water into the pool above the dam. It seems probable, therefore, that salt water would be locked into the pool and would contaminate the Farrington sand much more seriously than at present.

The route of the proposed canal follows the valley of the South River and passes through or very near the Duhernal well field. If salt water should be locked into the canal, it would undoubtedly contaminate the water from the Old Bridge sand. It is probable, therefore, that the construction of the ship canal would result in the destruction of ground-water supplies already developed in Middlesex County and yielding about 30 million gallons daily. The destruction of existing and potential ground-water supplies outside the county might be at least as great.

Another plan for the proposed canal contemplates a sea-level canal. In this case, there would be no locks to even retard the movement of salt water along the canal. The destruction of the ground-water supplies by a sea-level canal would be more rapid and possibly more complete than by the lock canal discussed above.

#### RARITAN FIRE-CLAY

The Raritan fire-clay, the lowest of the Cretaceous beds, includes the "Raritan potter's clay" of early reports and is an inconstant, variable member which, at its outcrop near Nixon, Bonhampton, Fords, Keasbey and Milltown, has a thickness ranging from zero to 35 feet. The average thickness probably increases to the southeast as wells at East Spotswood, Old Bridge, Runyon, Parlin and South Amboy have encountered from 27 to 86 feet of blue, brown, gray or red clay at this stratigraphic horizon. Typically, the basal part of the clay has a brick-red color identical in shade with the underlying Triassic red shale from which it was derived. It has this same appearance where exposed in a recent roadcut northwest of Patricks Corner; but there the red clay is only a foot thick and is overlain by gray clay. Near the mouth of Mill Brook, southwest of Nixon, the clay is mixed with sand and gravel, but half a mile to the northeast it is a relatively pure light-gray clay with a reddish tinge and is a little over six feet thick. The same clay is exposed in a pit half a mile south of the point where Lawrence Brook empties into the Raritan River. There its base is concealed, but the exposed portion (7 feet thick) is a gray, "fat" clay of good quality.

## TRIASSIC SYSTEM

### Newark Group

In the investigations upon which this report is based, the study of the water-bearing properties of the rocks of the Newark group has been less detailed than those of the Old Bridge and Farrington sands. However, the rocks of the Newark group form one of the three most important aquifers in Middlesex County. This is true both because of the large amounts of water developed from them and because of their relatively wide extent. In much of that part of the county underlain by the coastal plain formations, two or more aquifers can be tapped at any given point by increasing the depth of drilling. In the area covered by the Newark group, however, this is not true, because these rocks are very thick and essentially homogeneous, and because they are underlain by no other rocks that are capable of yielding any appreciable quantity of water.

## GEOLOGY

As shown on the map on page 20, nearly all of the bed rock in Middlesex County northwest of a line roughly from Plainsboro through Monmouth Junction, Milltown and Woodbridge to Carteret is of Triassic age. The younger Quarternary formations form a relatively thin veneer on portions of the Triassic, particularly in the northern part of the county. South of the line mentioned the Triassic is overlain by Cretaceous deposits, but it has been penetrated by wells at Dunhams Corner, Parlin and South Amboy, and probably by the deep well near the Runyon pumping station.

The Triassic rocks in New Jersey belong to the Newark group which is divided into three formations, all of which are found in Middlesex County. The oldest is the *Stockton formation* which consists of conglomerate and sandstone interbedded with red shale. Next above is the *Lockatong formation* and this consists of hard shale and argillite of various hues. These two formations are found only in a small area between Milltown and Kingston near the southwestern border of the county. To the east they are covered by the younger Cretaceous rocks. The Stockton and Lockatong formations cannot be well seen or studied in the county, and they are not differentiated on the geologic maps.

The *Brunswick formation* is the youngest of the three formations of the Newark group, and within Middlesex County it crops out in a much greater area than the other two Triassic formations combined. It is a dull red shale interbedded with siltstones and occasional layers of sandstone. When dry it is a dense compact rock but it quickly softens and disintegrates when exposed to weathering.

In Middlesex County all the sedimentary rocks of the Newark group dip to the northwest at angles of 5° to 15°. The formations are rather impermeable except along the numerous cracks which everywhere traverse the beds at high angles to the bedding. Some water may also follow along the bedding planes, although such movement must be very restricted judging from actual experience with wells.

