STATE OF NEW JERSEY
DEPARTMENT OF CONSERVATION AND ECONOMIC DEVELOPMENT

DIVISION OF WATER POLICY AND SUPPLY

SPECIAL REPORT 13

GROUND-WATER RESOURCES IN THE TRI-STATE REGION ADJACENT TO THE LOWER DELAWARE RIVER

PREPARED IN COOPERATION WITH
UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

1958

Ground-Water Resources in the Tri-State Region adjacent to the Lower Delaware River

By

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Prepared by the U.S. Geological Survey
in cooperation with the States of
New Jersey, Pennsylvania, and Delaware

State of New Jersey
Department of Conservation
and Economic Development
Joseph E. McLean, *Commissioner*

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Honorable Joseph E. McLean, Commissioner
Department of Conservation and Economic Development

DEAR SIR:

I am transmitting herewith a report on the ground-water resources of the tri-state region adjacent to the lower Delaware River which presents the results of a joint investigation begun in 1949 by the State of New Jersey and the Commonwealth of Pennsylvania in cooperation with the U. S. Geological Survey, in which the State of Delaware became a party at a later date. The joint investigation was recommended by the Interstate Commission on the Delaware River Basin in recognition of the need for an over-all study of the interstate aquifers of this region and the effects of the Delaware River thereon.

The report evaluates the relative importance of the various aquifers in general terms as to their present use and possible potential yield. Areas favorable for greater development and localities where ground-water problems now exist or may soon appear have been tentatively identified and scheduled for further study. The effects of induced recharge from the Delaware River are evaluated and discussed. Similar discussion is presented on the potential danger of salt-water encroachment, which may limit the optimum yield of some of the more important aquifers.

The information presented is of vital interest and importance to the rapidly developing metropolitan section of southern New Jersey to provide the basis for the safe development and protection of adequate water resources essential for its continued growth and prosperity. I therefore recommend that this report be published as a special report of the Division of Water Policy and Supply.

Respectfully submitted,
GEORGE R. SHANKLIN
Chief Engineer and Acting Director

June 26, 1957

LETTER OF TRANSMITTAL

Honorable Joseph E. McLean, Commissioner,
Department of Conservation and Economic Development.

Dear Sir:

I am transmitting herewith a report on the ground-water resources [illegible] of the Trenton region [illegible] presents the results of a [illegible] of New Jersey and the [illegible] with the U. S. Geological Survey [illegible] because a [illegible] Commission [illegible] for the [illegible] of the Delaware River Basin [illegible] of the [illegible] and the effects of the Delaware [illegible]

The report [illegible] the [illegible] importance of [illegible] as [illegible] to their present [illegible] areas [illegible] water development and [illegible] water problems [illegible] identification of [illegible] across both the Delaware [illegible] [illegible] results.

The information [illegible] the rapidly developing [illegible] to provide the basis for the [illegible] water resources [illegible] recommend that this report be [illegible]

June 26, 1957

ABSTRACT

The purpose of this report is to appraise and evaluate the ground-water resources of a tri-state region adjacent to the lower Delaware River that is centered around Philadelphia, Pa., and Camden, N. J., and includes Wilmington, Del., and Trenton, N. J. Specifically, the region includes New Castle County, Del.; Burlington, Camden, Gloucester, Mercer, and Salem Counties in New Jersey; and Bucks, Chester, Delaware, Montgomery, and Philadelphia Counties in Pennsylvania.

The peculiar advantages of ground water, such as its availability in many places without the necessity for expensive pipelines and its relatively uniform temperature and quality, make it an especially valuable resource in an industrial area. Large, readily available supplies of good, fresh water have contributed substantially to the recent rapid industrial growth of the lower Delaware River basin and will be vital to its continued prosperity. The major part of these supplies is drawn from the streams passing through the region, but very large quantities of ground water also are used.

The region is divided almost equally by the Fall Line, which extends in a southwesterly direction along the general course of the Delaware River from Trenton, N. J., to Wilmington, Del., and beyond. Northwest of the Fall Line is a region of consolidated rocks in which ground water occurs mainly in cracks, crevices, and openings created or enlarged by weathering. The capacity of the various geologic formations to yield water depends largely upon the degree to which they have been fractured and weathered. The yield of individual wells in this part of the region is generally small to moderate and not readily predictable. Ground water in this part of the region is generally low in dissolved minerals and suitable for many uses without treatment.

Southeast of the Fall Line lie the unconsolidated rocks of the Coastal Plain. Ground water occurs in these rocks largely in the pore spaces between the individual mineral grains. The major formations and the principal aquifers are rather uniform in their water-bearing characteristics over large areas. The yield of individual wells is moderate to very large and may be predicted with a reasonable degree of assurance. Sufficient quantities of ground water are available in most places for all ordinary purposes. The chemical quality of the ground water from the Coastal Plain aquifers is generally acceptable for most uses, but objectionable quantities of iron or other minerals are found in some places, and some waters have a low pH and are corrosive.

More than 40 distinct geologic formations occur in the region. They range in age from Precambrian to Recent. Nearly all will yield some water to wells. However, only about a dozen yield water freely enough to be considered major aquifers. Of these, the sands of the Raritan and Magothy formations have been developed most intensively, and the Cohansey sand appears to have the greatest capacity for additional development.

The present withdrawal of ground water in the region is estimated to average more than 200 mgd, of which more than half is drawn from the aquifers in the Raritan and Magothy formations. It is estimated that additional supplies of ground water, aggregating more than 1 billion gallons a day, can be developed within the region. Furthermore, substantial additional quantities can be developed outside the region for use within it if the need should ever arise.

Induced recharge from the Delaware River supplies a substantial portion of the total water drawn from the Raritan and Magothy formations. In some areas, the quality of the water from these aquifers is approaching that of the river. Increased withdrawals of water from wells along the river will tend to increase induced recharge. Thus, the maintenance of a good quality of water in the river, which is desirable for many other reasons, is imperative if the quality of the ground-water supply is to be maintained.

The proposed deepening of the Delaware River channel from Philadelphia to Trenton will greatly increase the opportunity for the interchange of water between the river and the adjacent aquifers. Whether this will be beneficial or detrimental to the ground-water supplies will depend upon the quality of the water in that reach of the river. If an acceptable quality of river water is maintained, the ground-water resources of the region will be augmented. If salt water from the ocean or excessive contamination from other sources should render the river water undesirable as a source of recharge, actual and potential ground-water supplies aggregating about 250 mgd would be endangered.

The danger of salt-water encroachment into the aquifers normally yielding fresh water may limit the optimum yield of some of the most important aquifers in the region. Encroachment may come either from salt water in the surface-water bodies of the region or from parts of the aquifers normally containing salt water. The protection of ground-water supplies against salt-water encroachment can be maintained only by constant vigilance, careful distribution of the pumping from the

aquifers, regular sampling of outpost wells in exposed localities, and adjustment of rates of pumping in the light of changing conditions.

The maximum beneficial utilization of the ground-water resources cannot be accomplished in haphazard fashion. It must be planned and controlled on the basis of sound, current information about the hydrology of the various aquifers. Continued and, in some areas, intensified investigations of the ground-water resources of the region should form the basis for such planning and control.

INTRODUCTION

PURPOSE AND SCOPE

Ground water has become essential to the industrial development and high standard of living of the people of this Nation. Its use has more than doubled in the last 15 years, and the demand continues to increase. The availability of ground water may become a critical factor in the further development of many rapidly expanding industrial areas such as the lower Delaware River valley. Knowledge of the geologic and hydrologic characteristics of the water-bearing formations is essential to the safe and complete development of the ground-water resources of this region.

This preliminary report presents the results to date of a joint investigation begun in 1949 by the State of New Jersey and the Commonwealth of Pennsylvania in cooperation with the U. S. Geological Survey. The State of Delaware became a party to the investigation when it became apparent that the inclusion of New Castle County, Del., would enhance the results.

The purpose of the investigation was to evaluate and appraise the total ground-water resources of that part of the lower Delaware River basin that is generally considered the Philadelphia-Camden metropolitan region or the Greater Philadelphia area (see figure 1). Particular attention has been given to the aquifers that extend into more than one State and to the relationship between the Delaware River and the quantity and quality of the ground water in the adjacent aquifers. Indeed, the need for an overall study of the interstate aquifers and the effects of this interstate river upon them was the primary reason for the investigation.

New Jersey and Pennsylvania have supported statewide ground-water investigations in cooperation with the U. S. Geological Survey for many years. Much of the data presented herein is a result of these separate statewide studies. However, in 1947 and 1948, interested parties in both States were involved in a contest over water rights in an interstate aquifer. The Interstate Commission on the Delaware River Basin (hereinafter referred to by its abbreviated title, "Incodel") therefore recognized the need for coordinated study of the problem and sponsored the joint investigations that form the basis of this report. The advantages of a broad study of the Philadelphia metropolitan region over a study limited to the interstate aquifers were recognized at the outset. The program was, therefore, set up as a joint investigation of the ground-water resources of the region.

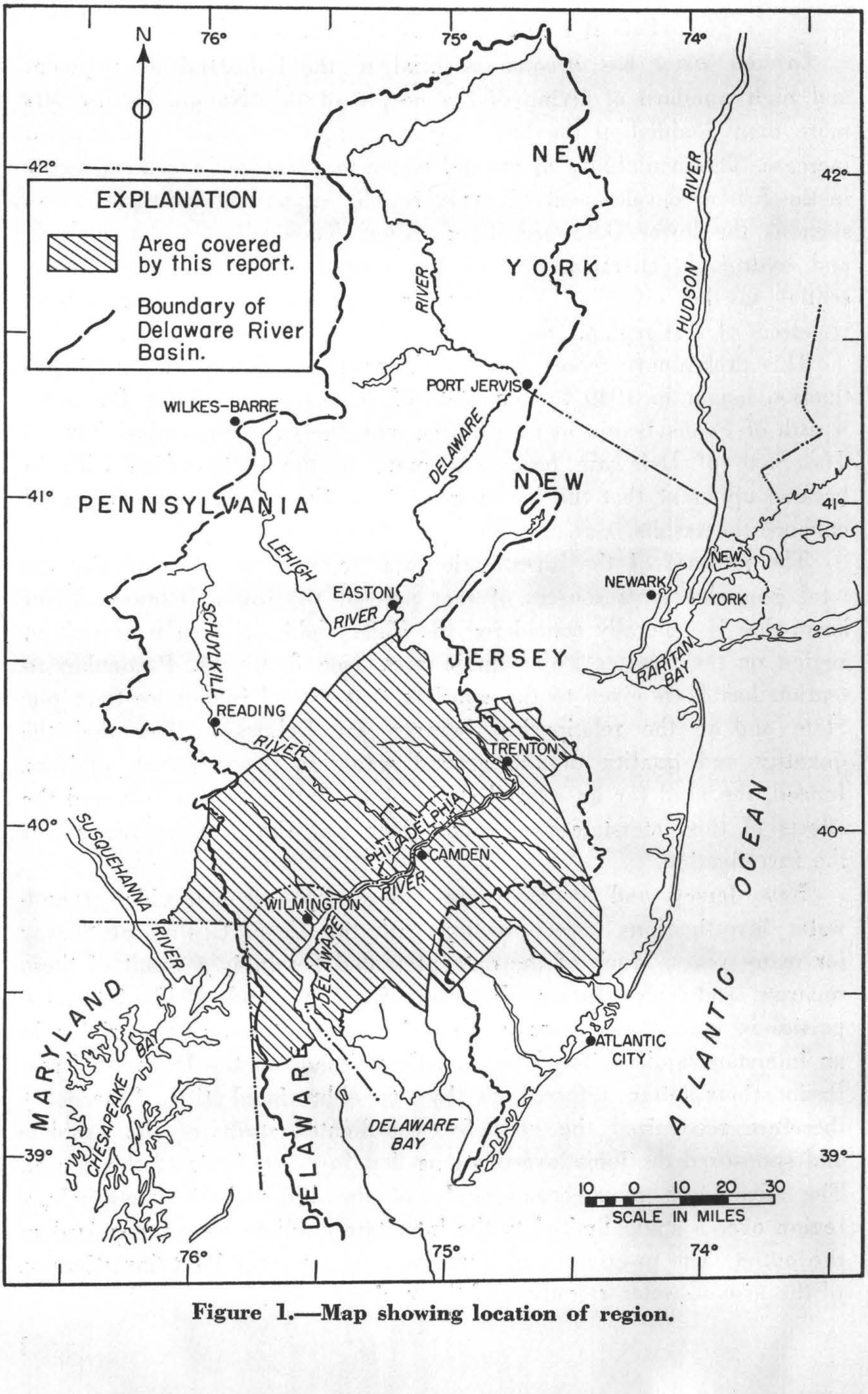

Figure 1.—Map showing location of region.

This report is a general appraisal of the region. It will be followed by detailed county reports. Reports on Bucks County, Pa., and on northern New Castle County, Del., have been completed. Preliminary manuscripts for Salem, Gloucester, and Mercer Counties, N. J., and South Philadelphia, Pa., have been prepared.

Most of the investigational techniques currently used in the field of ground-water hydrology were applied in this study. An extensive well inventory and water-level measurement program was conducted. Numerous aquifer tests were made to define coefficients of transmissibility and storage. Geologic work was undertaken to facilitate the correct interpretation of the geologic and hydrologic relations. Field mapping was done in Bucks and Montgomery Counties, Pa., and in New Castle County, Del. The identification, correlation, and mapping of subsurface aquifers of the Coastal Plain in New Jersey were done on the basis of well records and cuttings, outcrop samples, well-drillers' logs, and a few electric logs. In general, the published State geologic maps were used for areal identification of the formations.

Temperatures of ground water have been measured monthly since August 1950 in 30 wells located near the Delaware River in Camden and Burlington Counties, N. J. Temperature records in one well near the river in Bucks County, Pa., were obtained periodically for about a year and subsequently by means of a continuous recorder.

Samples of water have been collected from selected wells and analyzed for their chemical quality. In areas where it seemed possible that the quality of the ground water might be changing due to the effects of pumping and induced recharge, periodic samples have been collected and analyzed. Most of this work has been concentrated along the Delaware River and its tidal tributaries.

In general, the overall water-bearing properties of the principal aquifers are now known. Some knowledge is available of their recharge characteristics and present stages of development and of the chemical quality of the waters they yield. Areas favorable for greater development and localities where ground-water problems now exist or may soon appear have been tentatively identified and scheduled for further study.

PREVIOUS GROUND-WATER INVESTIGATIONS AND REPORTS

The geology and ground-water resources of the 11-county region have been studied intermittently during the past 100 years. The studies have sometimes been on a regional basis. More commonly, they have covered selected parts of the region. Some investigations based upon other regional units have covered all or a part of the region. Nearly all the early ground-water reports were restricted to general descriptions of the water-bearing formations, short lists of wells tapping the principal aquifers, and sometimes a few drillers' logs. Many of the older published well records are in geologic reports such as the Annual Reports of the New Jersey State Geologist. Early reports on the geology of Delaware were published by the Maryland Geological Survey. Several early publications of the U. S. Geological Survey contain ground-water and geologic data on the 11-county region (Bascom, 1904 and 1909).

The U. S. Geological Survey began quantitative ground-water investigations in New Jersey in 1923 in cooperation with the State Department of Conservation and Development. The State cooperating agency has changed from time to time as different agencies have been assigned the responsibility for administering the water resources of the State. For the past several years, the cooperating agency in New Jersey has been the State Department of Conservation and Economic Development, Division of Water Policy and Supply. Ground-water studies in Pennsylvania began in 1925. The Pennsylvania Department of Internal Affairs, Geologic and Topographic Survey, has been the cooperating State agency from that time to the present. In addition to the areal ground-water studies, a program to record changes in ground-water levels has been maintained in New Jersey and Pennsylvania since 1923 and 1931, respectively. Statewide cooperative ground-water investigations in Delaware were begun in 1950 with the State Highway Department and the State Agricultural Experiment Station as the cooperating agencies. In 1951, the Delaware Geological Survey was created, and it has been the cooperating agency since that time. From its beginning, the cooperative ground-water program in Delaware has included both areal investigations and a water-level observation program. The work in the lower Delaware River basin was necessarily limited by the need for work on other phases of the programs in the three States. With the inception of the present joint investigations, it first became possible to apply a more adequate effort to the appraisal of the ground-water resources of the region.

In 1932, a report on the ground-water supplies of the Camden area, N. J., was published (Thompson, 1932). In 1934, a report on the ground water in southeastern Pennsylvania was published (Hall, 1934). In 1951, a report summarizing information on the quantity and chemical quality of the water resources of southeastern Bucks County was published (Graham, Mangan, and White, 1951). In 1952, a report on the progress of the investigations in the 11-county region covered by this report was published in mimeographed form (Barksdale and Graham, 1952). In 1954, a report was released on the ground-water resources of the Philadelphia Naval Base (Graham and Kammerer, 1954), and one on the ground-water resources of the Newark, Del., area was published (Groot and Rasmussen, 1954). In 1955, three reports dealing with the ground-water resources of parts of the area were published; a preliminary work on the State of Delaware (Marine and Rasmussen, 1955); one on Bucks County, Pa., (Greenman, 1955); and one on the Lansdowne, Pa., area (Rima, 1955). In that year, a master's thesis on the crystalline rocks of Delaware (Ward, 1955) was also released.

The results of two studies of the quality of the surface waters of the region provided valuable data for the study of the effect of induced recharge from the lower Delaware River upon the ultimate quantity and quality of the ground water available from the adjacent aquifers. The first was a cooperative investigation of the quality of the surface waters of Pennsylvania, begun in 1944 by the Pennsylvania Department of Commerce and the U. S. Geological Survey. Three reports on this work (White, 1947 and 1951; Beamer, 1953) provide much information about the quality of the water entering the lower (tidal) reaches of the Delaware River. However, the presence of salt water from the ocean and of wastes discharged into the lower Delaware River made more detailed information essential to the ground-water investigation. Therefore, a conference of interested parties was called. As a result, the City of Philadelphia and the U. S. Geological Survey have been making a cooperative study of the quality of the water in the lower Delaware River since August 1949. A progress report was issued in 1954 (Durfor and Keighton, 1954).

Several brief articles in technical journals relate to ground-water conditions in this region (Graham, 1945, and 1950; Barksdale, 1952; Barksdale and Jones, 1953; Barksdale and Lang, 1955; and others).

PERSONNEL AND ACKNOWLEDGEMENTS

The studies in the 11-county region have been under the general supervision of A. Nelson Sayre, Chief of the Ground Water Branch, Water Resources Division, U. S. Geological Survey, and of the representatives of the cooperating State agencies. Howard T. Critchlow, Director and

Chief Engineer of the Division of Water Policy and Supply, New Jersey State Department of Conservation and Economic Development, and, since his retirement, his successor, George R. Shanklin, represented New Jersey. The late S. C. Cathcart, State Geologist, and his successor, Carlyle Gray, acted in this capacity for the Geologic and Topographic Survey, Pennsylvania Department of Internal Affairs. Johan J. Groot, State Geologist, represented the State of Delaware. James H. Allen, Secretary of the Interstate Commission on the Delaware River Basin, was largely responsible for the initiation of the project and the coordination of the different state interests.

The field studies have been under the direction of the district supervisors of the Ground Water Branch of the Water Resources Division of the U. S. Geological Survey. Henry C. Barksdale directed the work in New Jersey and coordinated the work of the three districts. The Pennsylvania phases were directed by Jack B. Graham and his successors, Paul H. Jones and David W. Greenman. The Delaware part of the project was directed by William C. Rasmussen.

The authors of this report have each had the assistance of the others to the extent that it is difficult to assign authorship to specific sections. Mr. Barksdale wrote the section on the Raritan and Magothy formations and much of the remainder of the report. Mr. Greenman wrote the sections on the hard-rock aquifers and on the chemical quality of the waters of the region. Minor sections were written by the junior authors and by Messrs. Horace G. Richards, William C. Rasmussen, and Irwin Remson. The assistance of Messrs. Jack B. Graham, Paul H. Jones, John C. Kammerer, Seymour Mack, James R. Randolph, Edward C. Rhodehamel, Paul R. Seaber, and others is also gratefully acknowledged.

Charles R. Austin prepared the index, assisted with the preparation of the bibliography and of the tabular matter, and drafted many of the illustrations. Mrs. Carolyn M. Howard also drafted many illustrations. Mrs. Veronica B. Kron typed the manuscript and assisted with the proofreading.

The writers are indebted to many individuals and to many organizations, both public and private, for useful information and valuable assistance of many kinds. The cooperating agencies in the three states made available a great volume of geologic, hydrologic, and well data. Dr. Meredith E. Johnson, State Geologist of New Jersey, furnished valuable geologic information, numerous well records, and helpful suggestions on the report itself. The officials of public water supplies and of many industrial plants furnished information on water use and made wells available for water-level observations and pumping tests. Consulting engineers and geologists and their clients furnished much useful infor-

mation. Special acknowledgement is made to the firm of Leggette, Brashears, and Graham, which probably furnished more significant hydrogeologic information than any other nongovernmental agency. Many well drillers furnished well records and samples of cuttings. Grateful acknowledgement is made for all this assistance.

GEOGRAPHY OF THE REGION

LOCATION AND EXTENT

The 11-county region covered by this report lies roughly between latitudes 39° 20' and 40° 40' north and between longitude 74° 20' and 76° 10' west. (See figure 1.) It includes the Cities of Camden, N. J., Philadelphia, Pa., Trenton, N. J., and Wilmington, Del. The City of Philadelphia, which is coextensive with Philadelphia County, is at the center of the region. Most of the region lies within a circle of 40-mile radius centered in Philadelphia. From Philadelphia it is about 95 miles to New York City and about 140 miles to Washington, D. C. The area of the region is about 4,600 square miles. Of this total, something more than 400 square miles is in Delaware, about 2,000 square miles are in New Jersey, and slightly less than 2,200 square miles are in Pennsylvania.

The region lies along both sides of the Delaware River from a point about 10 miles above Trenton, N. J., to a point about 25 miles below Wilmington, Del. It consists of Bucks, Chester, Delaware, Montgomery, and Philadelphia Counties in Pennsylvania; Burlington, Camden, Gloucester, Mercer, and Salem Counties in New Jersey; and New Castle County in Delaware (see figure 2). The region has been designated as the "Philadelphia-Camden metropolitan region," the "Philadelphia Tri-State district," and as the "Greater Philadelphia-Delaware-South Jersey area," etc., by various planning and economic groups.

CLIMATE

The climate of the 11-county region is characterized by a relatively moderate range of temperature, by mild winters, and by a generally dependable and sufficient rainfall. Average monthly temperatures for January range from 26° to 34° F. Average monthly temperatures for July range from 73° to 76° F. The highest temperatures occur in the southeastern part of the region near the Atlantic Ocean. Average annual precipitation ranges from 40 to 48 inches with the highest rates occurring in the central part of the New Jersey Coastal Plain.

Table 1 lists monthly temperatures and precipitation at Philadelphia, which are generally representative of the region, although there are small variations from place to place. Average annual snowfall at Philadelphia is 22 inches (roughly equivalent to 2.2 inches of rainfall). For the 10-year period, 1939-48, the temperature in Philadelphia reached or exceeded 90° F. an average of 19 days a year and was 10° F. or below an average of 2 days each winter.

The prevailing wind direction during the summer months is from the southwest, whereas northwest winds prevail during the winter. Destructive wind velocities are comparatively rare and occur mostly as gustiness during summer thunderstorms and in hurricanes that occasionally pass directly over the region. High winds occuring in the winter

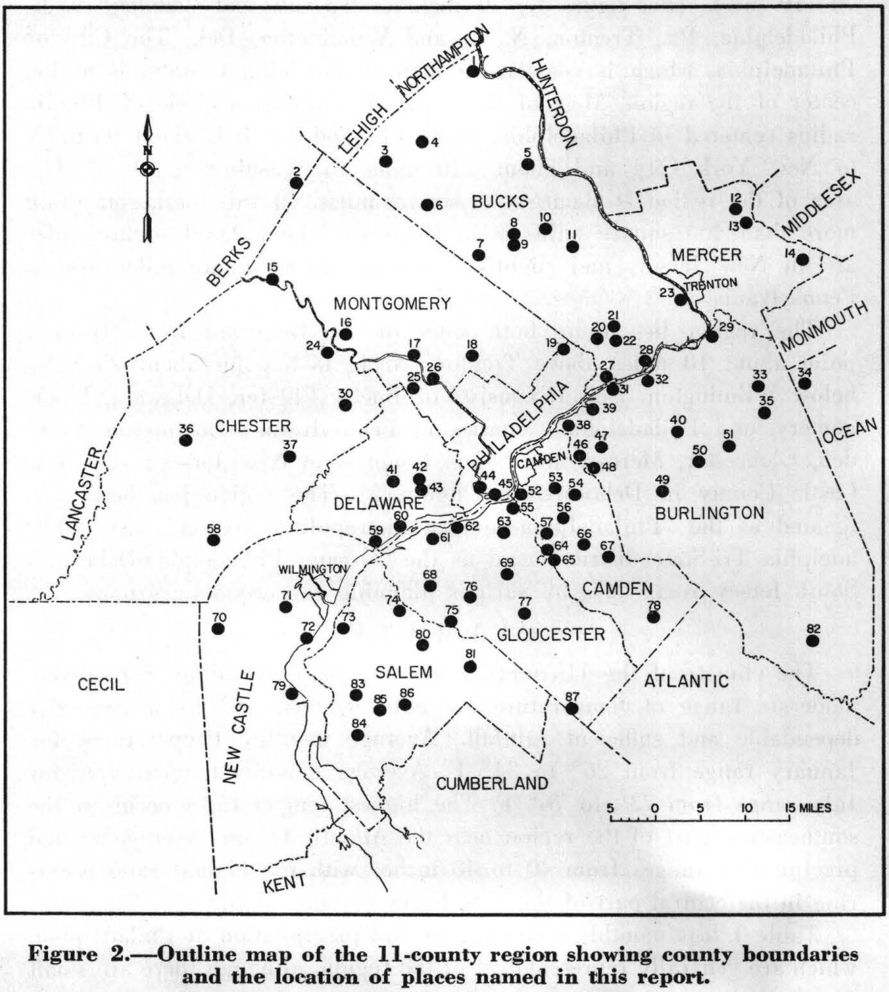

Figure 2.—Outline map of the 11-county region showing county boundaries and the location of places named in this report.

Key To Place Names (Fig. 2)

Numerical

1 Durham
2 Bally
3 Milford Square
4 Richlandtown
5 Camp Ockanikon
6 Sellersville
7 Chalfont
8 Doylestown
9 Edison
10 Buckingham
11 Pineville
12 Princeton
13 Princeton Junction
14 Hightstown
15 Pottstown
16 Collegeville
17 Norristown
18 Whitemarsh
19 Somerton
20 Parkland
21 Langhorne
22 Hulmeville
23 Morrisville
24 Phoenixville
25 Gulph Mills
26 Conshohocken
27 Eddington
28 Bristol
29 Bordentown
30 Paoli
31 Beverly
32 Burlington
33 Sykesville
34 New Egypt
35 Fort Dix
36 Coatesville
37 West Chester
38 Palmyra
39 Riverton
40 Mount Holly
41 Media
42 Lansdowne
43 Yeadon
44 Darby
45 Philadelphia Naval Base
46 Maple Shade
47 Moorestown
48 Fellowship
49 Medford
50 Vincentown
51 Pemberton
52 Gloucester
53 Collingswood
54 Haddonfield
55 Westville
56 Haddon Heights
57 Runnemede
58 Toughkenomon
59 Marcus Hook
60 Chester
61 Gibbstown
62 Paulsboro
63 Woodbury
64 Blackwood
65 Grenloch
66 Clementon
67 Berlin
68 Swedesboro
69 Sewell
70 Newark
71 Newport
72 New Castle
73 Deepwater
74 Auburn
75 Harrisonville
76 Mullica Hill
77 Glassboro
78 Ancora
79 Delaware City
80 Woodstown
81 Pittsgrove
82 Harrisville
83 Salem
84 Hancocks Bridge
85 Quinton
86 Alloway
87 Newfield

Alphabetical

Alloway	86
Ancora	78
Auburn	74
Bally	2
Berlin	67
Beverly	31
Blackwood	64
Bordentown	29
Bristol	28
Buckingham	10
Burlington	32
Camp Ockanikon	5
Chalfont	7
Chester	60
Clementon	66
Coatesville	36
Collegeville	16
Collingswood	53
Conshohocken	26
Darby	44
Deepwater	73
Delaware City	79
Doylestown	8
Durham	1
Eddington	27
Edison	9
Fellowship	48
Fort Dix	35
Gibbstown	61
Glassboro	77
Gloucester	52
Grenloch	65
Gulph Mills	25
Haddonfield	54
Haddon Heights	56
Hancocks Bridge	84
Harrisville	82
Harrisonville	75
Hightstown	14
Hulmeville	22
Langhorne	21
Lansdowne	42
Maple Shade	46
Marcus Hook	59
Medford	49
Media	41
Milford Square	3
Moorestown	47
Morrisville	23
Mount Holly	40
Mullica Hill	76
Newark	70
New Castle	72
New Egypt	34
Newfield	87
Newport	71
Norristown	17
Palmyra	38
Paoli	30
Parkland	20
Paulsboro	62
Pemberton	51
Philadelphia Naval Base	45
Phoenixville	24
Pineville	11
Pittsgrove	81
Pottstown	15
Princeton	12
Princeton Junction	13
Quinton	85
Richlandtown	4
Riverton	39
Runnemede	57
Salem	83
Sellersville	6
Sewell	69
Somerton	19
Swedesboro	68
Sykesville	33
Toughkenomon	58
Vincentown	50
West Chester	37
Westville	55
Whitemarsh	18
Woodbury	63
Woodstown	80
Yeadon	43

months usually come with the advance of cold air after the passage of an intense low pressure area.

Table 1.—Monthly and annual air temperature and precipitation at Philadelphia, Pa. (1921 to 1955)

	Philadelphia			
Month	*Air temperature normal (°F)*	*Total Precipitation (inches)*		
		Normal	*Maximum*	*Minimum*
January	34.9	3.39	6.74	0.96
February	35.1	3.03	6.87	0.84
March	43.5	3.37	9.10	0.38
April	52.7	3.38	9.76	0.61
May	63.7	3.58	9.46	0.54
June	72.6	3.97	10.06	0.30
July	77.2	4.21	10.30	0.75
August	75.2	4.62	12.10	0.46
September	69.3	3.43	12.09	0.20
October	58.5	2.61	6.66	0.09
November	47.8	3.08	7.45	0.43
December	37.4	2.77	7.35	0.83
Annual	55.7	41.44	55.28 (1873)	29.31 (1922)

Source: U. S. Dept. of Commerce, Weather Bureau, 1955, local Climatological Data, with comparative data. Extremes from earlier reports in same series.

The climate of the 11-county region is probably influenced more by its location than by topographic relief. The most important factor governing the climate is probably the moderating and moistening effect of the nearby Atlantic Ocean. However, the climate is also affected by the eastward movement of storms across the continent, by cold air masses from the north, and by warm air masses from the south. In summer, warm, moist air is forced in from the south and southeast by the Bermuda high-pressure cell. Frigid polar air moves into the region from Canada in winter.

Most of the precipitation falls as rain. Winter precipitation is caused primarily by warmer, moist air from the south moving into and riding over colder, dry air from the north. Much of the summer precipitation occurs during scattered thunderstorms, as heated ground air is lofted to cooler levels in the atmosphere. The precipitation is fairly evenly distributed throughout the year as shown in table 1. More precipitation falls as snow in the northern and western parts than elsewhere in the region.

Figure 3 shows the amount of yearly precipitation at Philadelphia, Pa., for the period 1901-56. By referring to the line for the normal precipita-

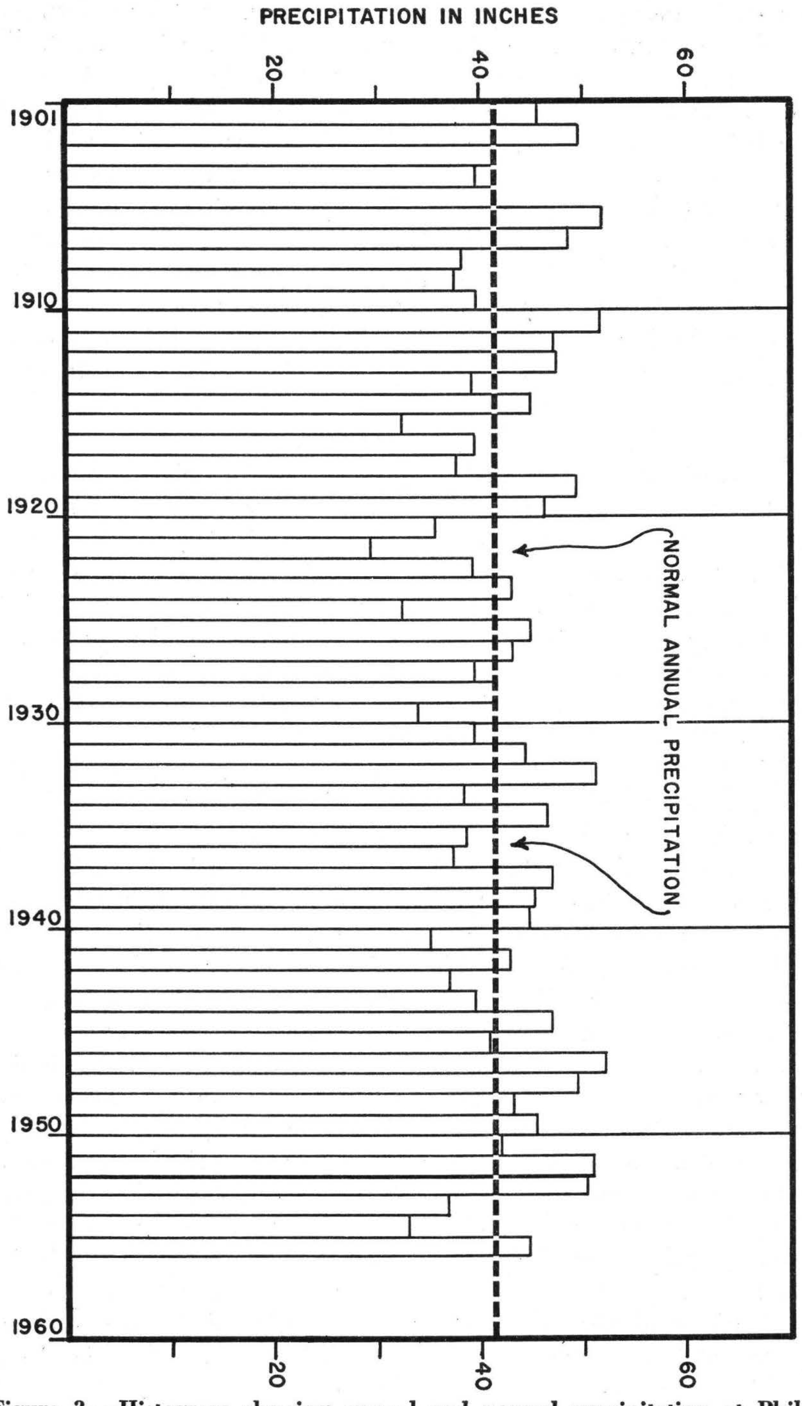

Figure 3.—Histogram showing annual and normal precipitation at Philadelphia, Pa., in inches of water, for the period 1901-56.

tion during the period, it can be seen whether the amount for a given year or series of years is above, below, or equal to the normal amount. For example, the precipitation was above normal during the period 1901-12 except for 1905, and below normal from 1913 through 1925 except for 1919-20 and 1924. The effects of high and low annual precipitation rates upon ground-water recharge and stream flow will be discussed in a later section. At this point, it is sufficient to point out that the correlation is not a simple and direct one but depends upon many factors, such as the intensity and distribution of the precipitation and whether it occurs in the growing season or when plants are dormant. It may also be added that the length of the dormant season is such that a moisture deficiency is seldom carried from one dry year into the next.

DRAINAGE

Most of the 11-county region is drained by the Delaware River and its tributaries. From Trenton to the sea, a distance of 135 miles, the Delaware River is a navigable tidal estuary, having two tide cycles daily. At Philadelphia, there is almost a 6-foot difference between mean high and mean low tides. The principal tributaries are also tidal in their lower reaches. Much water flows into and across the region from drainage areas outside its limits. The Delaware River basin (not including 782 square miles of tidal estuary) has a total area of 12,765 square miles, and the basin area below the head of tide and navigation at Trenton is 5,985 square miles. The average discharge of the Delaware River at Trenton is 12,070 cubic feet of water per second (adjusted for storage and diversion), equivalent to about 7.8 billion gallons a day (U. S. Geol. Survey Water Supply Paper 1,272, p. 220).

The largest tributary to the Delaware River is the Schuylkill River which flows through the region from the northwest, and joins the Delaware at Philadelphia. The Schuylkill drains an area of about 1,900 square miles, about half of which is in the report region. It discharges an average of 2,859 cubic feet of water per second (gaging station at Fairmount Dam, Philadelphia), equivalent to more than 1.7 billion gallons a day. Other principal tributaries to the Delaware River from the west in the region are Tohickson, Neshaminy, Pennypack, Darby, and Chester Creeks and the Christiana River. The chief tributaries of the Delaware from the east within the report region are the Assunpink, Crosswicks, Rancocas, Big Timber, Salem, and Alloways Creeks. The average discharge of these streams ranges from 50 to 400 cubic feet per second.

Northern Mercer County is drained northward by the Millstone River and thence through the Raritan River into the Atlantic Ocean.

The Great Egg Harbor and Mullica Rivers and some smaller streams drain the southeastern parts of Burlington, Camden, and Gloucester Counties, and enter the Atlantic Ocean.

The westernmost part of Chester County, Pa., and a small part of New Castle County, Del., are in the drainage basin of the Susquehanna River.

POPULATION, INDUSTRY, AND AGRICULTURE

The 11 counties that compose this region had a population of more than four million people in 1950 (U. S. Bureau of the Census). It has been estimated that the population will exceed five million by 1960 (Chamber of Commerce News of Greater Philadelphia, Aug. 24, 1955). The most densely populated parts of the region lie along both sides of the Delaware River from Trenton south to Marcus Hook, especially in the vicinity of Philadelphia and Camden. The density of population of the whole region was 900 persons per square mile in 1950. Pertinent data on the population, area, civil units, and larger municipalities are given in tables 2 and 3.

The region, especially that part of it along the Delaware River, is one of the major commercial and industrial centers of the nation. Much of it is highly industrialized, as shown in table 4. It is undergoing rapid industrial expansion. Adequate and suitable water for human consumption and for industrial uses will be a major factor in the continued industrial and commercial expansion of the region. Many industrial plants use large quantities of water, supplied either by municipal water works or by their own water systems. Many millions of gallons of water are used daily by such industries as petroleum refining, steam generating, metal refining and processing, alcohol distilling, food processing, ice making, and chemical manufacturing. Much water is also needed for cooling and air-conditioning in commercial and industrial buildings.

Table 5 shows the intensive development of agriculture in the 11-county region. Because of the emphasis on high-value crops, the use of supplemental irrigation is becoming widespread and is rapidly increasing. Supplemental irrigation is largely a consumptive use of water because most of the water applied is discharged to the atmosphere by transpiration and evaporation. On irrigated areas, the application of water for this purpose is in the order of 6″ to 12″ per year, depending upon the weather and the crops. The total quantity of water used is therefore considerable and must be taken into account in appraising the overall water supply situation in the region.

Table 2.—Area, population, and county seat of counties in the region

State and County	*Land area[1] (square miles) 1955*	*Population 1940[1] (thousands)*	*Population 1950[1] (thousands)*	*Estimated Population 1960[2] (thousands)*	*Political Subdivisions*			*County Seat*
					Cities	*Boroughs*	*Townships*	
DELAWARE								
New Castle	437	180	219	274	10	16[3]	11[4]	Wilmington
NEW JERSEY								
Burlington	819	97	136	204	3	6	31	Mount Holly
Camden	221	256	301	391	2	27	8	Camden
Gloucester	329	72	92	130	1	10	13	Woodbury
Mercer	228	197	230	293	1	4	8	Trenton
Salem	350	42	50	58	1	3	11	Salem
Totals	1,947	664	809	1,076	8	50	71	
PENNSYLVANIA								
Bucks	617	108	145	268	0	22	29	Doylestown
Chester	760	136	159	199	1	14	57	West Chester
Delaware	185	311	414	576	1	23	19	Media
Montgomery	492	289	353	501	0	24	38	Norristown
Philadelphia	127	1,931	2,072	2,249	1	0	0	Philadelphia
Totals	2,181	2,775	3,143	3,793	3	83	143	
TOTAL FOR REGION	4,565	3,619	4,171	5,143	21	149	225	

[1]Source: U. S. Dept. of Commerce, Bureau of the Census
[2]Sources: Chamber of Commerce of Greater Philadelphia; Greater Philadelphia Facts, 1956
[3]Unincorporated towns
[4]Hundreds: a small political division

Table 3.—Cities and boroughs in the region with a population of 10,000 or more in 1950[1].

State and County	*Municipality*	*Population 1940 (thousands)*	*Population 1950 (thousands)*	*Total area (square miles)*
DELAWARE				
New Castle	Wilmington	113	110	15.8
NEW JERSEY				
Burlington	Burlington	11	12	2.2
Camden	Camden	118	125	9.8
	Collingswood	13	16	2.1
	Gloucester City	14	14	3.4
	Haddonfield	10	10	2.8
Gloucester	Woodbury	8	11	2.2
Mercer	Princeton	8	12	1.8
	Trenton	125	128	7.7
PENNSYLVANIA				
Bucks	Bristol	12	13	1.5
Chester	Coatesville	14	14	1.4
	Phoenixville	12	13	2.4
	West Chester	13	15	1.7
Delaware	Chester	59	66	6.1
	Darby	10	13	0.9
	Lansdowne	11	12	1.2
	Yeadon	9	11	1.6
Montgomery	Conshohocken	11	11	1.1
	Norristown	38	38	3.7
	Pottstown	20	23	5.1
Philadelphia	Philadelphia	1,933	2,071	135.0

[1]Source: U. S. Department of Commerce, Bureau of the Census

Table 4—Industrial statistics by counties

State and County	Number of establishments 1947	Number of establishments 1954[1]	Manufacturing employment (thousand persons) 1947	Manufacturing employment (thousand persons) 1954[1]	Value added by manufacturer (million dollars) 1947	Value added by manufacturer (million dollars) 1954[1]	Industrial firms with 1,000 or more employees 1947	Industrial firms with 1,000 or more employees 1956
DELAWARE								
New Castle	251	300	24	27	122	254	4	11
NEW JERSEY								
Burlington	165	241	13	13	58	95	2[2]	3
Camden	391	512	44	46	228	366	4[2]	3
Gloucester	113	164	7	10	48	74	2[2]	2
Mercer	402	447	40	38	208	295	8[2]	5
Salem	48	48	12	11	86	136	2[2]	2
Total	1,119	1,412	116	118	628	966	18[2]	15
PENNSYLVANIA								
Bucks	322	435	17	36	74	261	2	4[3]
Chester	206	291	18	21	84	145	2	2[3]
Delaware	310	393	47	53	267	448	10	10[3]
Montgomery	648	836	57	62	284	459	12	9[3]
Philadelphia	5,244	5,244	329	310	1,730	2,208	45	41[3]
Total	6,730	7,199	468	482	2,439	3,521	71	66[3]
Total for region	8,100	8,911	608	627	3,189	4,741	93	92

[1]Preliminary data
[2]1950
[3]1954
Sources: U. S. Dept. of Commerce, Bureau of the Census
N. J. Dept. of Conservation & Economic Development, Research & Statistics Section

Table 5.—Agricultural statistics by counties for the region

State and County	*Percentage of land area in farms*			*All land in farms (thousand acres)*			*Number of farms*			*Value of farm products sold (million dollars)*		
	1945	*1950*	*1954*	*1945*	*1950*	*1954*	*1945*	*1950*	*1954*	*1944*	*1950*	*1954*
DELAWARE												
New Castle	64	—	60	280	—	168	1,382	—	1,130	7.8*	—	8.8
NEW JERSEY												
Burlington	34	40	40	176	212	208	1,629	1,905	1,835	12.0	17.0	22.0
Camden	23	24	19	33	33	27	1,111	929	658	3.2	4.1	5.7
Gloucester	55	52	48	115	109	101	2,255	1,917	1,608	11.1	14.5	18.2
Mercer	60	55	52	88	80	76	1,081	1,036	828	8.0	8.5	9.2
Salem	58	55	56	130	123	126	1,609	1,435	1,478	10.3	13.0	14.1
Total	44	45	44	542	557	538	7,685	7,222	6,407	44.6	57.1	69.2
PENNSYLVANIA												
Bucks	68	66	58	267	260	230	4,069	3,751	2,730	16.5	23.2	21.0
Chester	79	74	69	383	359	336	4,172	3,817	3,383	22.6	31.1	32.7
Delaware	38	32	26	45	37	31	669	630	493	2.6	4.3	4.1
Montgomery	57	51	46	178	161	146	3,294	2,802	2,505	10.1	15.7	15.1
Philadelphia	7	10	6	7	8	5	125	161	76	1.6	1.5	.9
Total	62	59	53	880	825	748	12,329	11,161	9,187	53.4	75.8	73.8

Source: U. S. Dept. of Commerce, Bureau of the Census, 1954.
*1949

GEOLOGY OF THE REGION

PHYSIOGRAPHY

The 11-county region lies within two commonly accepted major physiographic divisions, the Appalachian Highlands on the northwest and the Atlantic Coastal Plain on the southeast (Lobeck, 1948), (see figure 4). Between them and dividing the region almost in half lies the so-called "Fall Line." This "line" is actually a narrow zone of varying width, containing the outcrop of the geologic contact between the unconsolidated deposits of the Coastal Plain and the consolidated rocks of the Appalachian Highlands. It is called the "Fall Line" because of the common occurrence of falls or rapids where streams enter the lower and flatter Coastal Plain. Generally, these are the lowermost falls or rapids on the streams and form the head of navigation. For this reason and because of the water power available at the falls, many important cities have grown up along the Fall Line. The Fall Line in the 11-county region passes through Trenton, N. J.; Philadelphia, Pa.; Chester, Pa.; and Wilmington, Del. Much of the course of the Delaware River between Trenton and Wilmington lies near the Fall Line.

Topographically, the Coastal Plain is a low-lying gently rolling plain. In the 11-county region it attains a maximum altitude of 200 feet, and it slopes gently toward the Delaware River, except in the extreme southeastern parts of the region, where it slopes southeastward toward the Atlantic Ocean. Most of the Coastal Plain in this region is less than 120 feet above sea level. Large areas near the larger streams and in the coastal drainage lowlands of southern Burlington County lie at altitudes of less than 50 feet. It has tidal marshlands along the larger streams. The Coastal Plain is underlain by unconsolidated or poorly consolidated beds of clay, marl, sandy clay, sand, and gravel of Mesozoic and Cenozoic age. These beds thicken southeastward and overlie the buried southeastward

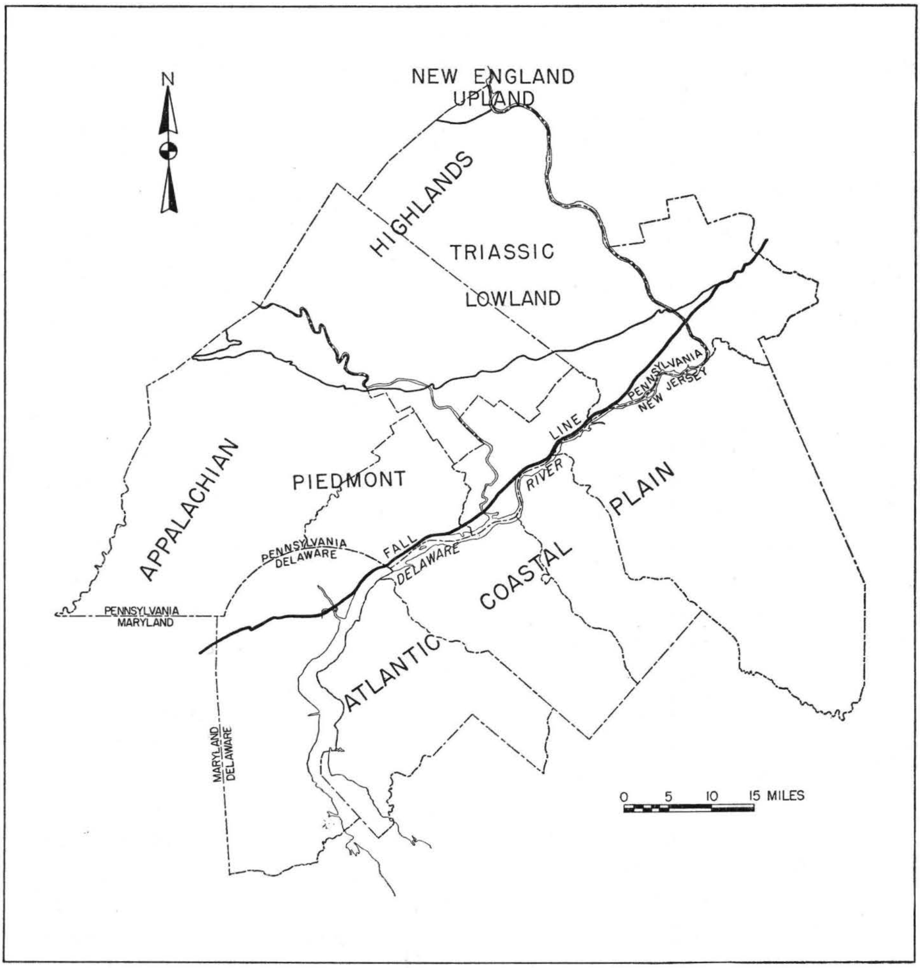

Figure 4.—Map showing physiographic divisions of the region.

extension of some of the consolidated rocks which are at or near the surface in the Appalachian Highlands .

The Appalachian Highlands has been divided into several provinces. In the 11-county region, it includes the Piedmont section of the Older Appalachian province, parts of the Triassic-Lowland province, and a small part of the New England-Upland province. In the northern part of the region, the Coastal Plain adjoins the Triassic Lowland. Elsewhere it adjoins the Piedmont (see figure 4).

The Piedmont section within the report region consists of a series of northeast-southwest trending uplands composed of rounded hills and plains cut by relatively narrow valleys. The whole region slopes gradually toward the southeast. Outside the region, these uplands reach a maximum altitude of about 1,100 feet above sea level near the Chester-Lancaster County boundary. Within the region, the altitude of the Piedmont ranges from 40 to 700 feet, and most of it is between 200 and 600 feet. Local relief is as much as 200 feet. The Piedmont includes small parts of Mercer County, N. J., and Bucks and Montgomery Counties, Pa., as well as the major portions of Delaware and Philadelphia Counties, Pa., and New Castle County, Del. The Piedmont part of the region is underlain by crystalline rocks of Precambrian and Cambrian age (see geologic map Plate I). It is bounded on the southeast by the Coastal Plain and on the northwest by the Triassic-Lowland province.

The Triassic-Lowland province is generally topographically lower than the Piedmont section and higher than the Coastal Plain. In the northern part of the region a more or less distinct rise exists between the Coastal Plain and the Triassic Lowland. The Triassic Lowland is characteristically a low hilly or rolling plain traversed by a few distinct and moderately steep ridges. The plain lies between altitudes of 100 feet and 600 feet, and the general slope is toward the southeast. Some ridge tops rise above 800 feet. Local relief seldom exceeds 300 feet. The major part of the province is underlain by shales and sandstones of Triassic age. The more distinct ridges are underlain by hard igneous rocks probably of the same age.

The New England-Upland province occurs in the 11-county region only in the northernmost corner of Bucks County. It is here a deeply dissected peneplane formed on folded and faulted Cambrian and Ordovician sedimentary rocks and Precambrian metamorphic rocks. The tops of some of the ridges reach altitudes of more than 850 feet, while the valleys descend to an elevation of about 180 feet.

GENERAL STRATIGRAPHY AND STRUCTURE

The geologic map (Plate I) shows the outcrop areas of rocks of Precambrian, Cambrian, Ordovician, Triassic, Cretaceous, and Tertiary age in the region. Figure 5 is a structure section on which faults, contacts between formations, and their structural attitudes are indicated. The slopes, or dips, of the faults and contacts shown in the section are much more steeply inclined than they actually are because of the great exaggeration of the vertical scale.

The Precambian and Paleozoic rocks of the Piedmont section of the Older Appalachian province and the New England-Upland province are greatly folded and faulted, and frequently considerably metamorphosed and intruded by granite or other igneous rocks.

The Triassic-Lowland province is characterized by consolidated sediments that dip to the northwest. They were deposited in a basin that was formed by faulting and folding. Toward the end of the period of deposition, the sediments were intruded by diabase dikes and sills. At the end of the Triassic period of sedimentation, movement along a series of northeast-southwest fractures divided the Triassic rocks of New Jersey and Pennsylvania into a succession of long narrow blocks that are tilted to the northwest .

All the rocks exposed in the Coastal Plain are sedimentary and nearly all are unconsolidated. They range in age from Early Cretaceous to Quaternary. The lowermost rest upon a gently undulating surface of Precambrian(?) and Triassic rocks. The beds dip gently to the southeast. Those that appear at the surface near the northwest margin of the Coastal Plain pass beneath successively younger strata toward the coast of New Jersey. In general, each successively younger formation has a more gentle dip than its predecessor. The essentially flat-lying Quarternary deposits overlie the Cretaceous and Tertiary deposits and in some places overlie still older rocks.

GEOLOGIC HISTORY

The earliest geologic history of the region is very vague, but may be said to start in Precambrian time with the deposition of sediments that have since been metamorphosed to form parts of the Baltimore gneiss, Byram granite gneiss, Pochuck gabbro gneiss, and Pickering gneiss. (See Plate I.) Portions of these ancient gneisses were also formed by the metamorphism of granites and other igneous rocks that intruded the sedimentary rocks during the Precambrian.

The geologic history of the region becomes a little clearer with the beginning of the Paleozoic era. At this time, high mountains existed on

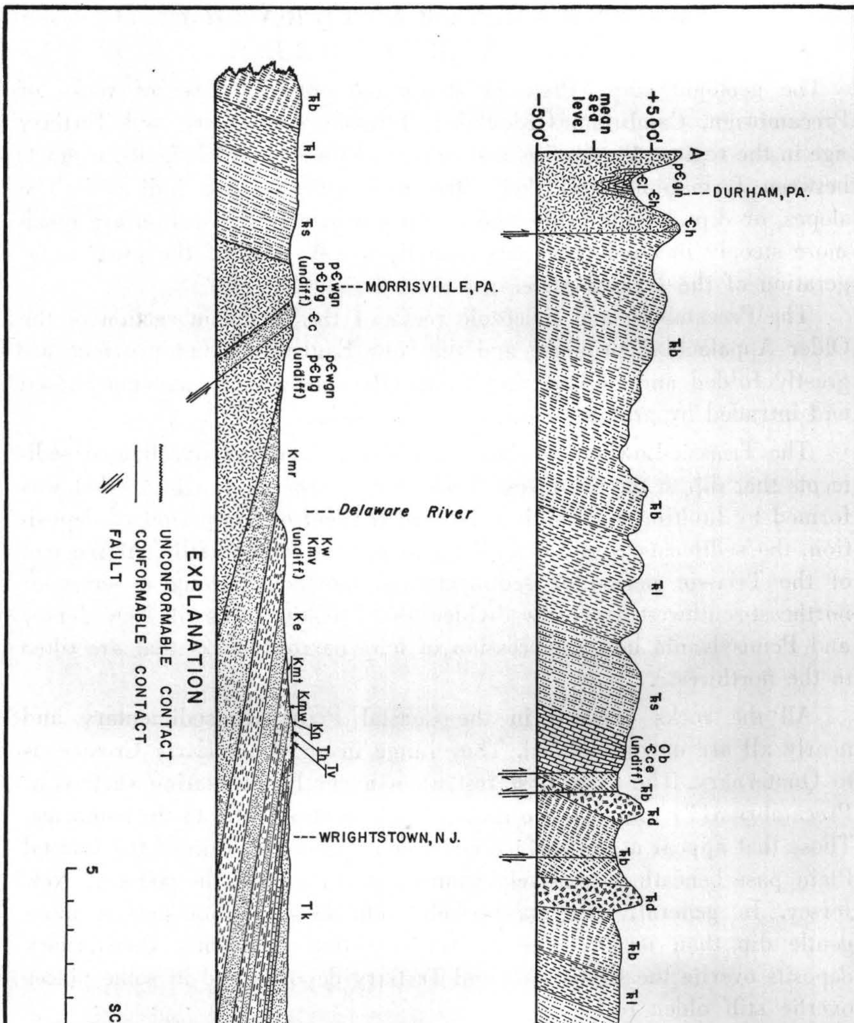

Figure 5.—Structure section across region along line A-B on geologic map (Plate 1) indicating major faults, contacts between formations, and their structural attitudes. (See Plate 1 for explanations of formation symbols.) Vertical exaggeration 18x.

what is now the Coastal Plain and extended far beyond the present shoreline, while a shallow inland sea covered the region now occupied by the Appalachian Mountains. At first, the streams flowing from the high lands (called Appalachia by geologists) into the inland sea carried coarse materials such as sand, later consolidated and metamorphosed to sandstones and quartzites. These constitute what is known as the Chickies and Hardyston quartzites and various related sandstones and quartzites of Early Cambrian age (see table 6).