Molten rock was intruded into the Newark group in late Triassic time and in this region it solidified beneath the surface of the ground in the form of steeply dipping dikes and relatively flat sills. The largest of these is a diabase sill which is now exposed to the north in

Bergen Hill and the Palisades, to the east on Staten Island, and to the west in Rocky Hill. Between these latter two exposures it is buried beneath a mantle of Cretaceous and Pleistocene sediments, but its position has been determined by the many wells which have encountered it and by geophysical exploration. Since it has an important bearing on the water supply of the region, its location has been shown on the geologic maps. The diabase sill stood as a ridge on the pre-Cretaceous surface and was continuous from Rocky Hill to Bayonne. Between Staten Island and Rocky Hill the surface was downfaulted prior to the deposition of the Cretaceous sediments. The first Cretaceous sediments were deposited on each side of the ridge but not on top of it. With continued deposition sandy material covered the higher slopes and then was deposited across it without a break as shown in figure 3. The Farrington sand is very thin or lacking on top of the buried trap ridge between Perth Amboy and South Amboy, but near the Borough of South River it is continuous across a lower segment of the ridge. Because of these geologic factors water cannot move easily from the intake area of the Farrington sand north of the ridge and near Perth Amboy directly south to the center of pumpage from the sand near Parlin; but near the Borough of South River it probably can and does readily move across the trap ridge to the wells in that area.

The intrusion of this thick diabase sill profoundly affected the adjacent beds of shale, those nearest being altered to a tough, dark, spotted rock as hard as slate but lacking its cleavability. With increasing distance from the contacts the alteration is less and less pronounced, the rock becoming progressively softer and changing in color from dark gray, brown and greenish gray to light gray, purplish red, and finally the typical brick red of the unaltered shale. North of Middlesex County where the sill and adjacent beds are exposed, the latter are altered for a thickness of 500 feet or more from the contacts. In this region similar altered beds may be seen in a gully west of Patricks Corner, which is more than half a mile distant from the nearest outcrop of diabase but which is unquestionably underlain by that rock at a depth of a few hundred feet; and near the mouth of Mill Brook, two miles northwest of Sayreville, where the nearest exposure of diabase is a small dike more than a mile distant. Metamorphosed or altered shale has also been encountered by wells drilled in Milltown, Keasbey, Perth Amboy and Woodbridge, and by two boreholes respectively two miles east-southeast of Plainsboro and two miles east-northeast of Dayton.

## PHYSICAL PROPERTIES

The facts that the materials composing the rocks of the Newark group are usually fine-grained and relatively impermeable and that the formations are water-bearing by virtue of the cracks and crevices in the rocks, introduce special problems in any attempt to appraise their water-bearing capacity. Laboratory tests of ordinary samples of material collected in the field would be of no particular value, because they must of necessity deal with fragments of the rock and cannot indicate the capacity of the cracks between the undisturbed fragments as found in nature. Pumping tests provide the best means of studying the capacity of the group to yield water but very few have been made.

The permeability and the specific yield of the Newark group depend upon the degree of cracking. Since the degree of cracking decreases with the depth, the permeability and specific yield of the rocks also decrease with the depth. An advantage of pumping tests is that their results represent a composite of the conditions from top to bottom of the water-bearing part of the formation. The results of a pumping test may be directly expressed as a coefficient of transmissibility and a coefficient of storage. The coefficient of transmissibility is a measure of the ability of the formation to transmit water. It is the product of the average coefficient of permeability and the depth of the saturated portion of the aquifer. Under water-table conditions the coefficient of storage as determined in a pumping test is essentially the same as the average specific yield of the material. The cracks in the rocks of the Newark group intersect one another at many different angles with the result that the water in the rocks can generally move in any direction and is essentially under water-table conditions. Thus, without actually determining the effective depth of cracking of the aquifer or its characteristics at any given depth, it is possible by pumping tests to determine coefficients that are accurate indices of its capacity to store and transmit water.