In Late Cambrian time and in Ordovician time, the streams ceased to transport great quantities of sediment, and the seas became clearer, permitting the deposition of limestones and dolomites, including those shown in table 6.

Sometime during the Precambrian or the early Paleozoic, a great thickness of sediments known as the Glenarm series was deposited in the 11-county region. These were subsequently metamorphosed to quartzite (Setters), marble (Cockeysville), and schist (Wissahickon).

If any sediments were deposited in the 11-county region during the remainder of the Paleozoic era, they have since been removed by erosion. By the end of the Paleozoic era (in Permian time) the inland sea was completely filled with sediment, probably in some places as much as 30,000 feet thick. Partly because of the weight of these sediments and partly because of pressure from the southeast, there occurred an episode of major uplift accompanied by folding and faulting, known as the Appalachian Revolution. This caused the sediments laid down during the Paleozoic in an inland sea to be uplifted into high mountains, the ancestral Appalachians. This uplift was followed by a long period of erosion.

During Triassic time, a series of elongated troughs was formed by faulting between the recently uplifted Appalachian Mountains and the remnants of old mountains to the east (Appalachia). Sediments were carried into these troughs or basins from both the east and west, and some 20,000 feet of sandstones, shales, and some limestones accumulated. During part of the Triassic period, the sediments were intruded by dikes and sills of diabase, and layers of extrusive igneous rock were deposited in the troughs.

The Triassic deposition was followed by another cycle of erosion extending through the Jurassic period into the Cretaceous period. This resulted in the erosion of the region to a nearly level plain.

Toward the close of the Early Cretaceous epoch, a deltaic mass of river sand with backbay silts and clays accumulated in northern Delaware and adjacent portions of Maryland. Fossil leaves, twigs, and tree trunks,

Table 6.—Stratigraphic table describing the formations in the 11-county region.

Era	*Period*	*Epoch*	*Formation or Group*	*Lithology*	*Thickness*
CENOZOIC	QUARTERNARY	RECENT	Alluvium	Mud, silt, and sand	0-50
			Eolian deposits	Sand, white	0-10
		PLEISTOCENE	Outwash (Wisconsin)	Sand and gravel	0-40
			Unconformity		
			Cape May formation	Sand and gravel, local clay	0-40
			Unconformity		
			Pensauken and Bridgeton formations undifferentiated	Sand and gravel	0-70
			Unconformity		
	TERTIARY	PLIOCENE (?)	Beacon Hill and Bryn Mawr gravel	Sand and gravel	0-20
			Unconformity		
		MIOCENE (?)	Cohansey sand	Sand, quartz, with occasional clay lenses	0-200
			Unconformity		
		MIOCENE	Kirkwood formation	Sand, mostly, some clay	65-190
			Unconformity		
		EOCENE	Manasquan marl	Sand, fine, mixed with greenish-white clay; glauconite	25
			Unconformity		
			Vincentown sand	Sand, limy; quartzose sand; glauconitic sand	25-100
			Hornerstown marl	Glauconitic sand and clay	30
			Unconformity		
MESOZOIC	CRETACEOUS	LATE CRETACEOUS	Red Bank sand	Sand, yellow and reddish-brown	0-20
			Navesink marl	Glauconitic clay and sand	3-40
			Mount Laurel sand	Sand, medium to coarse, some glauconite	5-60
			Wenonah sand	Sand, fine to medium	20-40
			Marshalltown formation	Clay, sandy, black to clayey, glauconitic sand	30-40

		Late Cretaceous	Englishtown sand	Sand, white and yellow, micaceous, slightly glauconitic	0-80
	Cretaceous		Woodbury clay	Clay, black, micaceous	50
			Merchantville clay	Clay, dark green, glauconitic	50-60
Mesozoic			Magothy formation	Clay, dark-colored, and sand, light-colored, alternating	25-175
			— Unconformity —		
			Raritan formation	Clay and sand, variegated, alternating	150-300
			— Unconformity —		
			Patapsco formation	Clay and sand, alternating	450
			— Unconformity —		
		Early Cretaceous	Patuxent formation	Clay and sand, alternating	350±
			— Unconformity —		
			Igneous intrusives	Dikes and sills of diabase	
	Triassic		Brunswick shale	Shale, red, and interbedded sandstone	6000-9000
			Lockatong formation	Shale, black, massive argillite	2000-4000
			Stockton formation	Sandstone, arkosic with interbedded shale	1000-5000
			— Unconformity —		
	Ordovician		Cocalico shale	Phyllite and slate, dark-colored	250±(?)
			— Unconformity —		
		Early Ordovician	Beekmantown group	Limestone, shaly, impure, micaceous, blue	500±
		Early Ordovician and Cambrian	Conestoga limestone		
		Late Cambrian	Conococheague limestone	Limestone	500 (?)
Paleozoic	Cambrian	Middle Cambrian	Elbrook limestone	Limestone, light yellow	300±
		Early Cambrian	Ledger dolomite	Dolomite, light-colored, massive, and nearly pure	600

Era	*Period*	*Epoch*	*Formation or Group*	*Lithology*	*Thickness*
PALEOZOIC	CAMBRIAN	EARLY CAMBRIAN	Kinzers formation	Limestone, shaly or micaceous	150
			Vintage dolomite	Dolomite, granular, dark blue	300±
			Antietam sandstone	Quartzite; occasionally a schist or gneiss	150
			Harpers schist	Phyllite or quartzite	280-1000
			Chickies and Hardyston quartzites	Quartzite or sericitic quartz schist; Hellam conglomerate member at base of Chickies quartzite	100-1300
			—Unconformity—		
PROTEROZOIC	PRECAMBRIAN (?)		Igneous intrusives	Granites; granodiorites; gabbros; serpentine, etc.	
			Peters Creek quartzite	Schist or gneiss	2000
			Wissahickon formation	Banded micaceous schist or gneiss	5000-8000
			Cockeysville marble	Marble, light-colored, sugary	200
			Setters formation	Quartzite or quartzitic schist, white or grey	1000
	PRECAMBRIAN		Franklin limestone	Coarse white marble	200±(?)
			Baltimore and Pickering gneisses, Pochuck gabbro gneiss and Byram granite gneiss	Gneisses, highly metamorphosed	

associated with the bones of dinosaurs, attest to the continental origin of this material.

During Late Cretaceous time, the sea advanced over most of the Coastal Plain, reaching at least as far inland as the Delaware River. This marine invasion was probably oscillatory rather than continuous for there were times of lesser and greater submergence as well as episodes of complete withdrawal.

There were various invasions and withdrawals of the sea in the Coastal Plain throughout Tertiary time, but none of these submergences was as extensive as those of the Cretaceous.

During the early Pleistocene, extensive river sands and gravels were deposited over much of southern New Jersey. They make up the Bridgeton and Pensauken formations and may represent several early glacial and interglacial stages .

During the last interglacial stage, sea level was some 30 feet higher and submerged the low lands along the coast. The resulting marine deposits comprise the Cape May formation. Upstream they merge with sands and gravels of fluviatile origin.

After the deposition of the Cape May formation, the sea withdrew and erosion began again. With the advance of the Wisconsin ice sheet into northern New Jersey and Pennsylvania, glacial meltwaters deposited outwash material in stream and river valleys, especially in the Delaware River valley. As the ice melted, sea level rose, and a large portion of the Coastal Plain was again submerged. Recent measurements indicate that sea level is still rising.

HYDROLOGY OF THE REGION

GENERAL

The ground-water hydrology of any region is an integral part of its overall hydrology. It is appropriate, therefore, to consider broadly the hydrology of the 11-county region and how it is affected by such factors as the climate, geology, topography, and vegetative cover. The "hydrologic cycle" is the general term used to designate the overall circulation of water through the atmosphere, through the interstices of the earth, and over its surface. It includes the transfer of water from the atmosphere to the surface of the earth and the return of water to the atmosphere by evaporation and by the transpiraion of vegetation. (The combined effects of evaporation and transpiration are frequently referred to as "evapotranspiration.") The earth's total water supply, which is essentially constant in quantity, is repeatedly purified and made available for reuse by the processes of the hydrologic cycle.

Three great reservoirs of water, from which and to which water moves in the course of the operation of the hydrologic cycle, are the atmosphere, the oceans, and the interstices of the earth. They are the common meeting grounds and storage places for waters from diverse sources. The atmosphere is the medium through which water is transferred most widely from one part of the earth to another. It also stores great quantities of water, releasing local excesses largely as precipitation, and is replenished by evaporation and transpiration. The oceans contain by far the largest single part of the earth's total water supply. They are the end level and reservoir toward which streams flow and into which most stream systems discharge. Through evaporation, they are a major source of atmospheric water. The interstices of the earth receive great quantities of water from precipitation and from bodies of surface water and store it either briefly or for very long periods. They discharge water both to the atmosphere and to bodies of surface water.

The total annual precipitation, or its average over a period of years, is a primary measure of the water resources of a region. It is not necessarily, however, a measure of the water constantly available for human use because the rate of precipitation is not uniform from year to year and within single years. Furthermore, the "losses" to evaporation and transpiration generally occur before man has an opportunity to convert precipitation to water supply. These losses vary widely from place to place.

Evapotranspiration amounts to about half the average annual precipitation in the 11-county region. This conclusion was reached by examining the long-term stream-flow records for drainage basins from which there appears to be no significant loss of water except to evapotranspiration. The Delaware River basin above Trenton was preeminently such a basin prior to the diversions to New York City. The average annual precipitation in the basin was approximately 42 inches a year. The average annual stream flow at Trenton was equivalent to approximately 24 inches of water over the drainage basin or a little more than half the precipitation. Similar figures for smaller stream basins within the Appalachian Highlands part of the 11-county region confirm this conclusion. Stream-flow and precipitation records indicate that evapotranspiration in the Coastal Plain is generally somewhat higher than in the Appalachian Highlands, and a little more than half the average annual precipitation.

All the water left after the demands of evaporation and transpiration have been met is available for human use. However, this residual quantity fluctuates widely from year to year and from season to season. The most valuable water resources are those that are continually available. If there are adequate storage facilities, either natural or man made, the continually available yield would be the difference between the average precipitation and the average evapotranspirative losses. In the 11-county region this would be about 21 to 24 inches per year, or a little more than 1 mgd (million gallons a day) per square mile. Unfortunately, adequate storage is not always available so that the continual yield may be much less. This is particularly true in the Appalachian Highlands part of the region where storage is restricted mainly to surface reservoirs. In the Coastal Plain part of the region, however, the storage capacity of the better aquifers equals or approaches the necessary magnitude. Consequently, the potential yield of some of these aquifers may be considered to be approximately 1 mgd per square mile of intake area. The storage capacity of some major aquifers in the Coastal Plain is limited by the size or sorting of the mineral grains that compose them, and they may not be capable of yielding such large continuous supplies.

Water is generally appropriated for human use either as it moves across the surface of the land (surface water) or as it passes through the interstices of the earth (ground water). Under some conditions, ground water flows into the streams of an area. This is the normal pattern of movement in the 11-county region. Under different conditions, such as occur naturally in arid regions or may be induced by heavy withdrawals of ground water in humid regions, water moves from the streams into the ground. In some places, therefore, it is possible to choose different methods of withdrawal of the same water, either by pumping from wells and thus reducing the streamflow and evaporative losses, or by withdrawing water from the streams perhaps using surface reservoirs, which increase evaporative losses. This is particularly true in the Coastal Plain part of the region where conditions are most favorable for the interchange of water between the aquifers and the streams and other bodies of surface water. It is important to recognize, however, that the total quantity of water available is limited by basic hydrologic factors.

GROUND-WATER HYDROLOGY

OCCURRENCE OF GROUND WATER

All water that occurs below the surface of the ground is subsurface water (Meinzer, 1923) and is thus, strictly speaking, ground water. It is customary, however, to think of ground water as that part of the subsurface water that is recoverable for human use. The materials beneath the land surface are divided into two main zones on the basis of their relative water contents. In the *vadose zone* or *zone of aeration*, the voids between the mineral particles are filled partly with air and partly with water. In the underlying *phreatic zone* or *zone of saturation*, all the voids between the mineral particles are filled with water. The top of the zone of saturation, as defined by Meinzer, is the *water table*. The position of the water table is indicated by the level at which water stands in a well tapping the zone of saturation.

The water in the vadose zone is not available for water-supply purposes until it has percolated down to the water table. Even below the water table, a part of the water adheres to the mineral grains and will not drain out under the influence of gravity. The part of the water that does drain out may be as high as 30 per cent or more of the total volume of the aquifer in a coarse, well-sorted sand, or it may be practically zero in a clay or other fine-grained rock. The ratio of volume of water yielded by gravity drainage to original saturated volume of the material is termed its *specific yield*.

Ground water is said to occur under *water-table conditions* if the top of the saturated portion of the aquifer is at atmospheric pressure. Such a condition occurs in a bed of sand, or other permeable rock, the lower part of which is saturated with water and the upper part of which is unsaturated and exposed to the atmosphere.

Ground water occurs under *artesian conditions* if the water at the top of the aquifer is under hydrostatic pressure. Such a condition occurs in an aquifer that is confined beneath an impermeable or relatively impermeable layer of material at a level lower than that of the water table in the intake area of the aquifer.

The occurrence of water under artesian or under water-table conditions affects the method of its withdrawal and the interference between wells and well fields. An artesian aquifer is completely saturated from bottom to top and may remain so even after the hydrostatic pressure has been lowered considerably. The withdrawal of water from an artesian aquifer results in a decline of the hydrostatic pressure at the point of withdrawal that is quickly transmitted to considerable distances.

An aquifer under water-table conditions is generally not saturated for its full thickness. The withdrawal of water results in a lowering of the water table at and near the point of withdrawal and an actual removal of water from storage in the aquifer there. The effect is transmitted slowly to other parts of the aquifer because it involves dewatering and the actual movement of water through the aquifer before the levels at remote points can be lowered.

Factors Affecting the Occurrence of Ground Water in the Region

The availability of ground water in the 11-county region is determined largely by the geology and topography. Climatic and other controlling factors do not vary enough from place to place in the region to make significant differences. From the standpoint of availability of ground water, the position of an area either northwest or southeast of the Fall Line is probably the most significant single factor. The Fall Line separates not only physiographic provinces but what may be considered ground-water provinces. To the northwest, in the Appalachian Highlands, the supplies available from wells are meager to moderate. To the southeast, in the Coastal Plain, they are moderate to very large.

The consolidated rocks of the Appalachian Highlands yield water almost entirely from secondary openings such as weathered zones, cracks, and solution openings that occupy only a very small part, probably one per cent or less, of the total volume of the rocks (Barksdale and others, 1943). Even the best aquifers in consolidated rocks, those in which the secondary openings are larger and more numerous, generally store only a small quantity of water relative to their total volume. The unconsolidated rocks of the Coastal Plain, on the other hand, store large quantiies of ground water between their mineral grains. In the better aquifers, the available water may be from 10 to 30 per cent of the volume of the aquifers. The Coastal Plain aquifers generally transmit water much more freely than the aquifers of the Appalachian Highlands.

The steeper slopes in the Appalachian Highlands favor more rapid surface runoff of precipitation and allow less time for infiltration than the gentler slopes of the Coastal Plain. However, this does not usually limit the availability of ground water in the Appalachian Highlands because the limitations imposed by the capacity of the rocks to store and transmit water are generally more stringent. In many storms, the limited storage capacity of the hard-rock aquifers above the water table is completely filled (over considerable lowland areas) so that subsequent precipitation must run off. On the other hand, the large storage capacities of the Coastal Plain aquifers are seldom exceeded. The difference in the storage capacities of the aquifers in the two parts of the region results in a greater reserve of ground water in the Coastal Plain, and in higher flood flows and lower dry-weather flows in the streams of the Appalachian Highlands. A comparison (Barksdale and Remson, 1955) of the extremes of flow in two watersheds adjacent to the 11-county area for the same period of record is significant. In the watershed of the Great Egg Harbor River, which drains an area of the Coastal Plain, the maximum observed stream flow was 75 times the minimum observed flow. In the watershed of the Neshanic River, which drains a part of the Triassic Lowlands, the maximum observed flow was 29,000 times the minimum.

In hard-rock aquifers that yield water mainly from cracks and other secondary openings, the best yields of water are generally obtained relatively near the surface. The cracks in the rocks are apt to be larger and more numerous near the surface due to the effects of weathering. Furthermore, with increasing depth, the load of the overlying materials increases, and the resulting pressure tends to close the cracks. Therefore, as a *general rule* in the Appalachian Highlands part of the 11-county region, wells should not be drilled deeper than about 300 feet. If adequate yield cannot be obtained in a drilled well at one site, usually productive cracks are more likely to be encountered at moderate depths at another nearby site rather than by continuing to drill to greater depth. This rule should be applied in the light of geologic knowledge because the average depth of weathering and of productive cracks varies from aquifer to aquifer and from locality to locality. In some aquifers the probability of a successful well diminishes at depths greater than 150 feet, whereas in others it may be wise to drill to as much as 500 feet or more. The secondary openings are frequently more numerous and larger in the valleys, and the water table is closer to the surface there than on the divides. Other things being equal, therefore, successful wells tapping the hard-rock aquifers are somewhat more numerous in valleys than on high ground.

In contrast, most of the aquifers of the Coastal Plain are widespread and relatively uniform. The depth to a given aquifer at a specific locality can be predicted roughly on the basis of its dip and the position of its outcrop. The yield is not dependent upon the depth of weathering but upon the permeability and storage capacity of the granular materials composing the aquifer. Hence the development of a moderate supply of water from wells—and in some aquifers of large supplies—is reasonably well assured.

FLUCTUATIONS OF WATER LEVELS IN WELLS

Records of fluctuations of water levels in wells are among the most useful means of determining the availability of ground water. The level of the water in most wells is fluctuating almost continually. Among the more common causes of fluctuation are: the recharge of the aquifer, the discharge of ground water from it, fluctuations in atmospheric pressure, and the loading or unloading of the land surface above the aquifer as by tides or even by the movement of heavy trains. Among the more unusual causes of fluctuations of ground-water levels are such phenomena as earth tides and earthquakes. Frequently more than one of these causes operates simultaneously. It is beyond the scope of this report to discuss all the causes and their effects on water levels in detail, but it should be evident that an analysis of

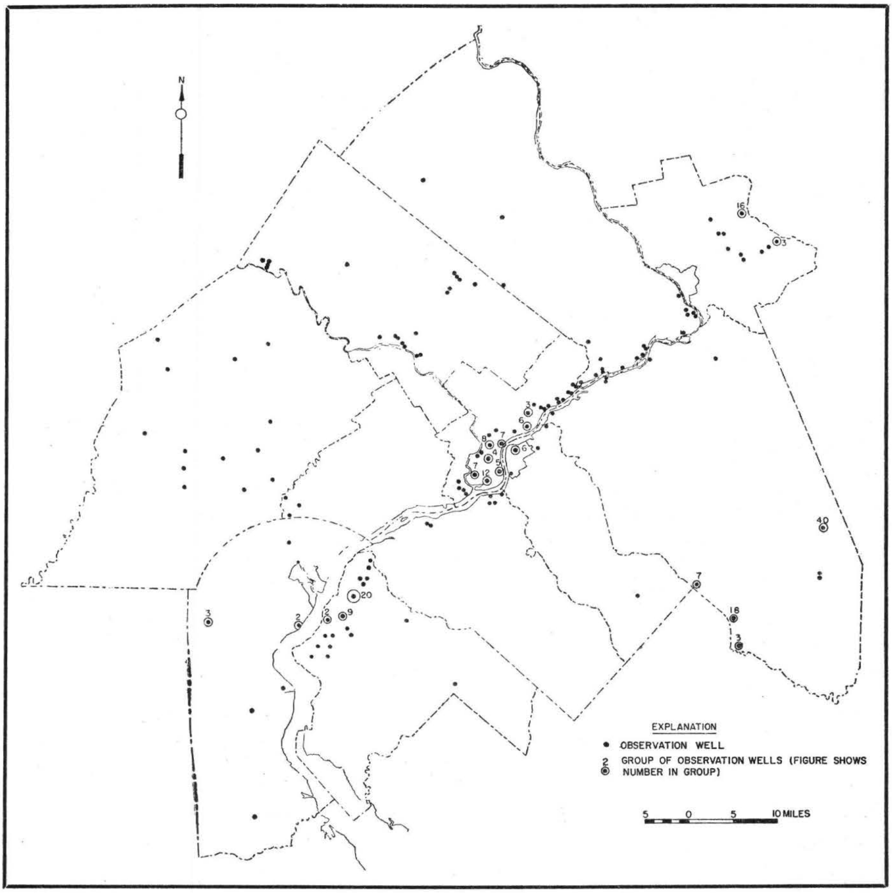

Figure 6.—Map showing network of observation wells in the 11-county region.

water-level fluctuations with respect to their causes is of great value in the study of aquifers and their utility.

The observation of water levels in wells has always been an integral part of the ground-water investigation in the three states that include parts of the 11-county region. It is fortunate that this is so because the value of most records of water levels increases with the length of the record. Some of the longest and most complete records of ground-water levels in the United States are from wells in New Jersey. Within the 11-county region, the records for one well at Camden, N. J., have been maintained continuously for more than 30 years. Since the initiation, in 1949, of the investigations that preceded this report, the water-level program in the region has been greatly expanded so that in 1957 there were more than 250 observation wells in use in the region. (See figure 6).

Records of water levels and of their fluctuations are useful to the hydrologist in many ways. The rate of ground-water movement in a homogeneous aquifer is proportional to the hydraulic gradient. It is possible, by means of suitable observations of water levels, to determine the general direction of ground-water movement. The rate of movement can also be determined if adequate information is available as to the permeability of the aquifer. Conversely, records of the fluctuations of ground-water levels studied in connection with records of pumping from wells or with some of the other causes of fluctuation may be used to determine the physical characteristics of aquifers such as their permeability and specific yield. Water-level records also indicate whether the aquifer is under water-table, or artesian conditions. The dry-weather flow of unregulated streams is maintained entirely by ground-water discharge which occurs at a higher rate when ground-water storage is high. It is possible, therefore, from an analysis of records of ground-water fluctuations in water-table aquifers to predict for a few weeks in advance the base flow of the streams they maintain (Merriam, 1948).

For water-table aquifers records of ground-water levels indicate the seasonal and long-term trends in the water storage. They provide an index of the net effects of recharge and discharge, both natural and artificial. Shown graphically in figure 7 are selected, typical, long-term records of water levels in wells in the report area. At the top of the graph is shown the combined record of two wells tapping the water table, at Bally, Pa., in the Appalachian Highlands, just outside the region. Below it is the record of a water-table well in the Coastal Plain, the Penn State Forest well, in Burlington County, N. J. Both records show that the long-term trend of the water levels, where not affected by pumping, has been horizontal, neither rising nor declining. They also show a typical seasonal fluctuation with high water levels in the winter and spring, and generally low levels in the summer and autumn. The rates of precipitation during the summer months are normally at least as high as during the winter months in the 11-county region. However, during the summer, much of the water from precipitation is removed from the soil by vegetation. Thus, only when vegetation is inactive does the rate of ground-water recharge consistently exceed the rate of natural ground-water discharge, causing the water table to rise. In some very wet summers, the usual summer decline is not as marked. In warm, dry autumns, the decline is accentuated.

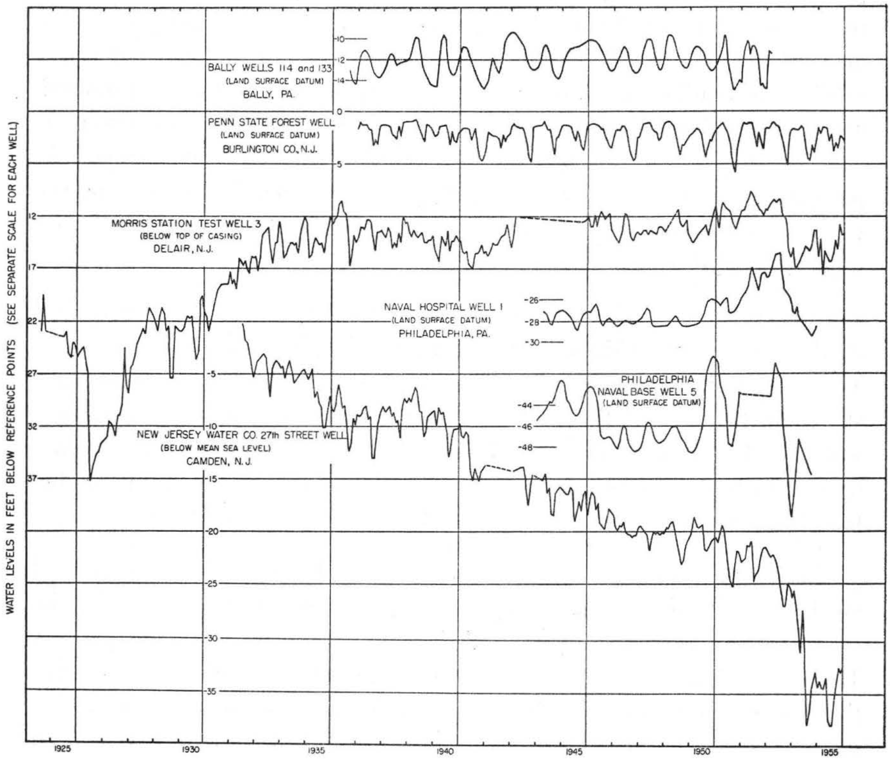

Figure 7—Graphs showing long-term fluctuations of water levels in selected observation wells in or near the 11-county region.

The other four records shown on figure 7 are for wells tapping artesian aquifers that are subject to fluctuating withdrawals of water from other wells in their general vicinity. Record for the Morris Station well shows a decline of the piezometric surface in response to nearby heavy pumping from 1923 to 1926 and thereafter a rising trend, as much of the pumping was progressively transferred to more distant areas. Record for the New Jersey Water Co. well shows a declining trend throughout the record period in response to gradually increasing pumpage in the vicinity, with an accentuated downward trend beginning in 1952 when large new wells were put in service nearby. Records for the Naval Hospital and the Naval Base wells also exhibit fluctuations related primarily to pumping in the surrounding areas. These four records show a rudimentary seasonal fluctuation as well as the long-term fluctuations, relating to seasonal changes in pumpage rather than in recharge. The use of water is heaviest in the warmer months to meet the demands for cooling, lawn sprinkling, and some industrial uses.

Figure 8 shows the fluctuations of water levels in an artesian well at the New York Shipbuilding Corp. in Camden for the year 1952. The record shows the effects of pumping nearby wells, which produce sharp fluctuations of three or four feet, and of pumping more distant wells which produce very minor fluctuations. The seasonal trend, upon which the fluctuations due to local pumping is imposed, is due largely to heavier regional pumping in the warmer months.

Figure 9 shows the fluctuations of water level in an artesian well on Pettys Island, Camden, N. J., for November 1 to 15, 1954. The record shows the effects of tidal loading upon the artesian aquifer. The fluctuations in this well have an amplitude of approximately half that of the tide in the river nearby. Except for this difference in amplitude, the water levels in the well faithfully reflect the tidal fluctuations with a slight time lag. The regional seasonal trend of water levels is upward in November. Sharp declines such as those on November 3 to 4 are due to the operation of a well some distance from the observation well.

These few graphs demonstrate the importance of observations of water levels in ground-water hydrology. Analyses of fluctuations of water levels in wells yield valuable information about the water-bearing characteristics of aquifers. In this report, the conclusions resulting from many such analyses are presented without the detailed records.

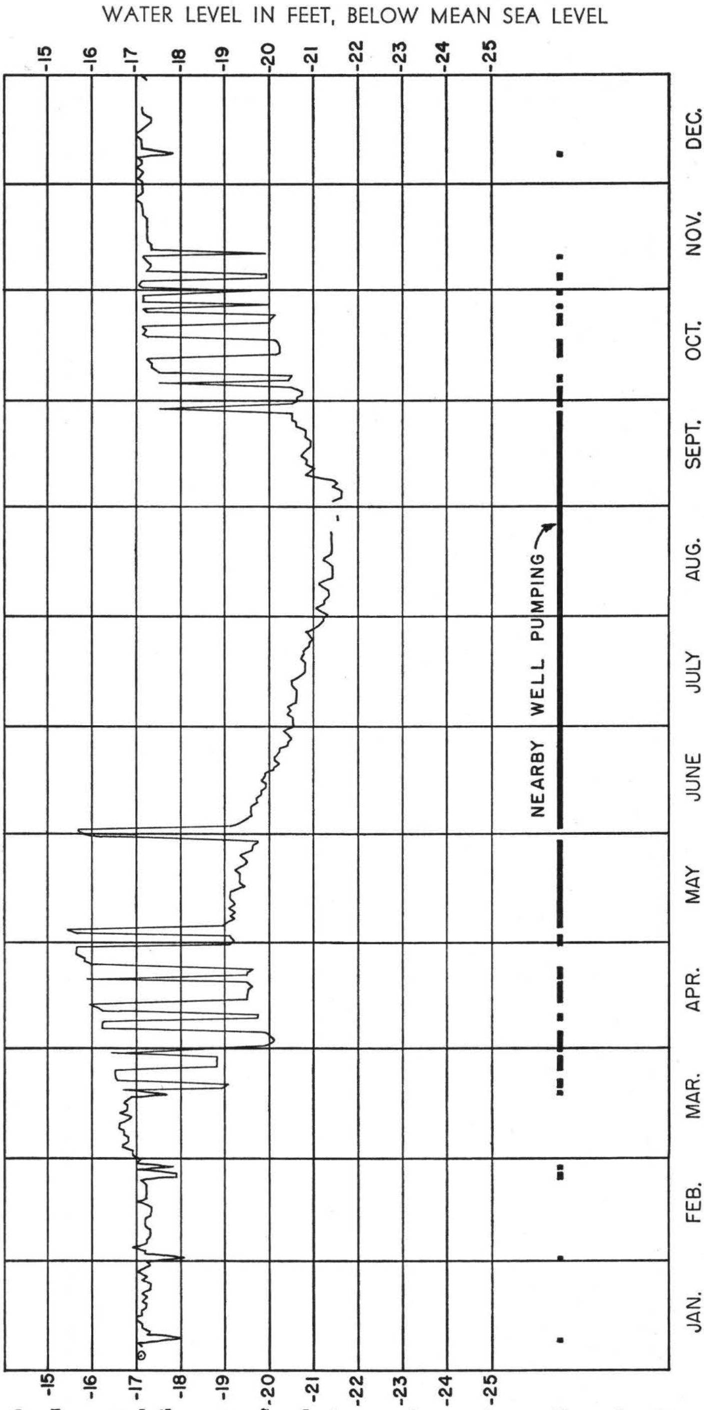

Figure 8—Lowest daily water levels in an observation well at the New York Shipbuilding Corporation's plant in Camden, N. J., 1952

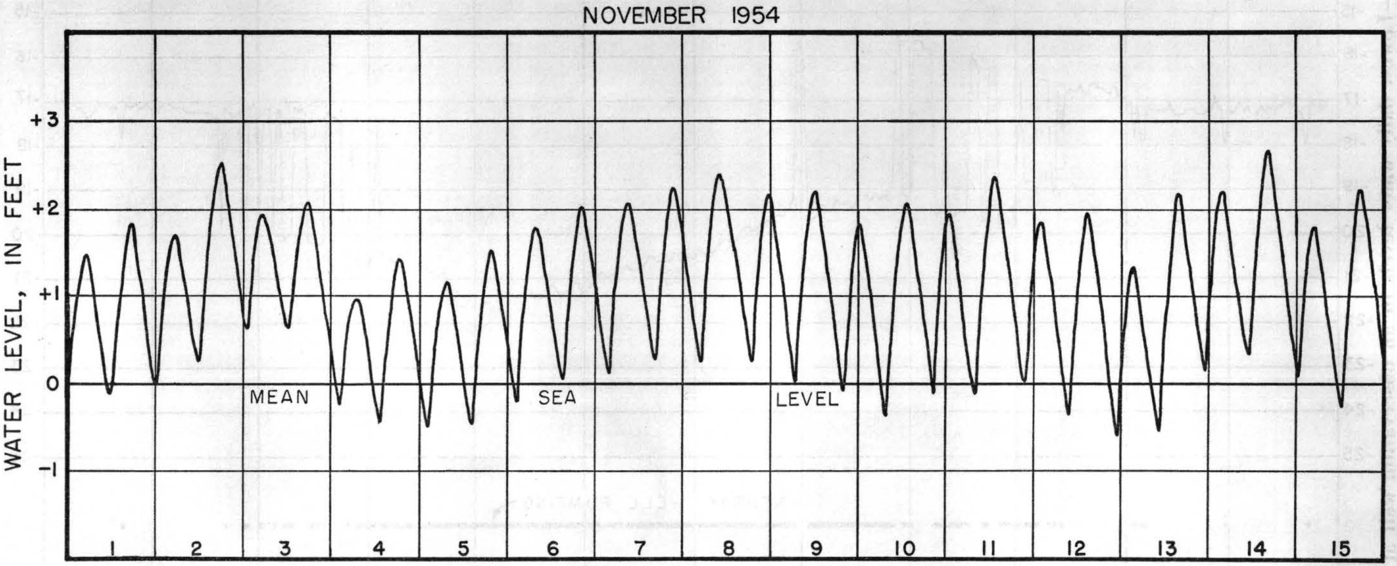

Figure 9.—Graph showing tidal fluctuations of water levels in Cities Service Co. Well 1 on Pettys Island, Camden, N. J.

RECHARGE OF GROUND WATER

All the available ground water in the 11-county region probably comes from precipitation within the region or immediately adjacent to it and from recharge within the region from bodies of surface water such as the Delaware River. There is no basis for the common supposition that some of the ground water in the region comes through underground channels from the Pocono Mountains or from some other remote source. As already indicated, the total precipitation is not available for ground-water recharge because of losses to evapotranspiration and because some part of it may run off via the land surface for various reasons. An aquifer that is full of water obviously cannot receive additional recharge. Similarly, water cannot enter ground that is solidly frozen. If the infiltration capacity of the soil has been exceeded, some water will run off. Potential ground-water recharge that runs off the intake area of an aquifer, for any of the foregoing reasons, is sometimes referred to as *rejected recharge.*

Not all the water that enters (infiltrates) the soil becomes ground-water recharge. During the season when plants are active, much water is held in the soil, absorbed by the roots of plants, and discharged to the atmosphere by transpiration. As the soil is dried, it releases first the water that is least strongly held by capillarity and molecular attraction. Thereafter, it gives up progressively more and more strongly held particles of water. The roots of plants exert a pull on the water in the soil that is much stronger than that of gravity. Consequently, in a given time they reduce the moisture content of the soil much more than it would have been reduced by gravity alone. Thus, during prolonged periods of drought, there develops a deficiency of moisture in the soil. Normally, it is necessary to replenish the supply of moisture in the soil and eliminate this *soil moisture deficiency* before any large part of the infiltration can move downward to recharge the ground-water reservoir. Because of these factors, precipitation that would produce substantial recharge when the plants are dormant and there is little or no soil-moisture deficiency, may produce relatively little recharge during the growing season.

Soil-moisture deficiencies have a similar effect on the relation between precipitation and runoff. After a prolonged drought, a storm of the size and intensity that would normally cause flood runoff may be absorbed almost entirely by the soil and result in little or no runoff. The great flood on the Delaware River in 1955 was produced by two hurricane storms in rapid succession, the first of which did little more than satisfy the soil-moisture deficiency so that nearly all of the second could run off.

Ordinarily, in a humid climate such as that of the report region, the water table slopes toward the streams and ground water is discharged into the streams. However, if the gradient of the water table is reversed by artificial withdrawals of ground water in the vicinity of a stream, water will flow from the stream into the aquifer. This results in the phenomenon known as *induced recharge.* Induced recharge has become an important factor in maintaining the yield of heavily pumped wells or well fields in many places along the Delaware River.

Artificial recharge is the deliberate introduction of water into an aquifer. It may be accomplished by spreading water on the land surface or by injecting it into the aquifer through wells or recharge galleries. Relatively little artificial recharge is now being practiced in the report area. A limited quantity of cooling water is returned to the ground, especially in parts of New Jersey where it is required by law or administrative regulation. There are also probably isolated cases of water disposal into wells. This is a form of artificial recharge, although it may be a highly objectionable form, depending upon the nature of the wastes.

MOVEMENT OF GROUND WATER

Detailed discussion of the probable directions and rates of movement of ground water through the major aquifers in the 11-county region will be presented with other factors relating to these aquifers. In general, however, the movement is from the intake areas toward the streams and other bodies of surface water. Ground water moves in accordance with well-defined natural laws. The movement of ground water takes place through an intricate network of voids within a solid framework. The properties of the fluid and of the framework and the forces of gravity and molecular attraction control the movement. The fluid properties that are most significant are viscosity, density, and their interrelation with temperature. The two most important properties of the framework are its porosity and its permeability. *Porosity* is a measure of the volume of voids in relation to the total volume of the framework material and is expressed as a percentage. *Permeability* is a measure of the facility with which fluids flow through the voids. The permeability of an aquifer may be different in different directions. The horizontal permeability of an aquifer is frequently different from and greater than its vertical permeability.

The ability of an aquifer to store, transmit, and yield water depends upon several important aquifer properties which may be defined as follows:

The *coefficient of storage* of an aquifer is the volume of water it releases from or takes into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface. It might amount to 25 percent in a water-table aquifer, where most of the water is obtained by dewatering the material, or it might be a small fraction of one percent in an artesian aquifer, where the water is yielded by elastic adjustment to pressure changes.

The *coefficient of permeability,* as defined and used by the Geological Survey, is the rate of flow of water in gallons per day through a cross-sectional area of aquifer of one square foot under a hydraulic gradient of one foot per foot at a temperature of 60° F. (Meinzer, 1923, p. 44). For field use the correction to 60° F. is neglected, and the "field coefficient" expresses the flow of ground water at the prevailing water temperature. Measured permeabilities of the Farrington sand member of the Raritan formation at Parlin, N. J., vary between 210 and 3,500 gallons per day per square foot (Barksdale, 1937). On the other hand, the measured permeability of a silty clay was 0.2 gallons per day per square foot (Wenzel, 1942).

The *coefficient of transmissibility,* as defined and used by the Geological Survey, is the rate of flow of water in gallons per day through a vertical strip of aquifer one foot wide, extending the full saturated thickness of the aquifer, under a hydraulic gradient of 100 percent at the prevailing water temperature (Theis, 1935). It is equal to the product of the thickness of the aquifer and the field coefficient of permeability. At Camden, the aquiclude (confining layer) between the two major aquifers in the Raritan and Magothy formations has a transmissibility in the order of 0.4 gallons per day per foot, whereas the aquifers above and below it have an average transmissibility of about 45,000 gallons per day per foot, more than 100,000 times as great. These important properties have been evaluated for different aquifers in the 11-county region by means of field and laboratory determinations.

Ground water moves in the general direction of decreasing head. Thus, movement usually occurs from high-level outcrop areas to low-level outcrop areas. It is also toward areas where ground-water heads have been lowered by natural or artificial withdrawals of water. Similarly, it is away from areas where ground-water heads have been raised by natural or artificial recharge.

The confining layers above and below an artesian aquifer have a relatively small coefficient of transmissibility as shown above for the

Raritan and Magothy formations at Camden. Thus, the quantity of water moving through the confining layer in a given time under a given hydraulic gradient would be slight in relation to the quantity that would move through the aquifer in the same time and under the same gradient. In time, however, millions of gallons of water might pass through each square mile of aquiclude, into or out of an aquifer, depending upon the gradients.

The direction of flow between an aquifer and an aquiclude, as between two parts of an aquifer, may be reversed by pumping. Assume that an aquifer is losing water to or through an aquiclude because the head is greater in the aquifer. If, by pumping, the head in the aquifer is lowered below that in the aquiclude, the direction of flow will be reversed, and water will move into the aquifer as recharge. The effect of such recharge may be observed and analyzed in a properly organized aquifer test using a single pumped well and several observation wells.

DISCHARGE OF GROUND WATER

Natural Discharge

Ground water is discharged from aquifers both naturally and artificially. Natural discharge includes the movement of water from the aquifer into springs and seeps; directly into streams or other bodies of surface water; and into other aquifers. A large amount of ground water is also discharged into the atmosphere by evaporation and by the transpiration of plants whose roots extend to the water table or to the capillary fringe. Artificial discharge includes all discharge that is the result of human activity.

Wherever the water table intersects the land surface, ground water is discharged as springs or seeps. Seeps occur as marshy or swampy ground, generally at a break in the slope of the land surface. Some of the stronger seeps develop a drainage channel which may in time concentrate the flow from the seep and convert it into a spring. Springs are points of concentrated discharge of ground water. The flow of springs varies from much less than a gallon a minute to many thousands of gallons a minute. In the eastern part of the United States the very large springs are usually derived from solution openings in limestone aquifers.

A large part of the natural ground-water discharge in humid areas is directly into streams, lakes, the ocean, or other bodies of surface water, through their banks and bottoms. In such areas, the water table normally slopes toward the streams and other surface-water bodies, and the flow of ground water is toward them. Ground water is discharged through all permeable parts of the stream bottom that are in contact with the aquifer. In permeable materials, the surfaces of streams and other bodies of surface water generally coincide with the water table along their margins. Dry-weather flow in all unregulated streams in the humid eastern part of the United States is almost exclusively ground-water discharge.

In areas where the capillary fringe extends up to the land surface, evaporation occurs from the land surface, and capillary forces tend to replenish the moisture at the surface as fast as it is evaporated. In such areas and also in areas where the water table is somewhat deeper but where it or the capillary fringe are still within reach of plant roots, the transpiration of plants removes water from below the water table. If the water table is sufficiently near the land surface to make the water readily accessible to the roots of plants, and the climate is favorable for plant growth, the ground-water supply may be depleted as effectively as by pumping a well field. The withdrawal of water from the ground by the roots of plants may result in a diurnal fluctuation of the water table (Barksdale, 1933) because the plants tend to use water most actively during the warmer daylight hours. Such fluctuations are very similar to those produced by intermittent pumping from wells.

Artificial Discharge

Ground water is discharged artificially by human activity. A part of this discharge is incidental to activities such as construction work and land drainage. A part is for the purpose of obtaining water supplies. In mines, tunnels, highway and railway cuts and similar excavations, the disposal of ground-water discharge sometimes becomes a serious problem. Land-drainage projects are also primarily concerned with the removal and disposal of excess ground water. In water-supply installations, on the other hand, the emphasis is upon establishing ground-water discharge where water is needed and upon the permanency of discharge rates and the reliability of the supply. In the 11-county region there are very large quantities of artificial ground-water discharge of both types, but those designed for water-supply purposes are of greater regional significance.

In appraising quantitatively the ground-water resources of the individual formations in the region, two considerations are important: (1) the quantity of water that may be expected from individual wells and (2) the dependability of the yield of the aquifer in terms of long continued use. The first depends upon the local water-bearing properities of the aquifer and may strongly influence selection of the method of development. The second may involve geologic and climatic conditions covering broad areas and long periods of time, particularly if the areas of intake are at considerable distances from the areas of withdrawal, as in some artesian aquifers.

The prolonged withdrawal from an aquifer of more water than is potentially available for recharge will result in some diminution of the water that many or all users can economically pump. It is of economic and hydrologic importance, therefore, that the development of an aquifer or any part of it proceed with caution. Overdevelopment may be indicated by serious and continuing declines of water levels, or undesirable changes in the chemical character of the water through induced inflow of water of poorer quality. In this event the factors that affect the yield of the aquifer should be analyzed before proceeding with additional large or continuing withdrawals of water. If the analysis shows that the existing diversions of water from an aquifer are excessive, it may be prudent to reevaluate the needs and ascertain whether any reduction in use is feasible. Of course, the most reasonable approach is to appraise the potential yield of an aquifer long before any overdevelopment occurs, so that its maximum utilization may proceed in accordance with sound principles of economics and aquifer management.

Optimum yield and the management of aquifers

The *optimum yield* of an aquifer is the rate at which it is found feasible and desirable to withdraw water. The feasible rate of withdrawal may be influenced by the capacity of the aquifer to intercept, to store, or to transmit water, and by the danger of contamination that may adversely affect the quality and hence the utility of the water. Of significance also may be the availability of water for recharging the aquifer. Although the feasible rate of withdrawal is influenced, it is not necessarily immutably fixed by the physical character, shape, and position of the aquifer. Thus some relevant factors may be modified by human activity in such a manner as to increase or decrease the optimum yield.

The capacity of the aquifer to receive water may be improved by appropriate land-use practices that increase the infiltration capacity of the soil in the aquifer intake area. Usually, however, it is not the infiltration capacity that is the limiting factor but rather the *infiltration opportunity*, or the availability of water to filter into the soil. It is possible under some circumstances to increase the infiltration opportunity by providing additional water in such a way that it can percolate into the aquifer. This practice is called *artificial recharge* and may be accomplished either by spreading water on the surface of the aquifer intake area or by injecting it into the aquifer through wells or infiltration galleries. Obviously, artificial recharge is practicable only when additional storage space is available in the aquifer.

The physical properties of an aquifer, relating to the storage and transmittal of water, are fixed by nature. Little can be done to modify these factors except very locally as in the development of a well by surging or by such practices as chemical treatment or fracturing the rock with explosives or otherwise. The storage capacity of many good aquifers in the region is extremely large, permitting withdrawals at a uniform rate throughout seasonal or even longer fluctuations of natural recharge. In areas of heavy withdrawals, good aquifer-management practices may include artificial recharging during wet seasons in order to increase the potential uniform rate of withdrawal or the potential withdrawal during periods of heavy demand for water.

The amount of usable water that may be withdrawn from an aquifer may be adversely affected by the careless or willful disposal of objectionable substances that contaminate the water. The disposal of inadequately treated industrial wastes on the intake areas of aquifers or directly into aquifers through wells has, in some localities in the region, seriously damaged the quality of the water and rendered it unfit for some uses. Increased awareness of the serious consequence of such actions has greatly reduced the practice in recent years, but some flagrant examples still exist and may have to be controlled by regulatory action.

Salt-Water Intrusion

Salt-water intrusion is the advance of salt water into aquifers normally yielding fresh water. The danger of salt-water intrusion limits the withdrawals from some aquifers in the region, or from parts of them, more seriously than any other factor. Salt water may enter an aquifer from bodies of salt or brackish water, especially from the ocean or its arms. It may also be derived from other aquifers or from parts of the same aquifer that normally contain salt water. Salt-water intrusion occurs only as the result of some change in the head relations between the fresh-water aquifer and interconnected bodies of salt water. To a considerable degree, it may be controlled by manipulating artificial withdrawals of ground water and the resultant changes in fresh-water head. Under favorable conditions it can be forestalled by carefully applied artificial recharge.

Salt water is heavier than fresh water and tends to fill the bottom part of an exposed aquifer. It is normally drawn upward into or toward wells when the head of the fresh water is decreased by pumping. Where salt water and fresh water come in contact in a water-bearing sand, the change from fresh water to very salt water may occur in 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 the salt water may actually have been advancing for a long time.

Where salt or brackish surface water is in contact with a fresh-water aquifer as along some reaches of the Delaware River, 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 of the aquifer, and no salt water will enter. At some level, there might conceivably be a balance between the head of the fresh water and that of the salt water, so that no flow occurs in either direction. In order to exclude all tidal salt water from an 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 if the fresh-water head were kept high enough to cause flow out of the aquifer at all times except during the highest part of the tidal cycle.

WATER SUPPLY

An abundant water supply is generally available to the 11-county region despite a number of more or less acute problems. The region has a relatively high and evenly-distributed rainfall, and is located along or near the lower reaches of a large river. The region contains large reserves of ground water, and additional large reserves of ground water may be found in adjacent parts of the Coastal Plain. The chief problems are: quality of water, both bacteriological and chemical; local availability of water; distribution of water from source to consumer; and potential local overdevelopment of ground waters in some areas of heavily-concentrated pumpage.

SURFACE WATER

AVAILABILITY AND USE

Surface water is available in sufficient quantities for present and reasonably foreseeable future uses within or adjacent to the region, although the distribution in time and space is by no means uniform. This statement is made on the assumption that the waters of the Delaware River will continue to be available to the region as needed and at a satisfactory level of quality. Not precluded, of course, is the development of upstream sources on the Delaware River or its tributaries and the transportation of water from them into the region, which may soon be necessary.

The Delaware River at Trenton, N. J., had a 40-year annual average discharge, adjusted for storage and diversion, of 12,070 cubic feet per second, or about 7,800 mgd, according to U. S. Geological Survey measurements, (Water Supply Paper 1272, p. 220). Recent and proposed diversions of water in the upper Delaware River basin will reduce the average flow of the river in this region. However, the works constructed or planned for this purpose are designed to increase the minimum flows, thus assuring better conditions and a larger supply during critical periods of low flow.

For most purposes, the chemical quality of water is as important as the quantity available. Tolerances vary with different uses, but grossly polluted or highly mineralized water is of limited utility or value. Current and proposed pollution-abatement policies and practices should improve the quality of surface water in the region. However, the present quality of water in some streams is poor for various reasons. Untreated sewage or industrial wastes are dumped into many streams, but this practice is gradually being eliminated as a result of educational campaigns and legal action. Water from coal-mining and coal-washing operations formerly carried large quantities of culm (minute coal particles) into the Schuylkill River. During the past few years, the Schuylkill River restoration project has greatly reduced this type of pollution.

A source of serious contamination of the fresh surface waters of the region is salt water from the Atlantic Ocean, which moves upstream through the Delaware Bay into the lower reaches of the Delaware River and some of its tidal tributaries during periods of low streamflow. At times of very low flow, this problem of salt-water invasion may become acute in the Delaware River as far upstream as Philadelphia (Durfor and Keighton, 1954). The proposed deepening of the Delaware River channel may aggravate this problem although there is considerable evidence from model tests and other studies made by the U. S. Army Corps of Engineers that it may not have serious adverse effects. Extensive studies are still being conducted on this problem by the Corps of Engineers, by the U. S. Geological Survey, and by various other agencies, both public and private.

Both on the basis of population served and on the basis of total water use, the public water supplies of the region draw much more heavily upon surface-water sources than upon ground-water sources. The Philadelphia Bureau of Water supplies the city with an average of about 350 million gallons a day, about half of which is from the Schuylkill River and about half from the Delaware River. Five boroughs and three townships in Chester and Montgomery Counties use Schuylkill River water for public supply. The City of Chester and 11 other municipalities in Delaware County use surface water from Octararo Creek, a tributary of the Susquehanna River. Trenton is the only New Jersey municipality in the report region that uses surface water, drawing from the Delaware River. Wilmington, Delaware uses water from the Brandywine Creek, a tributary of the Delaware River that flows through the city. Wilmington supplies some of the area adjacent to the city. In Delaware, about 60 percent of the population within the region that is served by public supplies is furnished surface water; in New Jersey about 20 percent; and in Pennsylvania about 95 percent.

All the surface water used for public water supply in the region is treated in some way before delivery to the consumer. The degree of treatment depends, of course, upon the character of the raw water. In some places the treatment is very extensive; in others, it involves little more than chlorination.

Many industrial establishments located along the streams of the region obtain surface water through their own intakes. Some of this water is used for various types of processing and washing either with or without previous treatment. It is apt to be returned to the stream in a more or less polluted condition, depending upon the use made of it and upon degree of treatment that the effluent rceives. In general, however, industrial waste water is receiving increasingly more adequate treatment in this region. By far the largest part of the surface water used for industrial purposes is used for cooling. Steel and other metal processing mills use vast quantities of water for cooling the rolls that shape the hot metal. Some of this water is evaporated, but most of it is returned to the stream warmer and (depending upon the process and upon the subsequent treatment, if any) perhaps with a higher organic or dissolved mineral content. Vast quantities of water are taken from the streams by steam power generating plants and used for cooling in condensers. This water is generally returned to the stream essentially unchanged except for higher temperature. The industrial establishments that use the largest quantities of surface water are, of course, located along the larger streams.

In recent years, the increased interest in supplemental irrigation has resulted in the diversion of considerable quantities of surface water from the streams of the region. This water is drawn from whatever stream is adjacent to the fields to be irrigated and consequently is taken mainly from the smaller streams. In some localities serious problems are arising as to the riparian rights of different owners along the small streams.

GROUND WATER

AVAILABILITY

Very large supplies of ground water are available in and adjacent to the 11-county region. Nearly all the rocks of the region will yield some water to wells, but only the more productive ones yield large quantities. (See figure 10). In general, ground water is most abundant in the Coastal Plain, southeast of the Fall Line, and relatively less available in the area northwest of the Fall Line. However, many variations in

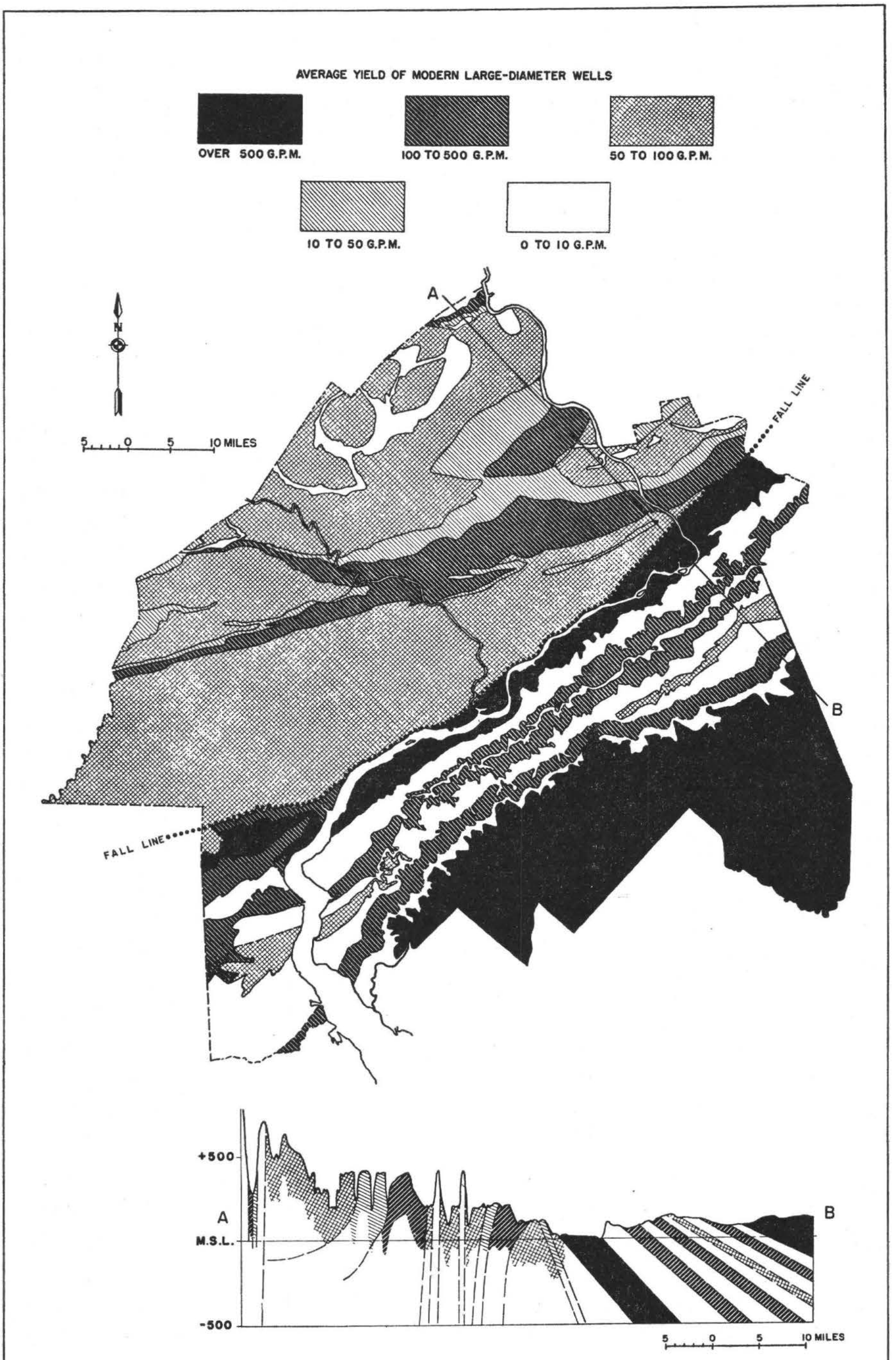

Figure 10.—Map and geologic cross-section showing the average water-yielding capacities of aquifers in the 11-county region.

yield occur throughout the region. The quantity and chemical character of the ground water available at any locality are closely related to the type of rock that contains the water. Therefore, an important phase of the investigations that preceded this report has been the study and evaluation of each geologic formation in the region to determine its water-bearing characteristics, its areal extent, and location within the economic reach of drilling. The individual formations are discussed in detail in a later section of this report.