Early in 1943 an opportunity arose to conduct a pumping test on some wells drawing from the rocks of the Newark group at Kenilworth, New Jersey, which is in Union County, about four or five miles north of the Middlesex County line at Rahway. At the site of the test the rocks of the Newark group were covered by a relatively permeable phase of the glacial till to a thickness of perhaps 30 or 40 feet. The results of the pumping test no doubt combine the characteristics of both the rock and the overlying materials to some extent. However, they are probably more representative of conditions in the shale than of those in the overlying till. The results of the pumping tests at Kenilworth indicate that the coefficient of transmissibility of the rocks at that location is about 25,000 and that the coefficient of storage is about 0.0044.

The results of a single test cannot be considered representative of the whole Newark group. Nevertheless, they furnish a basis for an interesting comparison of the group with the aquifers of the coastal plain formations. The Farrington sand, for example, is about 80 feet thick and has an average coefficient of permeability of at least 1,200. Its coefficient of transmissibility would be the product of its thickness and its coefficient of permeability or at least 96,000. This means that the Farrington sand could transmit four or five times as much water as the rocks of the Newark group under a given head and through a given width of section.

The difference in the capacity of the two aquifers to store water is even more striking. It was estimated that a block of the Farrington sand one square mile in area and one foot thick could store about 67 million gallons of available water. If the sand is 80 feet thick, one square mile of it would store about 5,360 million gallons. If the thickness of the water-bearing part of the Newark group is assumed to be 300 feet and its specific yield 0.0044, one square mile of this aquifer could store only about 275 million gallons. Of course where there are overlying permeable sandy deposits, substantial additional quantities of water stored in these deposits, may be available to wells tapping the rocks. The low storage capacity of the rocks helps to explain the high rate of runoff and low ground-water flows observed on streams draining areas underlain by the Newark group where there is no permeable covering.

## QUALITY OF WATER

With the exception of the waters that are contaminated by the intrusion of sea water, the water from the Triassic shales and sandstones of the Newark group is more highly mineralized than any other ground water obtained in Middlesex County. A majority of the wells tapping these rocks yield good water containing less than 200 or 300 parts per million of total solids, but it is not unusual to find several hundred parts per million of dissolved solids. The water is high in calcium and magnesium and the hardness is therefore high. The sulphates are high as compared with the carbonates and bicarbonates and much of the hardness is therefore noncarbonate or "permanent" hardness. In the water from one industrial well used for cooling, the total hardness expressed as calcium carbonate was reported to be 900 parts per million. Very often the waters from these formations also contain objectionable quantities of iron. The chlorides are usually fairly low.

The quality of the water from the Newark group varies from place to place and from one bed to another. The Stockton formation usually yields very good water. Water from the Brunswick shale, on the other hand, is sometimes more highly mineralized. In general, it may be said that where the beds yield water most freely its quality is likely to be better than in those localities where the crevices in the rock are small and the yield is low. Perhaps the greater circulation of meteoric waters through the more permeable beds has removed some of the objectionable soluble materials that have been retained in the less permeable rocks. The fact that better water is generally encountered near the surface than at greater depths tends to confirm this idea.

## DEVELOPMENT AND PUMPAGE

A great many wells have been drilled into the Newark group in Middlesex County. The vast majority of them have produced some water. In fact, one reason for the importance of this group of rocks as an aquifer is that they will generally yield at least a small quantity of water to a well in almost any locality where they are encountered. Numerous small wells have been drilled in these rocks for domestic and farmstead water supplies, and most of them have been satisfactory for this purpose. The yield of these wells ranges from a few gallons per minute to 100 gallons per minute or more.

A considerable number of wells have also been drilled into these rocks for municipal or industrial water supplies. Where conditions are most favorable such wells may yield from 100 to 500 gallons per minute, or even more, but very high yields are exceptional. With one or two exceptions the larger developments tapping this aquifer within Middlesex County yield less than 500,000 gallons daily, but there are several well fields yielding water supplies ranging from 100,000 to 500,000 gallons daily or more, and a considerable number that produce 25,000 to 100,000 gallons daily.

A total of approximately 9.6 million gallons a day was withdrawn from the aquifers of the Newark group in Middlesex County in 1941 for municipal and industrial use. About 8.5 million gallons a day or 89 percent of the total was withdrawn from wells in the municipalities north of the Raritan River. Nearly 6.5 million gallons a day or 68 percent of the total was pumped from wells in the Borough of South Plainfield, practically all from wells owned by the Middlesex Water

Company. This is the only public water supply deriving large amounts of water from the Newark group in Middlesex County.

A considerable amount of water is withdrawn from the Newark group by industries scattered throughout the municipalities north of the Raritan River, particularly those municipalities bordering the county line. Amounts exceeding 500,000 gallons a day were withdrawn from industrial wells in Middlesex Borough and Piscataway Township in 1941. Smaller amounts varying from 35,000 to 259,000 gallons a day were withdrawn in the Boroughs of Carteret, Dunellen and Metuchen, and from Raritan and Woodbridge Townships in 1941.

South of the Raritan River the largest withdrawals from the Newark group in 1941 were in the city of New Brunswick where approximately 535,000 gallons a day was withdrawn from industrial wells. Approximately 322,000 gallons a day was withdrawn from these rocks in Plainsboro Township and about 109,000 gallons a day from wells in Milltown Borough in the same year.

## FACTORS AFFECTING YIELD

The following discussion of the yield of these rocks is necessarily generalized to a considerable extent. There are, nevertheless, certain factors that control their capacity to yield water in any given area. The nature of the overlying soil or other material affects their intake capacity and their recharge. The degree to which the rocks are cracked affects their storage capacity and their transmissibility. The presence of surface streams or ponds may supply continuous recharge. The water in these rocks is essentially under water-table conditions, and a well tapping them usually cannot be benefited by favorable conditions that occur more than a mile or so from it.

*Nature of the overlying material.* The rocks of the Newark group weather to a relatively tight and impervious, clayey soil, which is usually thin and therefore incapable of storing much water. Where this soil occurs at the surface the infiltration capacity is relatively low, and the rate of runoff is high. This results in relatively small quantities of water percolating through the soil and reaching the water table. Not only is the infiltration and hence the recharge and the safe yield of the aquifers in these areas low, but the average yield of wells tends to be low also. This is possibly due to the filling of some of the cracks in the rock by the fine materials derived from its decomposition. At any rate, wells of large capacity are seldom found in areas where the rocks of this group have been exposed directly to weathering and are covered by a residual soil derived from the rocks themselves. The areas in which the Newark group is exposed without any cover except its residual soil are shown on the map on page 21. The total area thus exposed both north and south of the Raritan River is about 49 square miles.

Where the rocks of the Newark group are covered by relatively impermeable beds, the yields are generally about the same as in the areas where the rock is covered only by its residual soil. In the northern part of the county there is a considerable area covered by the Wisconsin till. In a few places the till is fairly permeable and conducts substantial quantities of water into the rock beneath it. In Middlesex County, however, the till, which was derived largely from the underlying rocks of the Newark group, has weathered to a soil that is about as impermeable as the residual soil that overlies the rocks where they have not been covered by any later deposits. South of the Raritan River there are several small areas where the rocks of the Newark group are covered by isolated patches of the Raritan fire-clay that have been separated from the main body of the Raritan formation by erosion. This clay is probably even more impermeable than the residual soil, and in the larger areas thus covered where recharge from outside the area is difficult, the chances of obtaining good yields from the rocks of the Newark group are very poor. In Middlesex County the total area in which the rocks of the Newark group are covered by relatively impermeable younger materials is about 35 square miles.

In marked contrast to the areas just described, a considerable number of very satisfactory wells have been developed in the rocks of the Newark group where they are covered by the permeable stratified drift or by the Cape May or Pensauken formations. The infiltration capacity of these materials is generally high, and they absorb substantial quantities of water from precipitation and hold it in contact with the underlying rocks until it can be absorbed by them. Because of the higher rate of recharge and because of the added storage capacity of the overlying sandy materials, the safe yield of the rocks is much higher in these areas. The average yield of individual wells tapping the rocks of the Newark group where they are covered by these sandy deposits is perhaps five times as great as that from the same rocks where they are covered by soil derived from their own decomposition. The greater circulation of fresh water from the overlying sandy materials has removed much of the objectionable soluble matter from the rocks, and they therefore generally yield water of better quality and also larger quantity than in areas where less water circulates through them. As shown on the map on page —, there are two principal areas in which the Newark group is covered by permeable materials. The largest and most important of these covers about 17 square miles and lies between the Raritan River and the terminal moraine. This area is overlain by stratified drift and other permeable materials. An area of about 7 square miles occurs in the southwestern corner of the county, where the overlying material is largely Pensauken.