The largest single reserve of ground water available for use in the region is that contained in the Cohansey sand in the central part of New Jersey, largely outside the region itself. It is essentially untapped and is capable of yielding very large quantities of excellent ground water. The magnitude of the potential supply has been estimated to be at least 1,000 mgd, but not all of this water would normally be available for use in the region. The use of a major part of this water in the industrialized lower Delaware basin will require extensive developments and long pipelines. The water supplies in the Cohansey should be cautiously developed and jealously protected. Its wise development will require careful planning based upon detailed basic information, most of which must still be collected.

On the basis of their present development, the aquifers in the Raritan and Magothy formations are the most important single source of ground water in the region. They underlie an intensely industrialized part of the region and currently yield more than 120 mgd to wells in this area. In many places along the Delaware River, conditions are favorable for inducing recharge to these aquifers from the river. Where this is so, the yield of ground water may be increased substantially. However, the quality of the ground water tends to approach that of the river water, and the permanency of a local supply of usable ground water depends largely upon the quality of the adjacent river water. The estimated reserve of undeveloped water from these aquifers is at least as great as the current rate of use so that they will probably yield a total of something like 250 mgd to wells in the region.

The potential yield of the remaining aquifers in the region is probably at least 500 mgd. Most of the forty or so formations in the region will yield some water to wells. They will not be discussed individually here, but all are described in some detail in a later section of this report. The more important aquifers are described briefly in table 7, and are listed in order of decreasing geologic age.

The important aquifers of the Appalachian Highlands are all hard rocks in which water occurs largely in cracks or solution openings. The more productive hard-rock aquifers are the Stockton formation, the

Cambrian and Ordovician limestones, the Brunswick shale, and the Wissahickon formation, in order of decreasing average yield to wells. The optimum yields of each of these aquifers depend upon their areal extent and upon a variety of other factors and are not estimated here.

The aquifers of the Coastal Plain are almost entirely unconsolidated sands and gravels, and water is stored in and transmitted through the primary pore spaces between the mineral grains. In general, the aquifers with the more uniform grain sizes have the highest storage capacity, and those with the largest openings between grains transmit water most freely. Thus, other things being equal, the better aquifers are those with coarse, well-sorted grains. The major aquifers of the Coastal Plain are relatively thin compared with the hard-rock aquifers, but they extend over wide areas. In the southeastern part of the region, it is possible to drill a well that will penetrate several aquifers. Most of the better Coastal Plain aquifers yield at least as much water to individual wells as the best of the hard-rock aquifers, and the yield from well to well is far more consistent. The most productive aquifers in the region are the Cohansey sand and the aquifers of the Raritan and Magothy formations. The other major aquifers of the Costal Plain are the Wenonah and Mount Laurel sands (which form a single aquifer), the Englishtown sand, the sands of the Patuxent formation, the sands of the Kirkwood formation, and the Vincentown sand. Sands and gravels of Pleistocene and Recent age are irregularly distributed throughout the Coastal Plain and are important as aquifers mainly along the Delaware River.

It should be emphasized that the estimates of potential yield given in this section and in this report are necessarily approximate. Much more detailed work is needed to determine the perennial yield of the important aquifers of the 11-county region. This work should be done in advance of major developments of ground water. New developments should be undertaken carefully and in the light of the most recent information. The water in the aquifers should be protected zealously against unnecessary contamination which may limit its utility. Where aquifers are exposed to salt-water intrusion, they should be developed with care in order to avoid loss of the supply.

USE

The present and future use of ground water is of vital importance to the 11-county region. The ground waters of the region are generally of good quality and of uniform temperature. Where geologic conditions are favorable, particularly on the Coastal Plain, ground water is usually available where needed without expensive transmission lines. The advantage of ground water for cooling alone is such that conversion to

Table 7.—Characteristics of the principal aquifers in the 11-county region

Name	*Geologic Age*	*Description*	*Yield of Wells in GPM*	*Remarks*
Baltimore gneiss	Precambrian	Dense, medium-grained, banded gneiss; includes graphitic schist facies. Invaded by granite and gabbro. Forms rolling uplands; weathers to fine sandy loam.	Min. 2 Max. 200 Avg. 45	An important source of rural, domestic, and small to moderate municipal and industrial supplies. Water occurs in the weathered zone near land surface, commonly from above a depth of 150 feet. Water generally contains less than 150 ppm of dissolved solids and is very soft.
Wissahickon formation and associated rocks	Precambrian (?)	Dense, medium- to coarse-grained mica schist or mica gneiss. Invaded by granite, gabbro, and serpentine. Forms rollings uplands; weathers to silty loam.		
Carbonate rocks undifferentiated	Cambrian and Ordovician	Highly contorted, thick-bedded, gray to blue dolomitic limestone; includes numerous siliceous beds and occasional thin beds of shale. Forms broad, flat valleys; weathers to light colored clay loam. Thickness 500 to 2000 feet or more.	Min. less than 1 Max. 1450 Avg. 25	An excellent source of large municipal and industrial supplies. Water occurs under both water-table and artesian conditions in solution openings which may occur to depths of 1,000 feet or more. Water is moderately mineralized and hard.
Stockton formation	Late Triassic	Irregularly bedded, light colored, coarse arkosic sandstone and conglomerate, brown siliceous sandstone, and soft red shale. Formation characterized by abundant arkose at the base, grading to siliceous sediments at the top. Forms gently rolling topography. Weathers to sandy clay loam. Thickness 3,000 to 5,000 ± feet.	Min. 1 Max. 900 Avg. 40	An excellent source of moderate to large supplis of water. Coarse materials are permeable and have some intergranular openings, but fine-grained rocks have a very low permeability that depends entirely on the size and number of secondary openings. Water occurs under both water-table and artesian conditions. Most wells more than 300 feet deep intercept one or more permeable zones containing water under artesian pressure. Water contains less than 300 ppm of dissolved solids, between 100 and 200 ppm of hardness. and less than 1 ppm of dissolved iron.

Brunswick shale	Late Triassic	Irregularly bedded soft red shale, locally interbedded with sandstone and black or gray shale; massive limestone-pebble and quartzite-pebble conglomerate along north-west border of formation. Altered to hornfels adjacent to diabase. Unaltered shale forms lowlands between ridges. Formation weathers to dark red clay loam. Thickness 6,000 to 9,000 ± feet.	Min. less than 1 Max. 420 Avg. 40[1]	A reliable source of moderate supplies of water from secondary rock openings which decrease in volume with depth. Largest yields are obtained from wells ranging in depth from 300 to 600 feet. Water is moderately mineralized, is hard at many places, but commonly is of satisfactory quality.
Sands of the Patuxent formation	Early Cretaceous	Fine to coarse quartz sand, in part feldspathic, interfingered with lenses of gray and varicolored clay. Total thickness of sands probably about 200 feet. Dips gently to southeast beneath younger beds.	Min. 3 Max. 800 Avg. 100[1]	A reliable source of moderate to large supplies of water in Delaware and Maryland. Not recognized in outcrop in New Jersey. May occur in subsurface in Salem County, N. J. Water slightly mineralized and soft. Contains objectionable quantities of iron in some places.
Sands of the Magothy and Raritan formations	Late Cretaceous	Aquifers in the Raritan formation are light-colored fine to medium quartz sand and some gravel. Those in the Magothy are generally gray to brown, fine sugary sand. Major aquifers are believed to be interconnected at distance although separated locally by varicolored red, gray, and yellow tough clays. Individual aquifers range from a few feet to 70 or 80 feet in thickness. Combined thickness of water-bearing beds in both formations in the order of 300 feet. Dips gently to southeast beneath younger beds.	Min. 10 Max. 1900 Avg. 500[1]	The most heavily developed aquifers in the area. Reliable source of large supplies of water. Sands crop out along or in some instances beneath the Delaware River in much of the region. Potential recharge thus very large. Water is normally slightly to moderately mineralized. Dissolved mineral content of uncontaminated water ranges from less than 50 to about 150 ppm. Iron content objectionably high in many places. Otherwise water is suitable for all ordinary purposes.
Englishtown sand	Late Cretaceous	Fine to pebbly quartz sand, slightly micaceous and glauconitic, with minor clay lenses. Thickness ranges from 0 to 70 or 80 feet in the region. Dips gently to southeast beneath younger beds.	Min. 5 Max. 520 Avg. 100[1]	Reliable source of small to moderate quantities of water in eastern part of the region. Wedges out southwest of Swedesboro, N. J. Thickens in Monmouth and Ocean Counties, N. J. Water normally contains less than 150 ppm of dissolved minerals and is suitable for all ordinary uses except that in some places it may require removal of iron.

Name	*Geologic Age*	*Description*	*Yield of Wells in GPM*	*Remarks*
Mount Laurel and Wenonah sands	Late Cretaceous	Salt and pepper or brown medium- to fine-grained glauconitic quartz sands. Combined thickness 40 to 100 feet. Dip gently to the southeast beneath younger beds.	Min. 5 Max. 300 Avg. 100[1]	The two sands function as a single aquifer. They are generally reliable sources of small to moderate quantities of water. Water normally contains less than 150 ppm of dissolved minerals and is suitable for all ordinary uses.
Vincentown sand	Eocene	Two recognizable facies: (1) a limy fossiliferous sand with some quartz grains, sometimes indurated; (2) a quartzose sand with varying amounts of glauconite. Thickness 25 to 100 feet. Dips gently to the southeast beneath younger beds.	Min. 2 Max. 400 Avg. 25[1]	A minor aquifer of local importance in southwestern New Jersey and northern Delaware. Water contains about 250 ppm of dissolved minerals, is hard and contains objectionable quantities of iron in some places.
Sands of the Kirkwood formation	Miocene	Several beds of light colored fine- to medium-grained sand. Sands generally finer in and near outcrop area. Dips gently to the southeast beneath younger beds.	Min. 5 Max. 860 Avg. 200[1]	Include at least two significant aquifers which yield moderate to large quantities of water. Major development outside the region in the Atlantic coastal communities from Point Pleasant to Cape May. Water soft and generally contains less than 150 ppm of dissolved solids. Little or no difficulty with iron.
Cohansey sand	Miocene(?)	Coarse to fine quartz sand, lenses of silt and clay. Estuarine and deltaic; possibly marine downdip to the southeast. Thickness ranges from a featheredge to more than 250 feet.	Min. 10 Max. 2000 Avg. 500[1]	Unconsolidated thick permeable aquifers. Potentially the most productive aquifer in the region but used only to a small extent. Chiefly unconfined, with direct recharge. Locally artesian. Water soft and normally contains less than 100 ppm of dissolved minerals. In some places it contains objectionable quantities of iron.
Sands and gravels	Pleistocene	Buff to brown, poorly- to well-sorted gravel, sand, silt, and clay in filled valleys and broad alluvial terraces. Generally thin and irregularly distributed.	Min. 2 Max. 1200 Avg. 25[1]	Unconsolidated permeable deposits containing unconfined water. A minor aquifer. The thicker channel sands are capable of large sustained yields. Water quality generally satisfactory for all ordinary uses, but removal of iron is necessary in some places.

[1]For drilled wells 6 inches or more in diameter.

the warmer surface-water supplies of the summer months might greatly increase the cost of some products.

Public water supplies are drawn from underground sources in every county in the region except Philadelphia and Delaware Counties in Pennsylvania (see figure 11). The use of ground water for public supply is much more common in the Coastal Plain, where adequate supplies are generally available, than northwest of the Fall Line, where such supplies are more difficult to obtain. For example, in the Coastal Plain part of the region in New Jersey, only one public water supply, that of Burlington, N. J., takes water from surface sources, and there it is used only to supplement a ground-water source. The largest municipal supply drawn entirely from underground sources in the region is that of the

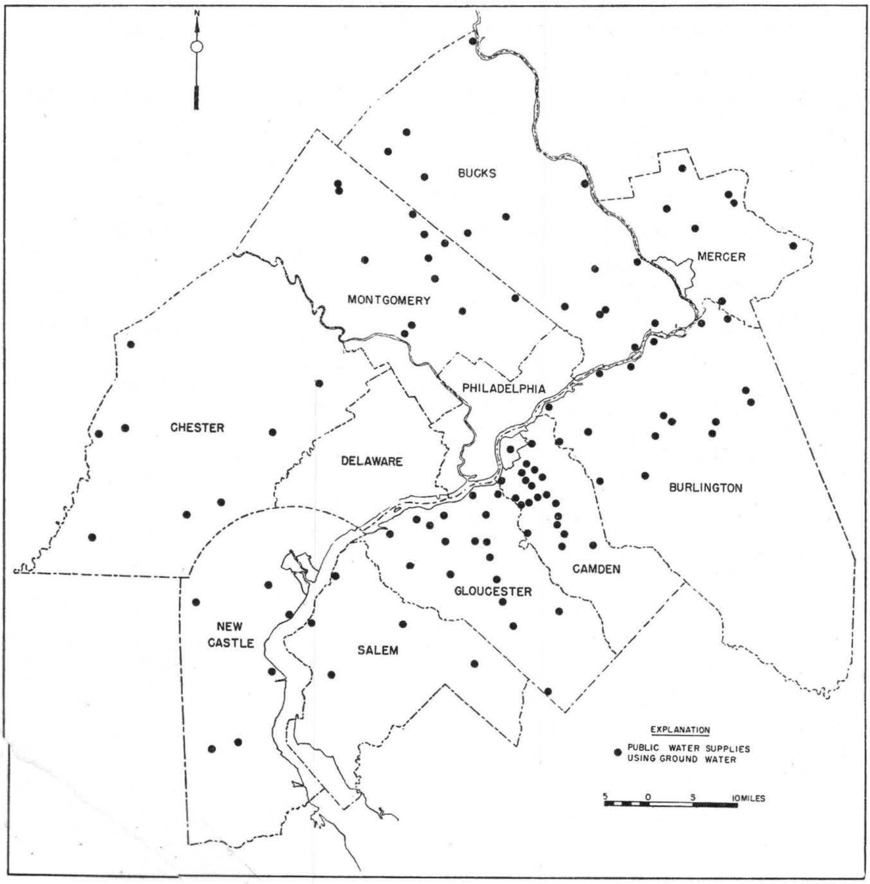

Figure 11.—Map showing public water supplies drawing from ground-water sources in the 11-county region.

City of Camden, N. J., which averages more than 20 million gallons daily.

Industrial water supplies from privately owned wells are common in many parts of the region, especially where conditions favor the procurement of moderate to large supplies. The uniform quality and temperature of ground water and its availability from a well at the plant site make it particularly appealing to industry. Even when large supplies of ground water are not available, many types of industry find it advantageous to have their own water supplies from wells.

Rural use of ground water for domestic and stock purposes is almost universal throughout the region. In coastal plain areas, where large quantities of ground water are available, its use for supplemental irrigation is increasing rapidly. Availability on the spot is particularly important in irrigation because the large areas can often be irrigated more economically from several scattered wells than from one central water supply.

Withdrawals of ground water in the 11-county region during 1954 averaged about 200 million gallons a day (see table 8). More than 80 percent of this was pumped from wells east of the Fall Line and more than half of it from wells in New Jersey. This pattern will continue because of the economic feasibility of developing large supplies from the unconsolidated deposits of the Coastal Plain. Although only moderate supplies are generally available in the consolidated rocks west of the Fall Line, they are locally of great importance. For example, in Mont-

Table 8.—Estimated ground-water use during 1954 in the 11-county region in million gallons daily.

STATE AND COUNTY	*Municipal*	*Industrial*	*Other*	*Total*
DELAWARE				
New Castle	5	3	1	9
Total	5	3	1	9
NEW JERSEY				
Burlington	7	4	6	17
Camden	37	16	3	56
Gloucester	5	13	3	21
Mercer	4	4	4	12
Salem	2	3	3	8
Total	55	40	19	114
PENNSYLVANIA				
Bucks	7	12	5	24
Chester	1	2	4	7
Delaware	0	0	1	1
Montgomery	5	23	2	30
Philadelphia	0	20	0	20
Total	13	57	12	82
GRAND TOTAL	73	100	32	205

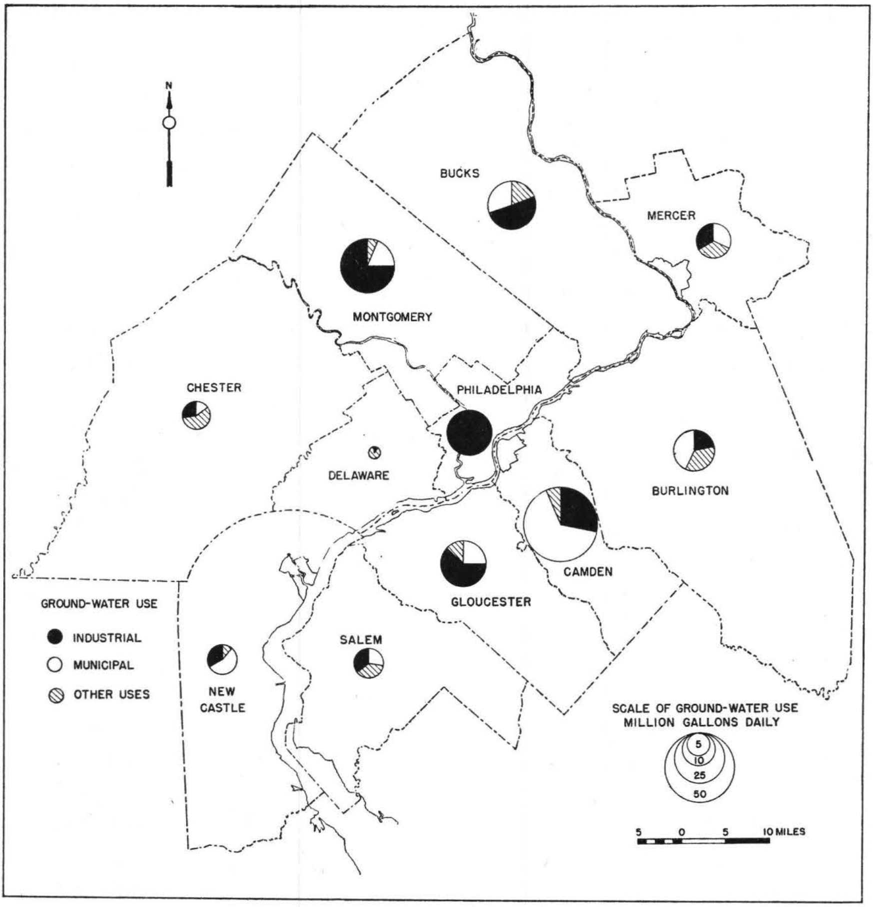

Figure 12.—Map showing ground-water use by type (municipal, industrial, and other) in each county of the region.

gomery County alone, there are more than 300 industries that use water from wells in the consolidated rocks.

The total withdrawal of water from wells in each of the 11 counties, differentiated by use, is shown in figure 12. The largest total pumpage is in Camden County, N. J., about 56 million gallons a day. The smallest use is in Delaware County, Pa., where only about 1 mgd is used. The total ground-water use for municipal supply is about 75 million gallons a day; for industrial use, about 100 million gallons a day; and for other uses, including irrigation and air conditioning, about 30 million gallons a day.

QUALITY OF THE GROUND WATERS OF THE REGION

INTRODUCTION

An adequate knowledge of the quality of its water is essential to the description of any aquifer. The chemical and physical characteristics of a water supply define its usefulness for various purposes; and they may also be useful as hydrologic aids in identifying sources of recharge to the aquifer.

All ground water contains dissolved mineral matter derived from the soil and rock with which the water has been in contact. The natural mineral character of ground water is a function of its geological experience—that is, the composition and solubility of the minerals around and over which the water has moved, the length of time of the contact, and the temperature and pressure at the point of contact. Consequently, the quality of ground water may differ greatly from one aquifer to another, but it commonly bears a distinct relationship to the aquifer in which it occurs.

The effects of human activities are superimposed upon the natural conditions. Disposal wells, cesspools, sanitary land-fill and the like have a direct effect on the quality of ground water because they are immediate sources of contamination to some aquifers.

Bacterial pollution is not a problem in most ground-water supplies because the water is filtered naturally in its movement through the minute openings in the rock. However, wells that tap solution openings in calcareous rocks or fractures in consolidated sediments or crystalline rocks may be subject to serious pollution if recharge is derived from a polluted source, because the water moves relatively freely and rapidly through the open channels with little filtration. The decomposition products of organic matter may also cause serious pollution in any type of aquifer because these materials are transported in solution and, therefore, are not removed by filtration.

Other human activities may have an incidental but more profound effect on the quality of ground water. For example, heavy pumping of an aquifer may cause significant changes in the quality of ground water. As the ground-water level declines in response to the pumping, mineral material in the unwatered zone may be oxidized to soluble forms, which may then be taken into solution and transported to the water table by downward percolating recharge. If the decline in water level is sufficient to expose the aquifer to recharge from a new source, such as an adjacent stream, the quality of the ground water may be further modified according to the character of the new source and the amount of recharge it contributes. In some instances, 90 percent or more of the yield of a well, or well field, is derived from induced recharge with the result that the ground water assumes the characteristics of the surface-water source of recharge.

Standards of quality of water differ according to the intended use of the supply. Properties and constituents that make a water unfit for a particular use may not affect its utility for certain other uses. Thus, a public supply must meet sanitary requirements and be free of objectionable tastes and odors; but for certain industrial uses temperature, or the concentration of some relatively minor constituent, may be of critical importance.

The constituents most likely to occur in objectionable concentrations in ground water are silica (SiO_2), calcium (Ca), magnesium (Mg), iron (Fe), manganese (Mn), chloride (Cl), nitrate (NO_3), bicarbonate (HCO_3), sulfate (SO_4), and dissolved carbon dioxide (CO_2). Silica contributes to the formation of hard "boiler scale" on heat exchange equipment and steam turbine blades. Calcium and magnesium together account for most of the hardness in water—"temporary" hardness when associated with bicarbonate and "permanent" hardness when associated with sulfate or chloride. Water containing large amounts of magnesium and chloride is likely to be corrosive. Chloride salts impart a salty taste to water when present in such concentration that the chloride content is more than about 250 ppm and render water unpotable to most tastes at concentrations greater than about 750 ppm. Iron and manganese cause stains on textiles and fixtures if their combined concentration exceeds about 0.3 ppm and may cause clogging of pumps, distribution systems, and fixtures at concentrations greater than 1 ppm. Nitrate, an end product of decomposition of organic matter, when present in concentrations of greater than 5 ppm may be indicative of pollution, and in concentrations greater than about 45 or 50 ppm is believed to be a contributing factor to the infant's disease, methemoglobinemia, a condition commonly known as "blue babies," (Bosch, H. M., and others, 1950; Walton, Graham, 1951). Carbon dioxide, also a decomposition product of organic matter, when present in concentrations greater than 20 ppm will cause corrosion of cement building materials and iron and carbon steel pipes and fittings.

CHARACTER OF THE GROUND WATER

The quality of the ground water in the 11-county region varies from one aquifer to another and from one place to another within the same aquifer. Most of the water is of excellent quality, however, for both domestic and industrial uses. The water commonly requires no treatment except for softening, or for removal or stabilization of iron.

The chemical constituents of ground water for which determinations are commonly made, in the analysis of a water sample, are silica, iron, calcium, magnesium, sodium, potassium, manganese, carbonate, bicarbonate, sulfate, chloride, fluoride, nitrate, total hardness, and dissolved solids. The physical characteristics and other properties that are commonly determined are temperature, color, turbidity, specific conductance, and hydrogen-ion concentration, as indicated by pH.

Analyses of representative samples from each of the more important aquifers are given in table 9, and the peculiarities of the waters from

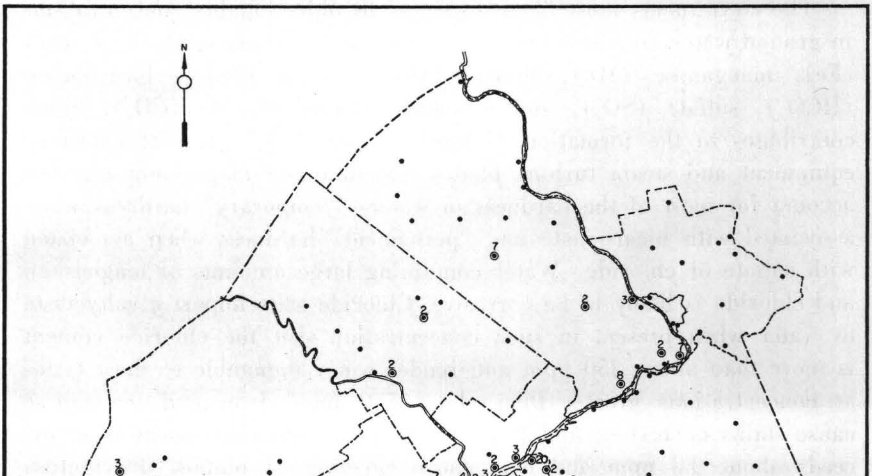

Figure 13.—Map showing the distribution of wells in the 11-county region for which chemical analyses are available.