*Degree of Cracking.* The degree and depth to which the rocks have been cracked obviously has an important effect on the water-bearing capacity of the Newark group. The rocks have been warped and faulted and intruded by masses of igneous rock, so that they are often intensely fractured. Since the rocks are generally covered by soil or by later formations, the yield of wells is, perhaps, the best way to judge the degree to which they are cracked. Major fault zones in these rocks are generally good water-bearing areas. In Middlesex County no such zones are recognized, but there are no doubt numerous minor zones of faulting. The condition of the cracks is also important. It has already been pointed out that some of the cracks may have been filled by material from the residual soil. Elsewhere filling may not have occurred or the cracks may have been enlarged. In the areas now covered by the stratified drift, for example, the yield of individual wells suggests that the cracks are more numerous or more open. In the absence of any obvious reason for more numerous cracks, it is suggested that the cracks may have been enlarged by the more continuous circulation of water made possible by the supply of water in the overlying sandy material.

*Recharge from surface water.* The presence of bodies of surface water provides a ready and continuous source of water for recharging these rocks, just as in the case of the other aquifers discussed in this report. The Raritan River and some of its tributaries, notably Lawrence Brook, have cut channels into these rocks. In various localities there are small lakes or ponds on these formations. Other things being equal, the safe yield of the aquifer in the vicinity of these bodies of surface water is higher than it would otherwise be. The constant recharge from the surface supplements the limited storage in the cracks of the rock.

## ESTIMATE OF SAFE YIELD

When all the above factors have been considered there still exists the uncertainty of yield common to most wells tapping rocks in which the water is carried mainly in cracks and crevices. At any given spot a well may or may not encounter adequate water-bearing cracks. Usually a well drilled into the rocks of the Newark group will encounter at least a few water-bearing cracks and yield at least a small supply of water. The yield of an individual well tapping these formations can probably never be predicted with any degree of certainty, but with more detailed and prolonged study the safe yield of the aquifer in the various areas may be determined with a fair degree of accuracy. Such studies are recommended, especially in the area north of the Raritan River and in the vicinity of Plainsboro because in these areas the rocks appear to be most productive.

The comparison, based on the Kenilworth test, of the Newark group and the Farrington sand member of the Raritan formation seems to indicate that the storage capacity of the rocks of the Newark group is the factor most likely to limit their safe yield. Because of the very small storage capacity of the Newark group, any sustained yield must depend upon frequent replenishment of the stored water. The intake capacity of the aquifer and its opportunity for recharge as affected by the overlying materials are therefore of primary importance. Readily and constantly available recharge, such as that provided by the water in the stratified drift and other permeable overlying materials would seem essential to any sustained large yield from these rocks.

The best that can be said at the present time is that where these rocks are well fractured and are overlain by thick layers of permeable sands, their safe yield is probably in the order of half a million gallons daily per square mile. Where they are covered by tight, residual soils the safe yield is probably only a fraction of this amount. In these latter areas the low yield of individual wells makes the cost of large developments prohibitive, and consequently the danger of exceeding the safe yield of the aquifer is not very great.

## Proterozoic Sequence?

### Pre-Cambrian?

*Wissahickon Formation.* The Wissahickon formation is an ancient, intruded and regionally metamorphosed rock of early Paleozoic or pre-Cambrian age. In its type locality, bordering Wissahickon Creek in Philadelphia, it is a gray, foliated rock characterized by an abundance of biotite. Included within the same formation however are schistose belts in which chlorite is the predominating mineral, and other belts in which the rock has a gneissoid character with quartz, feldspar and mica (either biotite or muscovite) the dominant minerals. This formation underlies the Pleistocene gravel deposits which constitute the surface material in most of the low ground between Philadelphia and Trenton, and it also crops out along the main line of the Pennsylvania Railroad near Clarksville and Princeton Junction in New Jersey. Rock of similar character has been penetrated by wells at Hightstown, East Spotswood, Runyon and the New Jersey State Home for Boys near Jamesburg; also by several boreholes about midway between Hightstown and Princeton Junction. It seems probable, therefore, that the Wissahickon formation extends from Trenton towards the northeast at least as far as Runyon in a continuous belt underlying the basal Cretaceous sediments.