Table 9.—Analyses of water from the principal water-bearing formations occurring in the 11-county region
(In parts per million except pH and specific conductance)

Analyzed by the U. S. Geological Survey

Sample No.	*Date Collected*	*Silica* *(SiO_2)*	*Iron* *(Fe)*	*Calcium* *(Ca)*	*Magnesium* *(Mg)*	*Sodium* *(Na)*	*Potassium* *(K)*	*Bicarbonate* *(HCO_3)*	*Sulfate* *(SO_4)*	*Chloride* *(Cl)*	*Fluoride* *(F)*	*Nitrate* *(NO_3)*	*Dissolved solids (residue at 180° C)*	*Hardness as $CaCO_3$*		*Specific conductance (micromhos at 25° C)*	*pH*
														Total	*Noncarbonate*		
								ROCKS OF QUATERNARY AGE									
1	1/14/46		0.52	98	90	170		150	579	185		53		660		1910	6.1
2	5/25/50	7.4		47	25	5.9	3.4	60	113	24	0.1	42	334	220	171	503	6.4
3	7/3/53	5.3	.20	13	4.5	3.8	1.8	40	24	4.2	.0	1.3	85	51	18	136	7.2
								ROCKS OF PLIOCENE(?) AGE									
4	12/18/51	11	.00	6.0	5.1	9.7	1.8	10	9.0	16	.1	24	88	36			5.6
								COHANSEY SAND									
5	8/8/51	4.1	3.2	.2	.7	1.8	.3	7	.0	2.9	.0	.1	13	3.6	0	16.2	6.7
6	4/23/51	5.5	.01	1.2	.8	2.7	.4	5	1.0	4.2	.0	5.0	25	8	4	33.6	6.4
								KIRKWOOD FORMATION									
7	5/28/51	34	.22	22	7.6	9.0		121	1.5	2.6	.3	.6	137	86	0	214	7.8
8	8/14/51	26	.10	.8	.9	2.9	2.2	1	10	3.1	.0	.1	49	6	5	48.8	4.7
9	4/17/56	34	.16	8.2	.8	18	2.8	65	12	3.4	.1	.5	115	24	0	140	7.8
								VINCENTOWN SAND									
10	12/21/50	36	1.9	60	8.7	7.4	4.9	212	24	5.6	.4	.7	254	186	12	390	7.6

Sample No.	Date Collected	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids (residue at 180° C)	Hardness as $CaCO_3$ Total	Hardness as $CaCO_3$ Noncarbonate	Specific conductance (micromhos at 25°C)	pH
								WENONAH AND MOUNT LAUREL SANDS									
11	5/28/51	10	0.37	25	3.9	6.8		99	7.5	2.5	0.1	0.7	112	78	0	181	7.4
12	6/21/51	13	.28	22	5.7	5.3	8.5	111	5.0	2.0	.1	.0	115	78	0	192	8.1
								ENGLISHTOWN SAND									
13	6/5/51	12	.32	24	4.9	5.2		99	8.0	1.0	.0	.5	107	80	0	182	7.3
14	5/28/51	16	.35	44	3.0	2.2	4.3	153	5.0	3.4	.1	.3	156	122	0	253	7.8
								RARITAN AND MAGOTHY FORMATIONS[1]									
15	11/28/49	7.0	.75	39	35	46	18	116	137	48	.1	52	460	241		735	6.0
16	4/24/51	9.4	.33	28	6.4	4.0	7.5	99	32	1.1	.1	.8	141	96	15	232	7.4
17	5/7/51	12	.11	3.0	1.0	118	4.6	292	6.2	19	1.6	.7	315	12	0	515	8.1
18	9/26/49	9.3	4.1	2.2	1.2	2.3	1.0	8	6.2	2.4	.1	.1	27	10		38.3	5.6
								PATUXENT FORMATION									
19	1/11/51	7.0	.75	13	3.1	14		80	4.2	3.4	.0	.2	86	45	0	151	7.0
								BRUNSWICK SHALE									
20	9/8/53	10	.14	42	15	9.0	.6	137	41	13	.1	5.1	239	166	54	380	7.8
21	3/26/53	20	1.8	38	19	14	1.0	157	59	8.5	.1	5.5	263	173	44	363	7.4

								LOCKATONG FORMATION									
22	4/27/53	11	.04	47	17	12	.8	164	61	11	.1	1.4	255	187	53	397	7.4
23	4/22/53	14	.04	28	15	7.0	.6	120	38	7.0	.0	2.1	229	132	33	376	7.4
								STOCKTON FORMATION									
24	3/26/53	22	1.2	23	8.6	8.1	1.0	80	24	7.0	0.0	13	147	93	27	225	6.9
25	9/27/49	27	.03	27	6.8	12	1.7	88	20	11	.0	12	158	95		247	6.7
								DIABASE									
26	4/20/53	18	1.4	48	15	11	2.3	196	34	8.5	.1	3.7	247	181	21	384	7.3
27	4/8/53	25	.4	94	9.1	4.4	1.0	126	169	2.2	.1	.3	398	272	169	536	7.5
								GNEISS									
28	4/8/53	13	.41	10	2.4	6.0	1.3	38	2.8	9.0	.0	3.8	78	35	4	100	5.3
29	9/7/53	8.7	.29	2.9	1.3	5.0	1.3	8	.3	7.0	.0	7.9	51	13	6	63.6	5.4
								QUARTZITE									
30	4/28/53	17	.18	9.1	2.9	6.1	1.2	29	5.1	6.9	.0	13	85	35	11	108	5.9
31	9/7/53	17	1.6	25	5.1	4.5	3.8	80	13	8.0	.4	.3	122	83	18	206	7.1
								CARBONATE ROCKS									
32	9/25/25	10	1.9	58	8.3	1.7	1.6	112	8.3	24		58	237	179			
33	9/28/25	14	.23	43	26	8.0	2.6	212	31	10		8.5	248	214			
								WISSAHICKON FORMATION									
34	2/3/54	25	21	38	25	100	1.8	98	116	144	.2	1.1	538	198	117	958	7.8
35	4/28/53	24	3.4	4.1	1.7	8.3	2.4	26	9.1	5.4	.1	.3	72	17	0	76.3	5.9
36	1/21/54	20	.15	14	8.3	7.4	2.8	26	18	16	.1	34	154	69	48	198	6.9

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

Rocks of Quaternary age

1. Philadelphia, Philadelphia County. Bower's Chemical Co. Well 1. Well 80 feet deep. Zinc 30 ppm.

2. Morrisville, Bucks County. U. S. Steel Co. Well 40 feet deep.

3. Beverly, Burlington County. Delaware River Water Co. Well 2. Well 45 feet deep. Manganese .33 ppm, Lithium .1 ppm, Carbon dioxide 4.0 ppm.

Rocks of Pliocene age

4. Newark, New Castle County. Newark Water Dept. Well 64 feet deep.

Cohansey sand

5. Lebanon State Forest, Burlington County. Pakim Pond Well, State of New Jersey. Well 80 feet deep. Manganese .09 ppm, Barium .0 ppm, Aluminum .4 ppm, Phosphate .0 ppm, Nitrite .0 ppm, CO_2 (Calc.) 2.2 ppm.

6. Newfield, Gloucester County. Newfield Water Dept. Well 2. Well 135 feet deep. Manganese .18 ppm, Carbon dioxide 3.2 ppm.

Kirkwood formation

7. Fort Dix, Burlington County. U. S. Army. Well 80 feet deep.

8. Harrisville, Burlington County. Unknown. Well 350 feet deep. Carbon dioxide 39 ppm.

9. Atlantic City, Atlantic County. Atlantic City Electric Co. Well 810 feet deep. Aluminum .0 ppm, Manganese .01 ppm, Lithium .2 ppm, Zinc .22 ppm, Copper .00 ppm, Phosphate .9 ppm. Radiochemical data: Beta-gamma activity (micromicrocuries per liter) <5, Radium (Ra) (micromicrocuries per liter) $<.1$, Uranium (U) (micrograms per liter) $<.1$.

Vincentown sand

10. Quinton, Salem County. Salem Water Dept. Well 133 feet deep. Phosphate .2 ppm.

Wenonah and Mount Laurel sands

11. Fort Dix, Burlington County, U. S. Army. Well 250 feet deep.

12. Vincentown, Burlington County. Vincentown Water Co. Well 150 feet deep. Carbon dioxide 1.4 ppm.

Englishtown sand

13. Fort Dix, Burlington County. U. S. Army. Well 457 feet deep.

14. Pemberton, Burlington County. Pemberton Water Dept. Well 1. Well 300 feet deep. Phosphate .2 ppm, Carbon dioxide 3.9 ppm.

Raritan and Magothy formations[1]

15. Camden, Camden County. Camden Water Dept. Well 6. Well 141 feet deep.
16. Haddonfield, Camden County. Haddonfild Water Dept. Well 3.
    Well 240 feet deep. Phosphate .1 ppm, Carbon dioxide 6.3 ppm.
17. Glassboro, Gloucester County. Glassboro Water Dept. Well 2.
    Well 630 feet deep. Phosphate .1 ppm, Aluminum .10 ppm.
18. Hightstown, Mercer County. Hightstown Water Dept. Well 1.
    Well 205 feet deep.

Patuxent formation

19. Wilmington, New Castle County. New Castle County Airport.
    (Composite sample from 3 wells 159 to 221 feet deep.)

Brunswick shale

20. Pineville, Bucks County. Van Pelt and Co. Well 75 feet deep.
21. Richlandtown, Bucks County. Richlandtown Boro Water Dept.
    Well 243 feet deep.

Lockatong formation

22. Edison, Bucks County. Neshaminy Manor Bucks County Home.
    Well 210 feet deep.
23. Camp Ochanikon, Bucks County. Bucks County Council. Well 330 feet deep.

Stockton formation

24. Chalfont, Bucks County. Chalfont Boro Water Dept. Well 187 feet deep.
25. Trenton, Mercer County. N. J. State Hospital Well 8. Well 372 feet deep.

Diabase

26. Milford Square, Bucks County. Milford Square Parts Co. Well 765 feet deep.
27. Sellersville, Bucks County. Sellersville Boro Water Dept. Well 765 feet deep.

Gneiss

28. Parkland, Bucks County. Parkland Water Co. Well 222 feet deep.
29. Langhorne, Bucks County. Langhorne Spring Water Co. Well 226 feet deep.

Quartzite

30. Somerton, Bucks County. Somerton Springs Swimming Club. Well 165 feet deep.
31. Langhorne, Bucks County. Langhorne Spring Water Co. Well 504 feet deep.

Carbonate rocks

32. Coatesville, Chester County. A. Westman. Well 70 feet deep.
33. Whitemarsh, Montgomery County. Ambler Spring Water Co. Spring.

Wissahickon formation

34. Philadelphia, Philadelphia County. Delta File Works. Well 156 feet deep.
35. Hulmeville, Bucks County. O. K. O. Plush Co. Well 300 feet deep.
36. Eddington, Bucks County. Publicker Industries, Inc. Well 90 feet deep.

[1]For additional analyses of water from the Raritan formation see table 11.

the different aquifers are discussed along with their other characteristics in the section on the geologic formations and their water-bearing characteristics. The locations of wells from which samples of water were collected and analyzed during the course of the investigations that preceded this report are shown on figure 13. From many wells, two or more samples were collected and analyzed at different times to detect possible changes in quality. In all, several hundred samples of ground water were collected and analyzed.

THE GEOLOGIC FORMATIONS AND THEIR HYDROLOGIC CHARACTERISTICS

PROTEROZOIC SEQUENCE

Rocks of Proterozic age are exposed at the surface in about one-fourth of the 11-county region (see geologic map, Plate I). They occur also as the rock floor beneath a considerable part of the Coastal Plain sediments. The major exposure of these rocks is in a great wedge-shaped area that lies marginal to the Fall Line for almost 70 miles from Princeton Junction in Mercer County, N. J., to the western border of New Castle County, Del. The western end of the wedge is about 40 miles wide and includes part of northern New Castle County, Del. and most of Chester County, Pa. Small isolated outcrops of these rocks occur in central and northern Bucks County, Pa. and in central New Castle County, Del.

The Proterozic rocks may be classified in two groups within which the various geologic formations differ relatively little from each other in so far as their hydrologic or water-bearing characteristics are concerned. The larger group includes those formations composed of schist, gneiss, quartzite, igneous intrusives, and similar rocks. For purposes of hydrologic classification in this report, this group is referred to as "the crystalline rocks." The smaller group is composed of limestones and marbles and is classified herein for hydrologic purposes simply as "carbonate rocks." On the geologic map accompanying this report (Plate I) the boundaries of the various formations of Proterozoic age are not shown and contacts are drawn only between units that differ in their water-bearing characteristics. To avoid repetition, the hydrology of the crystalline and of the carbonate rocks is discussed along with that of the hydrologically similar rocks of Paleozoic age.

GEOLOGY

Precambrian system

Baltimore and associated gneisses

The Baltimore gneiss occurs in a narrow belt southwestward from Trenton, N. J., across Bucks, Montgomery, Delaware, and Chester Counties, Pa., to the vicinity of Toughkenomon in Chester County, Pa., and beyond into Maryland. It is the oldest rock extensively exposed in the 11-county region. It is a medium-grained crystalline rock, which probably is partly of igneous origin and partly of sedimentary origin. The rock is predominantly gneissic and is characterized by alternating layers of mica and quartz or quartz and feldspar.

The Pickering gneiss, which is graphitic, occurs in small areas in Chester and Delaware Counties.

In northeastern Bucks County, the gneiss has been differentiated into two formations, the Pochuck gabbro gneiss and the Byram granite gneiss. They are easily distinguished in the field, and are intricately interlayered.

The Pochuck gabbro gneiss is a conspicuously foliated, medium- to coarse-grained crystalline rock that was probably derived from a basic igneous intrusive. It is characteristically dark colored, ranging from dark green or gray to black.

The Byram granite gneiss is a coarse-grained crystalline rock that was apparently derived from a granitic intrusive. It is distinguished from the associated Pochuck gabbro gneiss on the basis of color and structure. The Byram granite gneiss is a banded rock, but the banding is not as prominent as that of the Pochuck. Its color ranges from light gray, where the rock is fresh, to buff or brown on weathered surfaces, and contrasts sharply with the more somber hues of the Pochuck.

Franklin limestone

The Franklin limestone occurs as lenses of masive crystalline limestone in the Baltimore gneiss. It has been described by Hall (1934) as follows:

> "The Franklin limestone is a coarse crystalline limestone, or marble, the individual particles of calcite being, in some places, as much as an inch in diameter. Graphite in small bright flakes approximately 1/8-inch in diameter is scattered through the marble and in most places the graphite is accompanied by flakes of the brown mica known as phlogophite. In some areas numerous silicate minerals are associated with the calcite.
>
> "No bedding planes are visible in the Franklin limestone outcropping in Pennsylvania, and therefore strike, dip, and

thickness are undeterminable. However, it is probable that the maximum thickness does not exceed a few hundred feet."

Precambrian (?) rocks

Glenarm series

Unconformably overlying the Baltimore gneiss is the Glenarm series of formations which, in the 11-county region, consists of the Setters formation, the Cockeysville marble, the Wissahickon formation, and the Peters Creek schist. The age of the Glenarm series is in doubt. In some areas, notably in Lancaster and York Counties, Pa., the rocks of the series apparently overlie or are interbedded with rocks of Ordovician age. According to the oldest accepted interpretation, this association results from a major overthrust which placed the Precambrian crystalline rocks on top of Ordovician sedimentary rocks. However, a segment of modern geologic opinion (Cloos and Hietanen, 1941; King, P. B., 1951; Gray, Carlyle, personal communication) would classify the formations of the Glenarm series as metamorphic equivalents of Cambrian and Ordovician formations that have been recognized in other areas. Thus, the Setters formation is correlated with the Chickies quartzite of Early Cambrian age; the Cockeysville marble is correlated with Lower Ordovician limestone; and the Wissahickon formation and Peters Creek schist are correlated with the Martinsburg shale of Ordovician age.

Setters formation

The Setters formation consists chiefly of white to buff quartzite or quartzitic schist which grades into gray micaceous gneiss. It is apparently conformably overlain by the Cockeysville marble. The Setters formation is characteristically massive, but joints occur frequently, and bedding planes are more or less open.

Where exposed in Chester County, Pa., the Setters formation is approximately 1,000 feet thick. It commonly forms ridges which border valleys underlain by the Cockeysville marble.

Cockeysville marble

In the 11-county region, the Cockeysville marble occurs locally in southwestern Chester County, Pa., and northern New Castle County, Del. It is a dense, massive, white to blue-gray, medium-grained, crystalline marble. The beds are cut by numerous joints, many of which have been enlarged by solution, forming openings of considerable size.

The marble is about 200 feet thick. It weathers to a deep clay soil and is rarely exposed except in highway cuts or quarries.

Wissahickon formation

The Wissahickon formation is the most widespread of the crystalline rocks in the 11-county region. It occurs locally in Mercer County, N. J., in the vicinity of Trenton. It underlies broad areas in Bucks, Philadelphia, Chester, and Delaware Counties, Pa., and extends southwestward through northern New Castle County, Del., into Maryland.

The lithology of the Wissahickon formation varies greatly in both horizontal and vertical sections. The formation is generally believed to have been originally a sedimentary deposit composed chiefly of beds or lenses of sandstone, shale, and arkose. Although these materials have been deformed and recrystallized by subsequent metamorphism, the original banding of the sediments has been largely retained. In its present occurance, the Wissahickon is a medium- to coarse-grained foliated crystalline rock ranging in texture from gneiss to schist. It consists of alternating layers of mica schist and quartzite which range in thickness from less than an inch to several feet. The important mineral constituents of the rock are mica, feldspar, quartz, chlorite, and garnet. Chlorite is abundant in the schistose beds, and feldspar in the gneissic beds, but mica is generally the most conspicuous mineral in any exposure of Wissahickon formation.

Coarsely crystalline hornblende schist occurs as conformable sheets in association with the Wissahickon formation. The hornblende schist is believed to be an altered basic igneous intrusive, but no petrographic studies of this rock have been made. The rock is composed of hornblende, quartz, and feldspar, chiefly orthoclase, the hornblende accounting for nearly 50 percent of the mass. Owing to the abundance of the hornblende, the rock is characteristically a uniform dark gray or green in color in all exposures.

Peters Creek quartzite

The Peters Creek quartzite is typically a gray to greenish chloritic or sericitic quartzite. Gneiss and a chlorite-muscovite schist are also characteristic of the formation. The quartzite is massive, but it is rather thoroughly jointed, and its planes of schistosity are not completely closed.

Where exposed in western Chester County, Pa., the formation, approximately 2,000 feet thick, lies conformably above the Wissahickon formation, which it resembles lithologically.

PROTEROZOIC OR PALEOZOIC ROCKS

IGNEOUS INTRUSIVES

Granites and allied rocks

Granite, granodiorite, and related rocks are exposed in parts of Philadelphia, Montgomery, Delaware, Chester, and Bucks Counties, Pa., and in New Castle County, Del.

Not all these rocks had the same origin. Some were probably derived from magmas that were intruded into the Baltimore gneiss or the Wissahickon formation during late Precambrian or early Paleozoic time. Other granitic rocks were probably formed by action between the Wissahickon and alkali-rich hydrothermal solutions, and these may be regarded as metamorphic in origin (Postel, 1940). These granitic rocks are typically medium- to coarse- grained and light to dark gray in color. Faulting and jointing are not uncommon.

Gabbros and allied rocks

Gabbro, metagabbro, and related rocks have intruded the Baltimore gneiss, the granodiorite and other rocks in the Piedmont. Gabbro is a medium-grained, massive, igneous rock having a bronze or greenish-gray color. Joints are infrequent in the gabbroic rocks.

Serpentine rock and pyroxenite

Peridotite, pyroxenite, and allied ultrabasic igneous rocks intrude the Wissahickon schist in a number of places in southeastern Pennsylvania.

The original ultrabasic rocks have been largely altered, and the original rock-forming minerals are preserved only in the cores of some of the larger dikes. Serpentine is generally the principal alteration product , but in a few places talc, anthophyllite, or chlorite is dominant.

PALEOZOIC SEQUENCE

In the 11-county region, rocks of Paleozoic age crop out in relatively small areas within or adjacent to the areas underlain by the rocks of Proterozoic age (see page 66). They are similar in their water-bearing characteristics to the Proterozoic rocks and may similarly be classified on this basis as "crystalline rocks" and "carbonate rocks". On the geologic map accompanying this report (Plate I), the boundaries of the various formations of Paleozoic age are not shown and contacts are drawn only between units that differ in their water-bearing characteristics. To avoid repetition, the hydrology of the rocks of Paleozoic age is discussed along with that of the rocks of Proterozoic age.

GEOLOGY

Cambrian System

Chickies and Hardyston quartzites

In the 11-county region the Chickies quartzite crops out in a narrow, discontinuous belt that trends southwestward from Trenton across southern Bucks and Montgomery Counties and central Chester County; and in isolated belts in northern Chester County and central Bucks County. Its correlative, the Hardyston quartzite, is exposed in a narrow belt in the extreme northeastern corner of Bucks County.

The Chickies is a massively-bedded vitreous quartzite in which the individual quartz grains are clear white or blue. It weathers to buff or gray, and being a resistant bed, it forms conspicuous hills throughout its area of outcrop. The upper part of the formation is locally thin-bedded and weathers to a siliceous clay. The basal part of the Chickies is formed by the Hellam conglomerate member which consists chiefly of elongated blue quartz pebbles and pink feldspar in a matrix of granular quartzite or arkose.

The lithology of the Hardyston quartzite is similar to that of the Chickies quartzite except that no well-developed conglomerate is present at the base. Rather, thin beds of conglomerate occur throughout the formation.

The thickness of the quartzite, including the Hellam conglomerate member, ranges from less than 100 feet in northeastern Bucks County to over 1,300 feet in the southernmost belts of outcrop. The thickness of the beds increases to the south, apparently the result of the addition of the Hellam to the sequence. The quartzites rest unconformably upon older crystalline rocks. The upper contact is conformable and transitional where the quartzite is overlain by limestone or the Harpers schist but is unconformable where overlain by Triassic or Quaternary sediments.

Harpers schist

The Harpers schist is exposed in a small area in north-central Chester County. It is a bluish-gray argillaceous rock which has been metamorphosed locally into schists, phyllites, and quartzites. It weathers to a rolling lowland below the adjacent uplands underlain by the Chickies quartzite.

The thickness of the formation ranges from about 300 feet to over 1,000 feet. It is conformably overlain by the Antietam sandstone.

Antietam sandstone

The Antietam sandstone crops out in north-central Chester County. It consists of light gray quartzitic sandstone with calcareous cement;

locally it may be altered to schist or gneiss. The Antietam is only 150 feet thick in this area. It is grouped with the Harpers schist on the geologic map (figure 9).

Cambrian and Ordovician carbonate rocks (undifferentiated)

The nomenclature and correlation of the Cambrian and Ordovician limestones are subject to technical controversy. Bascom, Clark, Darton, and others (1909) mapped the entire sequence as a single unit which they called the Shenandoah limestone. Later investigations subdivided the Shenandoah limestone by correlating certain units with formations that are recognized in the Cumberland valley to the west. But their interpretations have not received general acceptance because the beds have not been systematically traced to the type areas of the formations. The names of some of these formations are shown in table 6.

In view of the uncertainty of the correlation of the carbonate rocks, they are identified herein as undifferentiated Cambrian and Ordovician carbonate rocks. From the standpoint of hydrology, the question is of only academic interest because the water-bearing characteristics of the various units are essentially identical.

The major occurrence of the Cambrian and Ordovician carbonate rocks is in a broad belt of outcrop in the Chester valley in Chester and Montgomery Counties. They also crop out in narrow belts in French Creek valley along the northern border of Chester County, and in the Buckingham and Durham valleys in Bucks County.

A typical exposure of the carbonate rocks consists of a thick sequence of blue-gray or white, generally massive, dolomitic limestone, which commonly includes numerous thin beds of quartz sandstone, edgewise conglomerate, and red and gray shale. The limestone weathers to a deep soil and forms wide, open valleys with few outcrops. Fossils are rare, but some marine animal forms occur, and a few beds consist largely of cryptozoan reefs, an algal form, as the principal rock-forming material. These beds, called biostromes, are persistent over wide areas.

The thickness of the limestone varies greatly among the different areas of occurrence, but it is impossible to determine with accuracy because most formational contacts are concealed. The estimated stratigraphic thickness of the limestone sequence ranges from 500 feet to 2,000 feet or more, but owing to the effects of faulting and folding, there is repetition of strata and as much as 6,000 feet of limestone may underlie some areas. The limestones commonly rest on basal Cambrian quartzite. The contact is interpreted as conformable and transitional where the Lower Cambrian limestone is present, unconformable where the Middle Cambrian limestone overlaps the quartzite. In some areas the limestone lies on Precambrian gneiss, a condition which is interpreted as a fault contact. The upper contact of the limestone is generally concealed beneath sediments of Triassic or Quarternary age, but it is known to be marked by a profound unconformity.

Ordovician system

Cocalico shale

The Cocalico shale is exposed in a small triangular area in east-central Bucks County, Pa. It is a dark-colored platy to finely-laminated rock that ranges in texture from phyllite to slate. In some exposures the shale exhibits a faint bedding that apparently dips gently to the north beneath the sedimentary rocks of Triassic age.

The Cocalico shale is in fault contact with limestone of Cambrian age on the east, and with shale of Triassic age on the south. To the north and west it unconformably underlies standstone of the Stockton formation of Triassic age. Beds of Cocalico shale having a stratigraphic thickness of about 200 feet are exposed in the area, but the total thickness of the formation is unknown, as neither the upper nor the lower contact is exposed in the area.

HYDROLOGY OF THE PROTEROZOIC AND PALEOZOIC ROCKS

Crystalline rocks

Although the crystalline rocks differ greatly in origin and in most of the chemical and physical characteristics which are used in describing rocks, their basic *hydrologic* properties are generally similar. All are dense, massive rocks which, in their unaltered state, are relatively impervious to water. Essentially all ground water in these rocks occurs under water-table conditions in openings resulting from faulting and jointing. The greater part of it occurs in the weathered zone near the land surface, where the openings have been enlarged by frost action, the roots of vegetation, and solution of the rock-forming minerals by circulating ground water. These cavities constitute only a small part of the total volume of the rock, but they provide for the storage and movement of considerable quantities of ground water.

The forces of weathering are most effective at the rock outcrop. With depth the water-bearing cavities decrease in size and number, as the weathered material grades into unaltered rock. The weathered zone is thickest in areas of low to moderate relief; it is best developed in valleys because there is continuous circulation of ground water in the vicinity of streams, which are the principal localities of natural discharge of ground water. The weathered zone is least thick, and may be absent, in areas of high relief. Judging from records of drilled wells, the maximum thickness of the weathered material commonly does not exceed about 150 feet, and yields of wells are not appreciably increased by drilling below that depth. Most successful wells obtain their supplies from the zone of partly weathered rock that lies between the disintegrated rock at the land surface and the fresh rock at depth. A few wells are reported to obtain water from depths of 500 feet or more, probably from faults, exceptionally large joints, or shattered quartz veins. Successful peep wells are the exception, however, and their aggregate yield does not constitute an appreciable part of the ground-water supply.

The storage coefficient of the crystalline rocks is in the low range of water-table values. It probably ranges from about 0.005 to about 0.02. The specific capacity of wells that tap the crystalline rocks is also moderately low to very low, as shown in the following table of reported specific capacities of wells.

Formation	*Number of wells*	*Average specific capacity*	*Range in specific capacity*
Wissahickon formation	8	1.70	0.17 - 5.0
Gneiss	3	2.69	1.27 - 5.29
Quartzite	2	.95	.23 - 1.67

From an analysis of the hydraulic characteristics of the crystalline rocks it is apparent that a typical well that taps these beds will exhibit appreciable drawdown at any pumping rate. The effect of the withdrawal is generally not transmitted any great distance from the well, probably no more than a few hundred feet in most localities, depending upon the degree of fracturing and the interconnection of the joints in the vicinity of the well.

In some areas the ground water may be semiconfined in the partly altered rock that occurs between the decomposed material at the surface and the fresh rock; or it may be confined in fault zones that occur at considerable depth in the fresh rock, or in the weathered rock that underlies the unconsolidated fill in the valley of the Delaware River. The upper part of the crystalline rock beneath the valley commonly consists of decomposed rock that serves as a confining bed on the underlying partly altered rock. Where the confining bed is continuous beneath the unconsolidated deposits, the water in the crystalline rock has a definite gradient riverward from the Fall Line. A few wells drilled through the valley fill into the crystalline rock have flowed at the surface. In most places, however, the confining bed is discontinuous and there is interchange of water between the crystalline and unconsolidated rocks. In these areas the water level in a well that taps crystalline rocks is about the same as the water level in a nearby well that taps unconsolidated beds. Occurrences of semi-confined conditions have little effect on the regional hydrology of the crystalline rocks, however, because their influence is local.

The crystalline rocks, particularly the gneisses, schists, and quartzites, are reliable sources of small to moderate supplies of ground water. Little is known of the water-bearing characteristics of the Cocalico phyllite, but it appears to be a less favorable source of water supply than the other crystalline rocks. The reported yield of wells that tap gneiss, quartzite, and the Wissahickon formation are summarized in the following table.

Formation	*Number of wells*	*Range in yield (gpm)*	*Average yield (gpm)*
Wissahickon formation	12	2 - 200	45
Gneiss	16	2 - 200	42
Quartzite	31	1 - 125	38

As to chemical quality, the crystalline rocks of Precambrian age yield the most desirable ground water available in the region. The water commonly is low in dissolved solids and hardness, and is free of objectionable mineral matter except iron, which may be present in concentrations that exceed the generally accepted limit of 0.3 part per million. Analyses of representative samples of water from gneiss, quartzite, and the Wissahickon schist are given in table 9.

Special mention should be made of the water-bearing characteristics of diabase because it is the poorest aquifer in the region—so poor, in fact, that many drillers will not accept contracts to make wells in this rock. The thickness of the weathered zone in diabase seldom exceeds about 75 feet and probably averages no more than 50 feet. Wells generally obtain their yields from depths of 50 feet or less, and the maximum depth from which a well in diabase in the region is reported to obtain water is 125 feet. The capacity of diabase to store and transmit water is extremely low, and many wells are failures. No specific-capacity tests are available for wells that tap diabase, but the average specific capacity is probably only a fraction of a gallon per minute per foot of drawdown of water level. The reported yields of five wells in diabase range from 2 gpm to 45 gpm and average 23 gpm. However, this accounting is based only on successful wells. If failures are included, the average yield of wells is probably less than 5 gpm.

The water from the diabase generally is moderately mineralized and hard, and sometimes has objectionable amounts of iron in solution. Some samples contain relatively high concentrations of sulfate and have corresponding high noncarbonate hardness. Analyses of two representative samples of water from diabase are given in table 9.

Carbonate Rocks

The calcareous rocks are similar to the crystalline rocks in that they have almost no primary porosity. But, owing to earth movements and destructive weathering processes, they commonly contain numerous secondary openings in the weathered zone near the land surface. Solution is the chief weathering agent in calcareous rocks. Limestone and dolomite are relatively soluble in water that is only slightly acid in reaction. Rainfall contains carbon dioxide dissolved from the atmosphere, making it a weak carbonic acid, and the acidity of the water is increased by solution of more carbon dioxide and of organic acids from the soil. Thus natural water is an effective solvent of carbonate rock, and where it moves along zones of weakness, such as joints or faults or bedding planes in the calcareous rock, it may erode solution channels or openings of considerable size and extent. The occurrence of the solution openings is extremely irregular. They are most numerous between depths ranging from 50 feet to about 300 feet, but some wells are reported to have penetrated large openings at depths of more than 1,000 feet. However, it is seldom profitable to drill deeper than about 500 feet in search of water in calcareous rocks.

Ground water occurs in the calcareous rocks under both water-table and artesian conditions. Water-table conditions prevail in the shallow aquifers, and the conditions of occurrence resemble those in the water-table aquifers of crystalline rock, except that the calcareous-rock aquifers probably have higher coefficients of storage and permeability.

Ground water occurs under semi-artesian and artesian conditions in solution openings in the calcareous rocks. The solution channels are recharged from the overlying water-table aquifers, or from sinks (undrained depressions) at the land surface. They may transmit the water many miles from the locality of recharge to points of discharge, but the channels may not be oriented in any recognizable pattern. Their occurrence cannot be predicted in advance of drilling. Consequently, it is often necessary to drill several wells at a selected location to obtain one successful supply well. The abundance of solution openings is usually greater near surface-drainage lines. In limestone terrane the surface drainage is commonly controlled by the concentration of subsurface solution openings. Therefore, stream valleys, topographic depressions, or lines of sinkholes are favorable locations in which to drill wells in limestone.

The coefficient of storage of calcareous rock aquifers, except near the land surface where water-table conditions prevail, probably ranges from about 0.001 to 0.0001. The average permeability is apparently high. No records of specific-capacity tests are available for wells tapping limestone, but well owners commonly report high yields with only moderate drawdowns of water level.

Calcareous rocks display perhaps more heterogeneity in their hydrology than any other rock type. From the calculated hydraulic characteristics of an aquifer it might appear that a typical well would exhibit low to moderate drawdown at any discharge rate, but that a decline of water level as an effect of pumping would be transmitted rapidly to relatively distant points throughout the aquifer. This effect does occur, of course, but it is seldom transmitted equally in all directions—it follows the courses of the interconnected solution openings tapped by the pumped well. Consequently, in limestone terrane, two nearby wells may tap different systems of openings in the rocks. Under these conditions, there is little or no mutual interference between the wells when they are pumped.

Successful wells in areas underlain by carbonate rocks supply the largest yields obtained from wells that tap consolidated-rock aquifers in the 11-county region. A summary of reported yields of wells in carbonate rocks is given in table 7. The yields range in general from 1 gpm to 1,450 gpm and average about 25 gpm.

No water from wells tapping calcareous rocks was sampled for chemical analysis in connection with this study. The following discussion of the chemical quality of water in limestone aquifers in southeastern Pennsylvania is taken from Hall (1934).

> "Analyses were made of a total of 41 waters obtained from limestone, dolomite, and marble, chiefly from the calcareous formations of the Cambrian and Ordovician systems. Nearly all of these waters are fairly high in total dissolved solids, their mineral contents consisting largely of the bicarbonate of calcium and magnesium, which give them considerable hardness. The 41 samples ranged in total solids from 75 to 889 parts per million but nearly three-fourths of them were between 200 and 500 parts and their average content of dissolved solids was 304 parts. The same samples ranged in hardness from 24 to 508 parts per million, nearly two-thirds of them having between 100 and 250 parts and nearly one-third having more than 250 parts of hardness. They showed an average hardness of 230 parts per million. The limestone waters are generally low in iron, only 2 of the 41 samples having more than 1 part per million and over half of them having less than one-tenth of 1 part per million of this undesirable constituent. Except for their hardness the limestone waters are as a rule excellent waters.
>
> "Wells deriving their water from solution channels are liable to serious contamination because of the rapidity with which the water moves along the channels. Care should therefore be taken in choosing a site for a well that is near sources of pollution."

MESOZOIC SEQUENCE

TRIASSIC SYSTEM

The following discussion of the geology of the Triassic rocks is taken largely from McLaughlin (unpublished manuscript), who has made the most detailed studies of these rocks in this area.

Rocks of Triassic age play an important part in the geology of the northeastern Atlantic seaboard from Nova Scotia to North Carolina. The character and occurrence of the deposits are remarkably similar throughout this area. All the Triassic rocks occur in structural basins elongated in a north-south or northeast-southwest direction. In general they consist of thick sequences of nonmarine sediments, predominantly red to brown in color. The sediments are intruded by diabase dikes and sills in many areas, and the upper strata are commonly interbedded with thick flows of basaltic lava. The beds frequently occur in large blocks that are tilted and separated from one another by normal faults. The underlying rocks range in age from Precambrian to Carboniferous, but they are always separated from the Triassic rocks by a profound unconformity.

The Triassic sedimentary rocks and interbedded lava flows constitute the Newark group, which was named for exposures in the vicinity of Newark, N. J. The igneous intrusives also are of Triassic age, but because they are not conformable with the stratified rocks, they are not included as part of the Newark group, and are at least in part of later origin. Owing to the similarity of the lithology, structure, stratigraphic relations, and fossil content of the Triassic rocks, the term Newark group is applied to all occurrences of these rocks in northeastern North America. However, it has not been possible to subdivide the group into formations or members that can be correlated from one basin to another, or even throughout any of the larger basins. Deposition was largely controlled by local environment, and similar conditions apparently occurred at different times in different areas.

The Newark group is believed to be of Late Triassic age. This correlation is based in part on paleontologic data, and in part on structural and stratigraphic evidence. Fossil plants and animals correspond within general limits to European forms, but it has not been possible to correlate equivalent beds in the European and American strata. The Newark group rests unconformably on older rocks, and it shows no effects of the structural deformation that occurred at the end of the Paleozoic era. On the other hand, the Newark group is distinctly older than the Cretaceous deposits. Rocks of the Newark group were intruded by diabase, then faulted and tilted, and finally peneplaned before deposition of Lower

Cretaceous sediments. The diabase does not have a name common to all areas of occurrence. It may carry a local name, but it is generally referred to simply as "traprock."

The Newark group and associated intrusives in the region occur in part of the largest belt of Triassic rocks in northeastern North America. The deposits occur in a broad, downfaulted intermontane basin that extends from southeastern New York State across New Jersey, southeastern Pennsylvania, and central Maryland into northern Virginia. The belt is broadest in Bucks County, where it attains a width of 32 miles.

In the 11-county region the Newark group consists chiefly of interbedded red shale and red sandstone, with subordinate amounts of conglomerate, arkose, and argillite. No lava flows have been identified in the area, but they are known to occur to the west in Berks County, and to the north and east in New Jersey. The great normal fault blocks are tilted toward the northwest, and most of the Triassic strata dip in that direction at angles ranging from 5° to 20°. Folding is not a prominent feature, but near the large faults drag folds occur, and beds have dips as great as 50°. Beds that underlie the large intrusive bodies in the northern part of Bucks County are warped into gentle synclinal folds which lie superimposed on the regional monocline.

Estimates of the total thickness of the Newark group in the region range from about 2,000 feet to more than 12,000 feet. The higher figure is favored by most investigators, but others claim that repetition of strata due to faulting gives the illusion of great thickness to deposits that are no more than 2,000 feet thick.

Kummel (1897) subdivided the Newark group into three lithologic units. They are, in ascending order, the Stockton formation, the Lockatong formation, and the Brunswick shale, named after type localities in western New Jersey. A fourth rock type, the border conglomerate, was identified as a facies of the other three units. The divisions established in New Jersey are applicable in the 11-county region, but a short distance to the west they grade into a two-unit group consisting of sedimentary rocks like those of the Stockton and Brunswick formations. Each division of the Newark group was originally designated a series, but the three divisions have since been redefined as formations in reports of the U. S. Geological Survey. In describing the beds, Kummel recognized that they are interfingering sedimentary facies which represent rapidly changing conditions of local deposition, and have little significance as time markers. This interpretation was expanded considerably by McLaughlin (unpublished manuscript), who attributed the interfingering to derivation of the sediments from different sources.

Stockton Formation

Geology

The Stockton formation crops out in three belts in the northern part of the 11-county region. The major exposure forms a sinuous belt of varying width that traverses the entire region in a generally west-southwest direction along the southern margin of the Triassic-Lowlands province. Another belt of outcrop trends southwestward across central Bucks County from the Delaware River to the vicinity of Chalfont where it is cut by a large normal fault. The Stockton formation is also exposed in a narrow belt that lies along the northwest side of a major fault in northern Mercer County.

The Stockton formation consists of light-colored coarse-grained arkosic sandstone and conglomerate, red to brown fine-grained siliceous sandstone, and red shale. In general, arkosic beds are more characteristic of the Stockton than is shale. The most conspicuous features of the beds are the dominant red color, and the abundance of arkose throughout the section except in the uppermost beds. The different lithologies are interbedded in no regular order and are frequently repeated. Single beds rarely can be traced for any appreciable distance along an outcrop. They commonly pinch out, or grade into beds having different textures and/or compositions, but certain sequences of beds may persist for many miles. Some of the thick arkose and red sandstone beds can be identified at widely separated points.

The rocks of the Stockton are cut by a well-developed system of joints and are extensively faulted. The beds commonly show ripple marks, mud cracks, and raindrop impressions. Crossbedding, lensing, and pinch-and-swell structures are characteristic features of the bedding, particularly in the arkose and conglomerate deposits.

The Stockton formation is about 3,000 feet thick in Bucks County. It overlaps crystalline rocks toward the west and thins to a minimum thickness of about 1,000 feet in northern Chester County. It rests unconformably upon rocks of Precambrian, Cambrian, and Ordovician age and is overlain conformably by the Lockatong formation.

The Stockton formation weathers to an undulating topography of moderately low relief. Most of the valleys are eroded into the soft red sandstone beds, whereas the uplands are underlain by more resistant arkose. Owing to the irregular character of the bedding, topographic features are not commonly oriented in any systematic pattern, but locally, as in the central belt of the Stockton exposures, some of the ridges parallel the strike of the beds.

Hydrology

The Stockton formation is the best source of ground water outside of the Coastal Plain in the 11-county region. Weakly cemented coarse-grained clastic sediments constitute a large part of the formation. Ground water is contained in joint cracks and in intergranular openings in the clastic sediments where the cementing material has been removed by weathering, particularly in the vicinity of the cracks. Thus, the occurrence and movement of ground water in the Stockton are in part, functions of the degree of weathering of the rock. The effectiveness of weathering and the number and size of the cracks decrease with depth, and the porosity of the Stockton has a corresponding decrease with depth, becoming negligible in the virgin rock below the weathered zone. The thickness of the weathered rock varies from place to place according to the topography, but it probably seldom exceeds about 500 feet, and it is not generally worthwhile to exceed that depth in drilling for water.

Ground water in the Stockton formation commonly occurs under artesian or semi-artesian conditions, chiefly in the sandstone and conglomerate beds that are interlayered with red shale throughout the formation. In some areas the artesian pressure is apparently a function of the bedding, the shale constituting the confining beds. These conditions are only of local significance, because the bedding is so lenticular and erratic that individual shale beds are not continuous for any appreciable distance, along either the dip or the strike of the formation. Furthermore, the dip of the bedding is so steep—averaging 10 degrees or more—that a selected bed is not water-bearing for any appreciable distance down dip, because it grades into unaltered rock at moderately shallow depths. The artesian pressure in the Stockton is more commonly related to vertical changes in permeability that occur in the formation. The cementing material is apparently less susceptible to solution in some zones than in others; furthermore, gradations in the texture of the sediments may account for significant vertical changes in permeability in the section. Thus the occurrence and movement of ground water in the Stockton formation is largely controlled by the configuration of the base of the weathered zone and by vertical changes in the permeability of the sediments. Recharge to the ground-water reservoir percolates downward in localities where confining layers are absent, joins the body of ground water, and moves laterally, under hydrostatic pressure, toward points of discharge.

The competency of the confining layer and the rigidity of the aquifer are reflected in the generally low values of the coefficient of storage of Stockton aquifers. Only a few pumping tests have been conducted on wells tapping the Stockton formation. Data are, therefore, not abundant, but preliminary tests indicate that the coefficient of storage probably ranges from about 0.00001, a value characteristic of artesian conditions, and the more nearly normal value, to about 0.001, a value characteristic of semi-artesian or possibly water-table conditions.

The Stockton formation has a wide range in permeability, but, considered in its entirety, it probably has the highest average permeability of the consolidated-rock aquifers in the region. The coefficients of transmissibility determined in pumping tests range from about 1,000 to about 35,000 gpd/ft (gallons per day per foot) with the more common values in the order of 5,000. Specific-capacity tests for 23 wells that tap the Stockton formation show a range in values from 0.35 to 44 gallons per minute per foot of drawdown and an average specific capacity of about 6 gallons per minute per foot.

In accord with these hydraulic characteristics of the aquifer, different wells in the Stockton have a wide range of drawdown for a given rate of discharge. The decline in water level in response to the withdrawal is generally translated rapidly throughout the aquifer in the vicinity of the well. Therefore, the proper spacing of wells is especially important for efficient utilization of the ground-water supply, because wells that are too closely spaced may be expected to have appreciable mutual interference, resulting in loss of yield and increased operation and maintenance costs.

The Stockton is the most reliable source of water for industrial and public supply in the upland areas of the region. Nevertheless, the largest and most dependable yields generally occur in the valleys where weathering is deep and bodies of surface water or saturated beds of permeable material overlying the rock offer ample sources of recharge. Records are available for 390 wells that range in yield from 1 gallon per minute to 900 gallons per minute and have an average yield of 41 gallons per minute.

The chemical quality of the ground water from the Stockton cannot be characterized by a single typical analysis. The water commonly contains low to moderate concentrations of dissolved solids and hardness-forming minerals and is generally low in iron content. Locally the water may be relatively highly mineralized and hard, usually because of larger concentrations of calcium associated with sulfate. The origin of the sulfate is not definitely known, but it is probably derived from the mineral glauberite. In general the water is satisfactory for most uses. Data on the quality of the water from the Stockton formation are given in table 9.

The temperature of the water ranges from about 52° F to about 57° F, according to the depth of the well. A few higher temperatures have been reported, but these probably result from storage of the water before it was sampled, and do not reflect conditions in the aquifer.

Lockatong formation

Geology

The outcrop pattern of the Lockatong formation is similar to that of the Stockton formation. It is exposed in three belts each of which lie to the northwest of, and in normal stratigraphic position to, the corresponding belt of Stockton beds. The Lockatong formation also is exposed in a number of narrow bands to the north of each belt where it interfingers with red beds of the overlying Brunswick shale. The interfingering relationship is not shown on the geologic map, because the scale of the map does not permit such detail.

The Lockatong consists chiefly of dull red and gray to black thick-bedded argillite (or mudstone) and occasional zones of thin-bedded black carbonaceous shale. Locally, thin layers of impure limestone and/or calcareous shale are present. The upper beds of gray argillite are extensively interbedded with dark red argillite. The rocks are evenly bedded and very fine grained; coarse-grained sediments are almost totally lacking except in those lower beds which are transitional with the underlying Stockton formation. Small crystals of calcite and pyrite are numerous in some of the argillite beds and absent from others. Ripple marks are rare, but mud cracks occur almost everywhere throughout the formation.

The Lockatong formation does not exhibit the chaotic interbedding and intergrading of deposits of different textures that is so characteristic of the Stockton formation. Many individual beds or sequences of beds can be traced for considerable distances along the strike. McLaughlin (unpublished manuscript) has used the more persistent strata in subdividing the Lockatong formation into several distinct members which can be recognized throughout the area of outcrop.

The thickness of the Lockatong formation varies greatly from place to place. According to McLaughlin (unpublished manuscript) the thickness of the formation in Bucks County is nearly 4,000 feet in the northernmost belt and ranges between about 2,000 feet and 3,000 feet in the southernmost belt. The Lockatong thins to the west, and is absent in northwestern Chester County.

The Lockatong formation conformably overlies the Stockton formation with only local interfingering of beds. The top of the Lockatong formation is conformable with the overlying Brunswick shale but the contact is transitional and marked by a thick sequence of interbedded red and gray shale. Northeastward in New Jersey and westward in Berks County, Pa., where the Stockton and Brunswick formations are in conformable contact with one another, the Lockatong is entirely absent from the section.

Argillite of the Lockatong is a prominent ridgemaker throughout the area. The courses of the smaller streams are largely controlled by the bedding; hence, the outcrop area of broad belts of the Lockatong is characterized by broad ridges that approximately parallel the strike of the argillite beds. Where interbedded with the less resistant Brunswick shale, the Lockatong tends to form rather distinct ridges.

The boundary between the Stockton and Lockatong formations is commonly marked by a sharp change in topographic slopes, and in places by a steep escarpment, the upland level of the argillite of the Lockatong being as much as 200 feet above the terrane of the Stockton.

Hydrology

The hydrology of the Lockatong formation is somewhat comparable to that of the crystalline rocks. The Lockatong contains both fracture and solution porosity where it has been faulted and jointed and exposed to the forces of weathering. Ground water occurs under water-table conditions in the secondary openings, to the depth of the base of the weathered zone.

In general, the Lockatong is inferior to the crystalline rocks as a source of water. The residual weathering product of the mudstone tends to fill the voids in the rock, thus the capacity of the Lockatong to store and transmit water is very low. The specific capacities of 65 wells for which records are available range from 0.02 to 2.0 gallons per minute per foot of drawdown of water level and average slightly more than 0.6 gallon per foot. Reported yields of 205 wells that tap the Lockatong range from 0.2 gpm to 55 gpm and average about 10 gpm.

The water in the Lockatong characteristically is moderately to highly mineralized and hard, but it is generally free of objectionable quantities of iron. The analyses of two samples given in table 9 are representative of water in the formation having better than average quality. Hall (1934) lists analyses of 7 samples from the Lockatong. The concentration of dissolved solids ranged from 199 ppm to 1,050 ppm and averaged 418 ppm; and hardness ranged from 162 ppm to 533 ppm and averaged 285 ppm. Despite the relatively high mineral content, the water from the Lockatong does not commonly contain objectionable concentrations of any constituents except the hardness-forming minerals. It is used for domestic and stock purposes without treatment, but it is generally softened when used for industrial or public supply.

Brunswick shale

Geology

The Brunswick shale has a heterogeneous outcrop pattern owing to the effects of faulting, intrusion by igneous rocks, and interfingering with the underlying Lockatong formation. Thus it does not crop out in belts in the manner of the Stockton and Lockatong. The lower beds of the Brunswick shale occur in sinuous bands which alternate with similar bands of the Lockatong formation; the upper beds of the Brunswick occur in irregularly-shaped exposures.

The Brunswick shale is the most uniform lithologic unit in the Newark group. It is a sequence of monotonously similar, irregularly bedded, soft red argillaceous shales locally interbedded with fine-grained red sandstone. The lower beds of the Brunswick in the zone of transition with the Lockatong formation, include a considerable thickness of thick-bedded hard red argillite and occasional beds of tough gray shale. The argillite grades upward into typical soft red shale, and near the top of the formation, there are rare recurrences of the more resistant rocks like those of the Lockatong.

The Brunswick shale does not display a prominent cleavage, but it contains numerous cracks or joints which are commonly inclined at high angles to the plane of the bedding. Ripple marks, mud cracks, and raindrop impressions occasionally occur in the shale.

Near the northern border of the Triassic basin, the Brunswick shale commonly contains beds of fanglomerate interbedded with the red shale. These occur from the bottom to the top of the formation in this area, but they are more numerous and thicker, and contain coarse-grained sediments, in the upper part. A typical occurrence of fanglomerate is described by McLaughlin (unpublished manuscript) as follows:

> "The transition from red shale and sandstone to fanglomerate is gradual. As a sandstone bed is traced north towards the border, at first a few scattered pebbles appear in it. Farther north the pebbles are more numerous; the bed thickens, and additional bands of conglomerate appear."

The conglomerate consists chiefly of well-rounded quartzite pebbles, but pebbles of limestone and calcareous sandstone are common. Locally the pebbles become angular and calcareous forming a limestone breccia.

The Brunswick shale has been extensively intruded by diabase dikes and sills. Near the instrusive bodies the shale has been altered to a hard, dark-colored hornfels that often closely resembles the argillite of the Lockatong but is somewhat harder. The apparent width of the altered zone, as evidenced in the outcrop, ranges from a few feet to a mile or more, but the true thickness of the altered rock probably never exceeds a few hundred feet.

The Brunswick is the thickest of the Triassic formations. The true vertical thickness probably equals or exceeds 6,000 feet at many places in the region.

The relationship between the Brunswick and the underlying Lockatong is described above in the discussion of the Lockatong formation. In general, the Brunswick shale conformably overlies the Lockatong, but the lower beds of the Brunswick extensively interfinger with an appreciable thickness of beds of the Lockatong. The youngest beds of the Brunswick shale have been eroded away in the 11-county region. In the valley of the Delaware River, deposits of Cretaceous, Pleistocene, and Recent age unconformably overlie the shale.

Eastward and westward of the 11-county region, the Brunswick shale grades along the strike into sandstone and conglomerate. Northward, toward the source of its sediments, the Brunswick thins along the bedding and also grades into the border-conglomerate facies. In many places the northern limit of the Newark group is determined by faults, but in some areas the Brunswick overlaps rocks of Paleozoic age. The marginal faults probably represent local post-depositional movement, not regional movement along the entire northern border of the basin.

Hydrology

The Brunswick shale contains water under both water-table and semi-artesian conditions in the weathered zone of the formation, which may extend to depths of 600 feet or more. A water-table aquifer of low permeability, comprising the highly-weathered zone of the formation, occurs to depths of about 250 feet. One or more rather permeable semi-artesian aquifers, consisting of beds of partly altered rock rarely more than 20 feet thick, occur to depths of about 600 feet. In both types of aquifers the saturated voids are believed to be mainly vertical joint fractures, many of which have been enlarged by solution. The water-table aquifer contains many more fractures than the semi-artesian aquifers, but the near-surface rocks have been so thoroughly decomposed that many of the cracks are filled with clay residual from the weathering of the shale.

The water-table aquifer is recharged chiefly by preciptation, a part of which seeps through the soil mantle to the water table. Locally the beds may be recharged by induced infiltration of surface water from a nearby stream. The semiconfined aquifers which underlie the water-table aquifer are, in turn, recharged by drainage from the water-table zone; because of their low storage capacity, however, the total supply of water in storage is essentially that in water-table storage. Ground-water storage in the shale is low, ranging from 1 to 2 percent of the total volume of saturated rock in the upper 300 feet and even less at greater depths (Herpers and Barksdale, 1951, p. 27).

Many wells in the Brunswick shale tap both water-table and artesian aquifers, and their yields are derived in part from both sources. Consequently, coefficients of transmissibility and storage determined by the analysis of field pumping tests must be considered in the light of local conditions and may not be compared with coefficients from other tests. In some cases the coefficients may be meaningless because they represent combined effects of withdrawals from aquifers of different types. The semi-artesian aquifers are more permeable than the water-table aquifers, but their yield of water is accompanied by rapid declines in artesian pressure and there results a hydraulic gradient downward from the water-table to the artesian zone. A typical well may have a relatively high yield when drilled, but the yield declines as the water-table aquifer around the well is unwatered. The ultimate yield of a well is related to the saturated thickness of water-table aquifer it penetrates, and the rate at which the semi-artesian aquifers it taps are recharged from above. The history of many drilled wells shows that the long-term yield of a well is commonly no more than about one-third of the initial yield.

The Brunswick is a reliable source of water for domestic, industrial, and public supply. In New Jersey this is particularly true where wells are located adjacent to permanent surface-water sources hydraulically connected to aquifers and where the shale is overlain by saturated layers of permeable sediments. The reported yields of 325 wells for which records are available in the 11-county region range from 0.5 to 420 gpm and average 16 gpm. The average yield for drilled wells 6 inches or more in diameter is 40 gpm.

The water from the Brunswick is generally moderately mineralized and moderately hard to hard. The mineral content of the water increases with depth, but it does not commonly contain objectionable amounts of any constituents. Its iron content is rarely high enough to be objectionable. A few wells yield water that contains relatively large amounts of sulfate, perhaps from local solution of the minerals glauberite and gypsum which have been noted in the rock.

The water is generally of satisfactory quality for most uses. It is commonly of acceptable quality for public supply according to the suggested standards of the U. S. Public Health Service. Except for use in steam boilers, it is satisfactory for most industrial purposes. The temperature is nearly constant and ranges, in individual wells, from about

50° F in shallow wells (50-150 feet deep) to about 55° F in deep wells (more than 400 feet deep). Chemical analyses of representative samples of water from the Brunswick shale are given in table 9.

Diabase

In northern Mercer County, N. J., and in Bucks and Montgomery Counties, Pa., beds of Late Triassic age, particularly the Brunswick shale, are extensively intruded by diabase, popularly known as trap-rock. It occurs in nearly vertical dikes, which cut across the bedding of the sedimentary strata, and in sills which commonly are conformable with the bedding. As the diabase has greater resistance to erosion than the sediments, it forms conspicuous ridges where dikes are exposed and prominent uplands where sills are exposed.

The lithology of the diabase is remarkably uniform. It contains nearly equal amounts of plagioclase feldspar and augite, with magnetite, ilmenite, quartz, and apatite as accessory minerals. Diabase weathers to boulders which, when exposed, are often covered with a rust-colored oxidized coating; fresh surfaces are greenish gray in color and have a conchoidal fracture. The texture of the diabase varies somewhat according to its mode of occurrence. In the thinner dikes the rock may be exceedingly fine grained, but the larger dikes and sills consist of medium- to coarse-grained rock that may resemble granite.

The diabase intrusions occurred late in the Triassic period. They cut rocks that range in age from Precambrian through Triassic, but they do not share in any of the crustal movements that occurred prior to the Triassic period.

The hydrology of the diabase is similar to that of the crystalline rocks of the Proterozoic and Paleozoic sequences.

CRETACEOUS SYSTEM

Lower Cretaceous series

Patuxent formation

Geology

The Patuxent formation was named for its development in the upper valleys of the Little and Big Patuxent Rivers in Maryland (Clark and Bibbins, 1897, p. 481). It crops out in a narrow belt which crosses Maryland and Delaware. This belt has not been identified in New Jersey, but heavy-mineral data indicate that it occurs in the subsurface in Salem County. The width of its outcrop is one to two miles in Delaware. The Patuxent formation is mainly sand, predominantly crossbedded and containing feldspar, partly kaolinized. It is generally unconsolidated, but a gravel at the base is cemented by iron oxides. Lenticular beds of clay are enclosed in the sand. The sands range in color from white to buff and purple: the clays are white, brown, red, and purple. Plant remains found in the clays and clayey sands have provided the paleontologic basis for assigning the Patuxent formation to the Early Cretaceous.