In Philadelphia a few wells have obtained large supplies of water in this formation, but the yield of most wells has been small. In Middlesex County the formation is deeply buried and because the overlying formations are better aquifers, wells are usually stopped before they strike the Wissahickon. In fact, so far as known, not one single well has ever been completed in this county so as to draw water from this formation, and for the reasons stated it is recommended that all future water wells also be completed in one of the overlying aquifers.

## POSSIBLE SOURCES OF ADDITIONAL WATER SUPPLIES

The two most productive aquifers in the county, the Old Bridge sand and the Farrington sand, appear to have been developed about to their capacity. Additional developments from the rocks of the Newark group should not be made without a more thorough study of their capacity. Most of the other aquifers are not capable of producing very large quantities of water. It seems probable, therefore, that any future developments of large supplies of water from sources within the county must necessarily be drawn from surface water sources.

In the extreme southeastern part of the county a few million gallons of water daily can probably be drawn from the Englishtown sand. In this area it occurs at a moderate depth and contains water under artesion conditions. Approximately 10 square miles of intake area are available to supply wells located there. It is probable, however, that some water is already being drawn from this sand at Englishtown and other communities down the dip in Monmouth County. In this same part of the county it is possible that a small amount of water might be taken from the Mount Laurel and Wenonah sands.

The sands of the Magothy formation are fine-grained and their permeability is low, so that they cannot transmit large quantities of water. This sand will, therefore, probably continue to be used only as a source of small supplies for domestic or farmstead use. It appears to be of very little importance as a source of any large future water supply.

The Old Bridge sand appears to be developed about to its safe yield. No further development of water supplies from this sand should be undertaken unless it is accompanied by adequate works to provide artificial recharge of the sand. In the vicinity of Old Bridge and South Amboy, salt-water intrusion should be carefully guarded against even if this should ultimately mean some reduction in pumpage at these places.

In the vicinity of Old Bridge the regular collection and analysis of samples from the outpost wells tapping the Old Bridge sand should be continued, and the system of wells should be extended somewhat in order that any possible salt-water intrusion may be detected before it has proceeded very far and in order that timely remedial measures may be taken. Two principal remedial measures appear to be available, and either or both of them should be used if necessary. A reduction in pumpage might stop the advance of the salt water. If this is impossible or undesirable, the encroachment of salt water can be checked by the following procedure: dams should be constructed across the South River and Deep Run above the railroad bridges near Old Bridge in order to impound fresh water and build up the fresh-water head to prevent the advance of salt water from farther downstream. They should be high enough to stop any high tides, or should be protected by efficient and well-maintained tide gates. If necessary, the bottoms of the ponds should be dredged in order to admit the fresh water in the ponds to the sand. The water in the ponds should be protected from all forms of pollution, and undesirable industrial and other wastes from points upstream should, if necessary, be conducted past the dam by means of a trunk sewer.

At the South Amboy Water Works outpost wells should be constructed between the well field and the Raritan Bay. They should be sampled regularly in order to detect any possible advance of salt water toward the wells. The disappearance of the fresh-water pond between the South Amboy pumping station and the bay is a danger signal which should not be ignored. The City of South Amboy should be prepared to reduce its pumpage from this sand and to seek another source of supply if salt-water intrusion should be indicated by the test wells.

The Farrington sand appears to be definitely overdeveloped near the Raritan River and very little additional water can be taken from it.

It is possible, however, that most of the pumping now concentrated in the vicinity of Parlin, Old Bridge and South Amboy could profitably and wisely be moved into or near the intake area of the sand just south and southwest of Milltown. If developments are made in this area, however, they should most certainly be accompanied by a very material reduction in pumping in the area just referred to above. If a development should be undertaken in the intake area of the Farrington sand without a substantial decrease in the Parlin and South Amboy area, the water supply from the entire sand might be most adversely affected.

The shales and sandstones of the Newark group have not been studied in sufficient detail to justify a statement as to whether they may be developed more extensively. Over much of the county, however, these rocks do not yield large supplies of water to wells. Most of the nine and one-half million gallons of water taken from these rocks in 1941 came from the areas overlain by permeable materials. In these areas it may be possible to develop some moderately large additional water supplies. These areas are already rather heavily developed, however, and no more developments should be undertaken without careful consideration of the possibility that the capacity of the aquifers might be exceeded. Further studies should be made to determine what the safe yield of these rocks may be.

Careful studies may indicate the possibility of developing some additional relatively small supplies of water from the Quaternary deposits, particularly from the Cape May formation where it is not serving as an intake area for one of the major aquifers or from the glacial deposits in the northern part of the county. Developments should not be made from these deposits, however, unless it is certain that they will not interfere with the supply of existing developments from the underlying rocks.

Most of the future development of water supplies in Middlesex County must, therefore, come from surface streams and not from subterranean sources. The two principal streams that are mainly within the county are Lawrence Brook and the South River. Lawrence Brook has been developed for the water supply of the City of New Brunswick. It can be as completely developed as is economically feasible by raising the Farrington dam which was originally constructed in such a way that its height can be increased. The South River has not as yet been fully developed, but it is impounded in the Duhernal Lake, at which point it has a drainage area of about 95 square miles. Additional storage at the site of the Duhernal Lake is not feasible, but there are some sites suitable for storage reservoirs on some of its branches. As indicated in an earlier section, some of the water from the South River is now being diverted as artificial recharge for the Old Bridge sand in the vicinity of the Duhernal wells. Furthermore, it is anticipated that industrial water for the Duhernal interests may be taken directly from the pond if the demand for water at these plants should ever exceed the capacity of their present sources of supply. Certainly it will be necessary to draw from the lake if the supply from the Farrington sand at Parlin should be destroyed by salt-water intrusion. Some additional water is available at present, however, from the South River by the development of additional storage.

Below the Duhernal dam there are two relatively small tributaries to the South River; Deep Run and Tennent Brook. Tennent Brook is already fully developed for recharging the Old Bridge sand in the vicinity of the Perth Amboy Water Works. Deep Run has not yet been developed, although it probably recharges the Old Bridge sand to some extent where the wells of the Perth Amboy Water Works are near it. Near Old Bridge, Deep Run has a drainage area of about 16 square miles. Not all of this drainage area is available above a suitable reservoir site, but it was estimated by Johnson[30] that a storage reservoir could be constructed to impound the drainage from an area of about 12 square miles and that about 7 million gallons of water daily could be developed. In this report Johnson recommended that the South River be considered as the best source of water supply for the City of Perth Amboy. In view of the industrial development on this stream near the Duhernal Lake, it is doubtful whether much water is available to the city from the South River. The city should, therefore, consider the development of Deep Run as a source of additional water supply. Not only should it be possible to develop approximately 7 million gallons daily of surface water from this stream, but it should also be possible to use some of the runoff from the drainage area below the reservoir site for recharging the Old Bridge sand and feeding additional wells. The fact should not be overlooked that at the present time Deep Run is bringing salt water up into the area adjacent to the Perth Amboy Water Works wells, and the need for construction of a dam or other works to prevent salt water moving so far up the stream, would be even greater if the flow of the stream should be reduced by surface water development.

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[30] Johnson, George A., Report on Additional Water Supply for the City of Perth Amboy, Fifteenth Annual Report of the Superintendent of the Perth Amboy City Water Works, 1918.

The Raritan River, although the largest stream passing through the county, is tidal as far as New Brunswick, and it is at the present time very heavily polluted by industrial wastes between New Brunswick and the county line. However, large quantities of water can be developed from this stream and its tributaries outside the county but within a relatively short distance of its boundaries. A discussion of these possible developments is not within the scope of this report. The various possibilities of providing additional water supply for the city of Perth Amboy from surface sources were discussed by Johnson in the report referred to above. The northern part of the county is within the area generally considered as the northern metropolitan district of New Jersey, and several carefully considered plans for additional water supply for this district have been proposed. Some of these plans include the development of Raritan River basin. It is possible that the industrial districts along the south side of the Raritan River might also be supplied from one of these proposed major supplies, or it may be possible to take care of the needs of this area for water supply by expanding the developments of Lawrence Brook and the South River.