The strike of the Patuxent formation is approximately northeast, and the dip ranges from 40 to 140 feet per mile southeast. The thickness of the formation is difficult to determine, because it is not possible to distinguish it from the Patapsco and Raritan formations in well logs. Near the outcrop it probably does not exceed 350 feet in thickness.

In Delaware, the Patuxent formation rests unconformably upon the eroded surface of the older rocks of the Appalachian Highlands, such as the schists and gneisses of the Wissahickon formation. In Delaware, and probably in New Jersey, the Patuxent is overlain unconformably by the Patapsco formation. Exposures of the Patuxent formation may be seen near Newport, Delaware.

Hydrology

In New Castle County, Del., the Patuxent formation is an important aquifer, which supplied about 1.5 million gallons of water a day (mgd) during the period 1951 to 1956. The principal users were the Tidewater Oil Company near Delaware City, the Artesian Water Company (Tuxedo Park field), and the town of Newport. It is planned to increase pumpage at the oil company refinery to about 4 mgd.

The water from the Patuxent formation is generally of excellent quality. A representative analysis from 3 wells at the New Castle County Airport indicates a neutral water (pH 7.0) of bicarbonate type, relatively low in dissolved solids (86 ppm), and soft (hardness 45 ppm). Iron, at 0.75 ppm, is more than the Public Health Service standard of 0.3 ppm, (U. S. Public Health Service, 1946, p. 383). The water is usable for many purposes without treatment.

A large-scale test was run using wells believed to tap an aquifer in the Patuxent formation near Delaware City, Del. in January-February, 1955. One well was pumped at 500 gpm for 17 days, and water levels were observed in it, and in 5 observation wells. An average coefficient of transmissibility of 7,500 gpd/ft, and an average coefficient of storage of 0.0002 were obtained.

Yields of 52 wells in the lower aquifer in Delaware, equivalent to the Patuxent formation, ranged from 800 gpm to 3 gpm, and averaged 104 gpm, according to Rasmussen and others (1957). The specific capacities for 22 of these wells ranged from 10.6 to 0.40, and averaged 2.0 gpm per foot of drawdown. The variable nature of the Patuxent formation from place to place is indicated by these divergent values; however, some of the divergence may be due to differences in well construction. This, in turn, is determined to some degree by the needs of the well owner.

There is some question as to whether the aquifers of the Patuxent formation are hydraulically connected to those of the Patapsco formation and from there to the Raritan and Magothy formations. Certainly, in channel sands of this sort, connection at a distance if not locally is not unlikely. However, the connection, if present, may be quite devious, and relatively ineffective. Consequently, the Patuxent is considered a distinct unit in this report.

The outcrop of the Patuxent formation in Delaware covers about 30 square miles, disregarding the thin mantle of Pleistocene deposits. Part of this outcrop area is covered by clay members of the formation. Assuming that only half of the outcrop area is intake area for the infiltration of precipitation, at the rate of 1 mgd per square mile, and assuming further that recharge from the intake area in Maryland is not available for use in the 11-county region, then it may be concluded that insofar as intake capacity is concerned, the Patuxent might yield about 15 mgd in Delaware.

Still another factor that may limit withdrawals from the Patuxent is the danger of salt-water intrusion if the aquifer is exposed to salt water where it crosses the Chesapeake Bay or the Delaware River estuary.

The Patuxent formation in the 11-county region is probably capable of yielding substantially more than the 1.5 mgd currently being withdrawn from it.

Upper Cretaceous series
Patapsco formation

Geology

The Patapsco formation was named for the Patapsco River basin in Maryland in which these deposits were first recognized (Clark and Bibbins, 1897, p. 489). In the literature prior to 1948, this formation was considered to be Lower Cretaceous. The Upper Cretaceous dating has been questioned by Dorf (1952). This formation crops out throughout Delaware and Maryland. It is believed to be present in a subsurface section in Salem County, N. J. The breadth of outcrop of the Patapsco ranges from 2 to 5 miles in Delaware. It is not known to occur in outcrop in New Jersey. Because its lithology is similar to that of the Raritan formation there is a possibility that some of the beds mapped as lower Raritan in New Jersey may actually be Patapsco, or conversely, that some beds mapped as Patapsco in Delaware may actually be Raritan. Lithologically, the Patapsco formation consists of sands and clays differing from the Patuxent in the predominance of the clayey deposits, especially variegated clays having shades of red, gray, and chocolate. These clays are intercalated and interbedded with sandy clays, light colored sand, and gravelly sands. Lignite and pyrite are found in these deposits. Plant remains have been found in the Patapsco.

The strike of the formation is generally in a northeast direction, and the dip ranges from 40 to 100 feet per mile southeast. In Delaware, the Patapsco is considered to rest unconformably upon the Patuxent and to be overlain unconformably by the Raritan. The thickness of the Patapsco formation is difficult to determine because it cannot be separated in well logs from the Patuxent and Raritan formations on lithology alone. Preliminary clay mineralogy on samples from a well near Delaware City indicates that the Patapsco formation may be as much as 450 feet thick (Glass, 1955).

Hydrology

The Patapsco formation yielded about 1.6 mgd to wells in Delaware in the period 1951 to 1956. Yields of 29 wells in the middle aquifer of the nonmarine Cretaceous sediments in Delaware, a unit approximately equivalent to the Patapsco formation, ranged from 12 to 500 gpm and had an average of 89 gpm (Rasmussen and others, 1957). Similarly, specific capacities of 21 wells ranged from 0.32 to 5.3 and averaged 1.6 gpm per foot. These are low, and indicate the silty nature of many of the sand members of the formation.

Because the Patapsco formation has not been differentiated from the Raritan formation in parts of the 11-county region and because the aquifers in the Patapsco are believed to be interconnected with those of the Raritan, deviously if not directly, further consideration of its hydrology will be included in discussion of those formations.

Raritan and Magothy formations

Geology

The Raritan and Magothy formations are considered here as a unit because there is reason to believe that the major aquifers in them are connected with each other at distance, if not locally. In Delaware, the Patapsco formation is included in this unit for similar reasons. Both the aquifers and the intervening clays appear to lack continuity, with the aquifers being somewhat more continuous than the clays. The Magothy formation is overlain by a thick and apparently continuous layer of clay that prevents interconnection with higher aquifers. Likewise, the aquifers of the Raritan formation or of the Patapsco formation, where present, are underlain by confining materials that appear to prevent interconnections with any lower aquifers. Thus the aquifers in the three formations are generally interconnected, are separated from overlying and underlying aquifers, and may be considered very broadly as a single hydrologic unit in spite of the fact that in many places they are locally distinct. The geology of the Patapsco formation was discussed in the preceding section because of the relatively small area that it occupies in the region. This section will therefore be limited to a discussion of the geology of the Raritan and Magothy formations. In subsequent sections on hydrology, the Patapsco will be included where appropriate because it is believed to be a part of the same broad hydrologic unit.

The combined Raritan and Magothy formations have a maximum thickness of about 475 feet near their outcrop area. They crop out or are covered only by a relatively thin veneer of permeable deposits of Pleistocene or Recent age in a band several miles wide that extends from northeast to southwest from Long Island across New Jersey and Delaware into Maryland (Richards, 1945). Within the 11-county region, the outcrop area follows closely the general course of the Delaware River between Trenton, N. J., and Wilmington, Del. (See Figure 14.) The two formations dip gently to the southeast. The top of the Magothy dips at an average rate of about 45 feet per mile, and the basal beds of the Raritan dip at about 60 feet per mile. The two formations are overlain by progressively greater thicknesses of younger materials as they extend to the southeast. Presumably they extend beneath the coastal plain sediments south and east of this outcrop area all the way to the continental shelf, which is about 100 miles offshore along the coast of southern New Jersey. The Raritan and Magothy formations have been identified in deep test wells on the eastern shore of Maryland (Rasmussen and Slaughter, 1955). Recently a marine phase of the Raritan formation consisting of clay with a zone of massive limestone was encountered at the depth of 1,650 feet in a test well near Harrisville, Burlington County, N. J., (Richards, 1956a).

The thickness of both formations increases toward the southeast. The Raritan and Magothy formations lie as a great, slightly wedge-shaped layer sloping gently toward the southeast with only minor undulations. The thinner part of the wedge lies at shallower depths than its thicker portion. For example, in the vicinity of Camden, N. J., where the formations are near the surface, they have a combined thickness of about 400 feet. In the vicinity of Atlantic City, 40 or 45 miles down the dip, where the top of the Raritan is probably about 3,000 feet below the land surface, the combined thickness is estimated to be in the order of 1,500 feet.

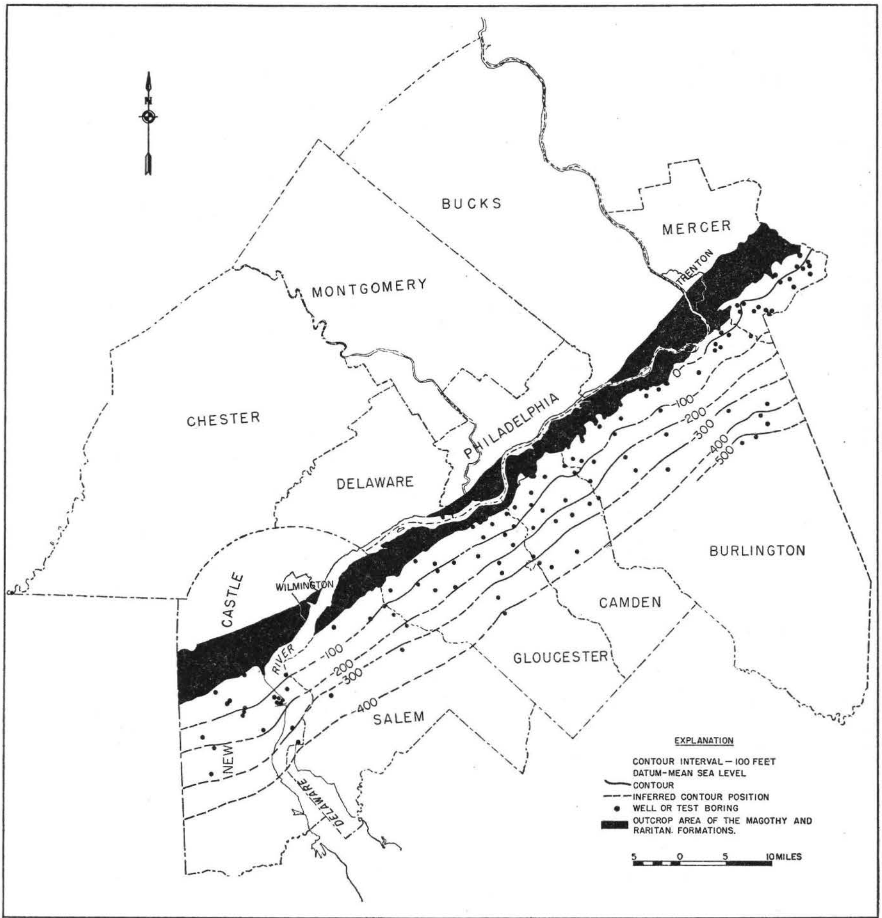

Figure 14.—Map showing the outcrop area of the Raritan and Magothy formations in the 11-county region and, by contours, the elevation of the top of the Magothy formation.

The Raritan formation derives its name from the Raritan River in Middlesex County, N. J. Typically it is composed of light-colored medium, to coarse-grained quartzose sand, containing some gravel, and vari-colored clays. Shades of white, yellow, brown, red, and light gray are characteristic of the materials. Lignite and pyrite occur in some beds. The Magothy formation derives its name from the Magothy River in Maryland. Typically it consists of beds of dark gray or black clay, that are often lignitic and contain pyrite, and alternating beds of white micaceous fine-grained sand. Rapid changes in the character of the Raritan and Magothy sediments are extremely common so that it is difficult to trace one bed or layer very far.

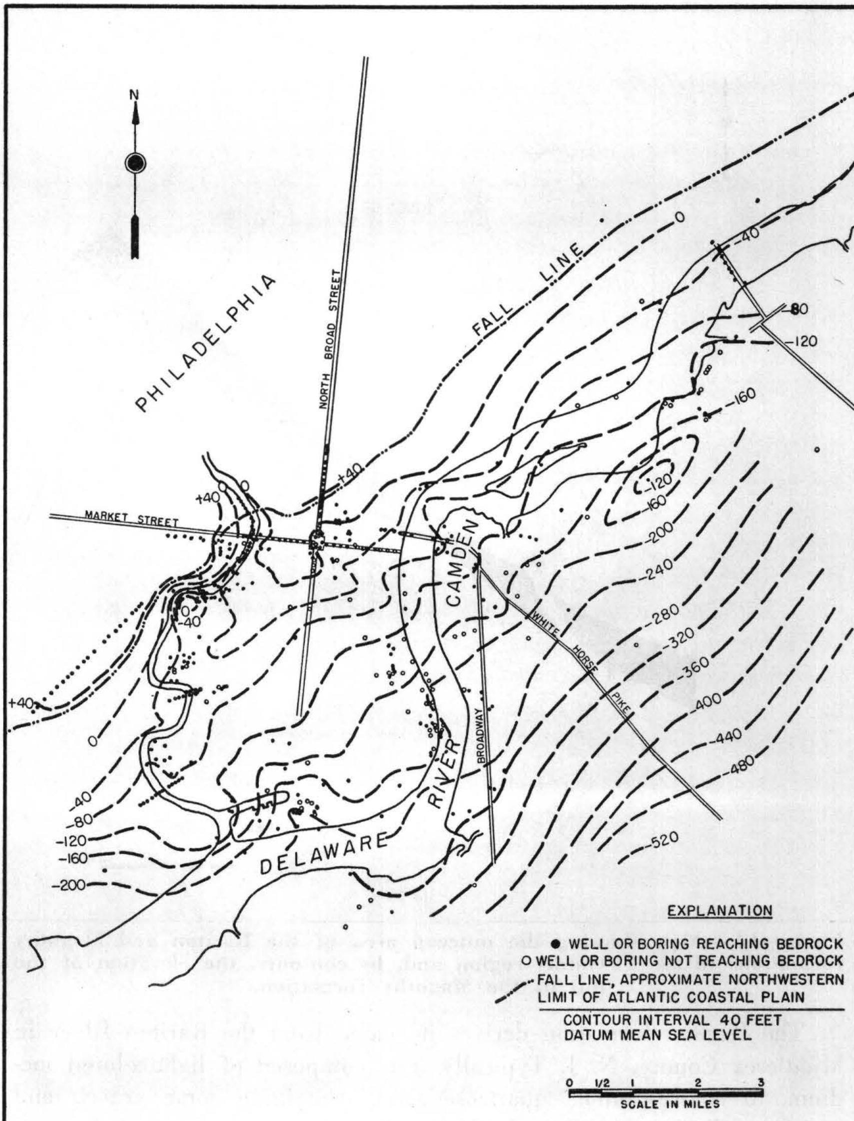

Figure 15.—Map showing by contour, the elevation and configuration of the bedrock in the Philadelphia-Camden Area.

In and near the outcrop area, the clay units in the two formations are generally composed of dense, tough, plastic clays. Exceptional beds appear to have been hardened until they approach the consistency of soft shales, but have not lost their plasticity. Many of the clays, particularly those of the Raritan formation, are suitable for use in the ceramic industry and some for the manufacture of fine china. They have been extensively mined for these purposes.

The sand units are usually well sorted. They vary in texture from very fine-grained sands in the Magothy to medium-, or coarse-grained sands and to fine-grained gravel in the Raritan. Rarely, small boulders or large cobbles, several inches in diameter, are observed in the outcrop of the Raritan or are recovered from wells that tap it.

In Pennsylvania and in most of New Jersey, the Raritan formation lies unconformably upon the eroded surface of much older rocks that range in age from Precambrian to Triassic. The approximate shape of this pre-Raritan surface in the Philadelphia-Camden area, where it has been reached by many wells and test borings, is shown on figure 15. At the land surface in Delaware and below the land surface in parts of southern New Jersey, the Raritan formation lies unconformably upon the Patapsco formation. The Magothy formation lies unconformably upon the Raritan formation and is overlain unconformably by the Merchantville clay. Lithology characteristic of the Magothy formation is rarely encountered in the central part of the 11-county region. Whether this is due to a change of facies of the Magothy or to its absence is not clear.

In Middlesex County, N. J., the Raritan has been divided into several members of alternating sands and clays (Ries, Kummel, and Knapp, 1904; Barksdale and others, 1943). Beyond the limits of that county, and to some extent within its borders, these members tend to lose their identity, and it has not been possible to trace them for any great distance. Counterparts of the two major water-bearing sands in Middlesex County appear to exist at Asbury Park, N. J., and in the Camden, N. J.-Philadelphia, Pa. area, but it has been impossible to correlate these sands between any two of the three localities. It seems probable that they may have been deposited more or less contemporaneously, but they may not be continuous from one locality to another.

The Raritan formation is considered to have been deposited largely by the action of streams along the margin of the continent. This accounts for the discontinuity of the individual beds of sand and clay. Throughout most of its extent, the only fossils found in the Raritan are plant remains. In a few localities, marine fossils have been found, indicating that at least a part of this formation was deposited under marine conditions. Likewise, the Magothy formation is partly marine and partly nonmarine. It contains marine fossils near Cliffwood in Monmouth County, N. J., as well as many plant remains.

Good exposures of sediments characteristic of the Raritan formation may be seen in the Ward sand pit near Palmyra, Camden County, N. J. Good exposures of the Magothy formation may be seen in the Chesapeake and Delaware Canal in New Castle County, Del.

Hydrology

Importance of Aquifers:—On the basis of developed capacity and of potential capacity to yield water, the aquifers in the Raritan and Magothy formations are by far the most important hydrologic unit in the 11-county region. The aquifers in the Patapsco formation, where present, are believed to be a functional part of the unit. However, they are relatively thin and occur only in a small part of the region. The major aquifers in this unit are in the Raritan formation. Others yield small to moderate quantities of water. Some of them probably furnish recharge to the major aquifers through interconnections either locally or at a distance.

The Raritan formation contains some of the best aquifers in the 11-county region. The sands in the Magothy formation are generally finer and less productive than those in the Raritan. This is particularly true in the northeastern part of the region and in Middlesex and Monmouth Counties, N. J., where very few, if any, large capacity wells are developed from the Magothy. To a degree, this may be due to the fact that aquifers in the Raritan are generally found beneath the Magothy, and wells are usually drilled deeper to encounter them without attempting to develop the Magothy. In this area and to a considerable extent throughout the 11-county region, the sands in the Magothy serve primarily as a source of recharge for the more permeable sands of the Raritan formation.

The reliably anticipated yield of wells tapping the aquifers in the Raritan is higher than that from any other aquifer in the 11-county region, except for wells tapping the Cohansey sand, which appear to be about equally productive. The yield of individual wells depends, of course, upon the construction details and upon many local conditions. With this in mind, it may be said that the yield of wells tapping aquifers in the Raritan ranges from a few gallons a minute for household wells to at least 1,400 gallons per minute for large, carefully constructed and favorably located municipal or industrial wells. Many wells tapping the Raritan yield from 300 to 1,000 gallons a minute.

Physical Properties of Aquifers:—During the investigations that preceded this report, 10 aquifer tests were made by pumping wells tapping the sands in the Raritan formation (see table 10). Analysis of the test data indicates an average coefficient of transmissibility of the aquifers

Table 10.—Coefficients of permeability, transmissibility, and storage in the Raritan formation.

Owner and Location	*County*	*Range in Coefficient of Transmissibility (gpd/ft)*	*Range in Aquifer Thickness (ft.)*	*Range in Coefficient of Permeability (gpd/ft²)*	*Range in Coefficient of Storage (dimensionless)*	*Source of Data*
Air Reduction Co., Riverton, N. J.	Burlington	150,000	100*	1,500	1.5×10^{-4}	U.S.G.S. unpublished data
California Oil Co., Barber, N. J.	Middlesex	4,000 to 14,000	10 to 24	240 to 660	8.1×10^{-2} to 4.0×10^{-5}	-do-
Camden Water Dept., Camden, N. J.	Camden	23,000 to 79,000	19 to 46	680 to 2,500	1.7×10^{-4} to 5.6×10^{-4}	U.S.G.S. and Leggette and Brashears unpublished data
E. I. duPont deNemours, Gibbstown, N. J.	Gloucester	47,000	25±	1,480	1.5×10^{-4}	U.S.G.S. unpublished data
N. J. Water Co., Haddon Hts., N. J.	Camden	124,000	70±	1,800	1.0×10^{-3}	-do-
N. J. Water Co., Stockton Station, Camden, N. J.	Camden	53,000 to 64,000	45 to 50	1,060 to 1,400	7.2×10^{-5} to 8.6×10^{-5}	-do-
N. Y. Shipbuilding Corp., Camden, N. J.	Camden	62,000	24+*	2,600*	1.2×10^{-3}	-do-
E. I. duPont deNemours, Parlin, N. J.	Middlesex	50,000 to 76,000	85	590 and 890	3.7×10^{-5} and 8.6×10^{-5}	-do-
Hercules Powder Co., Parlin, N. J.	Middlesex	100,000	66	1,500	1.55×10^{-3}	-do-
Perth Amboy Water Dept., Old Bridge, N. J.	Middlesex	17,000 to 67,000			2.4×10^{-3} to 5.8×10^{-4}	-do-
Texas Co., Westville, N. J.	Gloucester	51,000 to 68,000	40 to 67	1,020 to 1,400	1.7×10^{-4} to 9.0×10^{-5}	-do-
U. S. Navy Yard, Philadelphia, Pa.	Philadelphia	51,000 to 69,000	54 to 63	920 to 1,200	2.0×10^{-4} to 8.0×10^{-5}	U.S.G.S. open-file memorandum by Graham and Kammerer

*Aquifer probably not fully penetrated

of about 45,000 gpd/ft, an average coefficient of storage of about 0.0003, and an average coefficient of permeability of about 1,000 gpd/ft^2 (gallons per day per square foot).

Laboratory tests were not made during this investigation on samples from the aquifers in the 11-county region, because it was felt that the pumping tests would be more significant. However, laboratory tests were made on samples from the Raritan and Magothy formations in the course of an earlier investigation in Middlesex County, N. J., (Barksdale and others, 1943). These tests gave permeabilities for various levels in the aquifers in the Raritan, ranging from 25 to 3,500 gpd/ft^2. The weighted average was about 1,300 gpd/ft^2. The tests also showed porosities for the aquifers in the Raritan ranging from 26 to 46 percent of the volume of the sediments and averaging about 40 percent. They indicated an average specific yield for the aquifers in the Raritan formation of about 35 percent by volume. For the sands of the Magothy, the permeability was about 400 gpd/ft^2, the porosity about 45 percent, and the specific yield about 40 percent.

Quality of Water:—By far the major part of the water from the Raritan and Magothy formations is of excellent chemical quality and is suitable for most uses with little or no treatment, except that it is necessary to remove iron or to reduce acidity in many instances. Throughout most of the region, the water from the Raritan and Magothy formations contains less than 150 ppm of dissolved solids and in some areas, it contains less than 50 ppm. The water from a majority of the wells sampled in the investigations that preceded this report contained concentrations of iron that would require its removal for many uses. Fewer samples indicated a need for the reduction of acidity. The water from many wells is low in all dissolved mineral constituents. The overall quality of the water from these aquifers in different parts of the region, as indicated by its dissolved mineral content, is shown on figure 16.

At a considerable distance downdip from the intake area, the aquifers are believed to contain salt water. This water has either remained in the aquifers from the time of their deposition or has re-entered them from the ocean after changes in the levels of the water table in the intake area and/or in sea level. At equilibrium, the position in the aquifers of the transition zone between fresh and salt water is determined by the altitude of the intake area and the relative specific gravities of the waters involved, in accordance with the dynamics of the system and the principles of Ghyben and Hertzberg.

The variations in the quality of the water from these aquifers show a definite relation to the sources of recharge and to the pattern of water movement through the aquifers. The water in and near those parts of

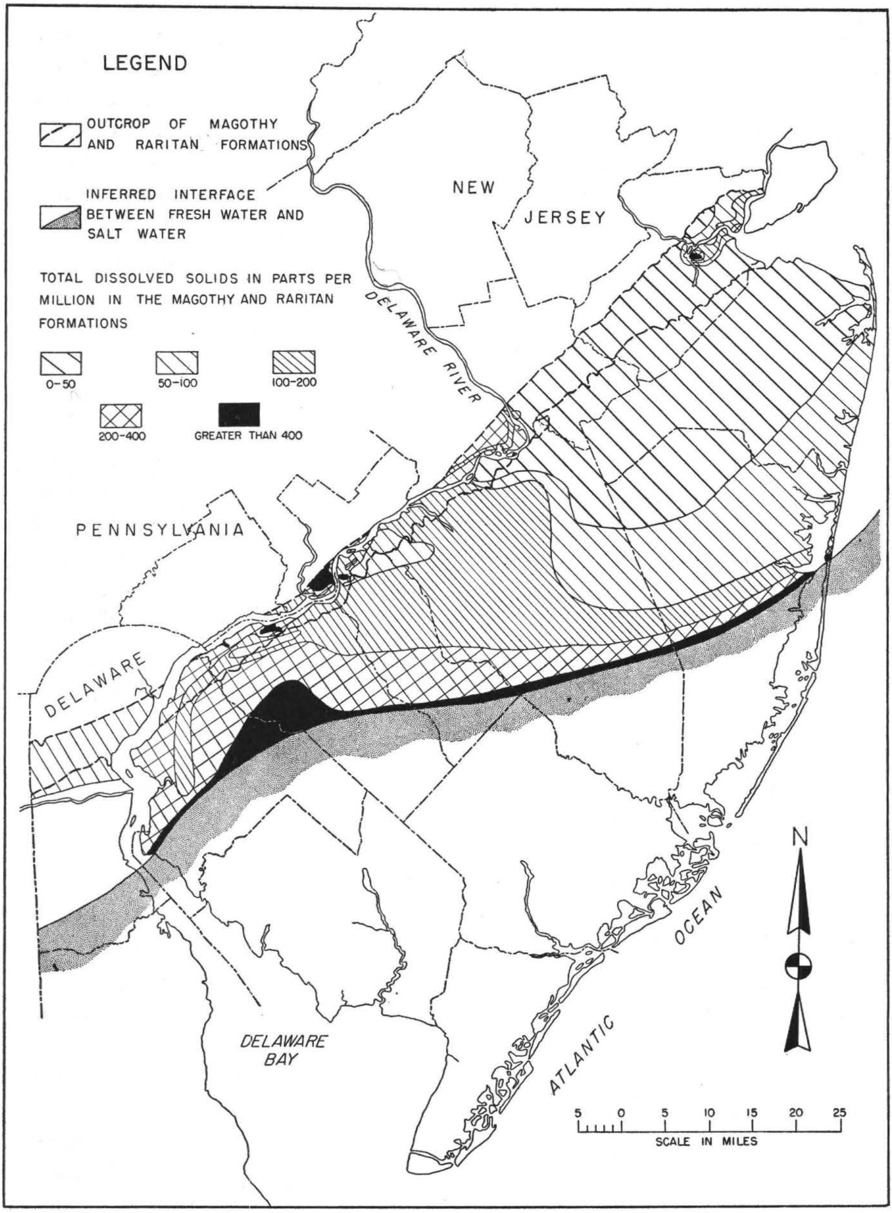

Figure 16.—Map showing, by shading, the regional variation in the dissolved mineral content of water from aquifers in the Raritan and Magothy formations and the inferred interface between fresh water and salt water in these aquifers.

the intake area that receive their recharge from precipitation is soft and only slightly mineralized. However, the pH indicates slight acidity and some corrosiveness. Most of the samples of water analyzed from these areas did not contain objectionable concentrations of iron. In areas farther down the dip, where the water has moved slowly through the aquifers for considerable distances, the water is moderately mineralized, soft to moderately hard, moderately alkaline according to its pH, and noncorrosive. It generally contains quantities of iron in solution that would be objectionable for some purposes. During its long contact with the aquifer, the water presumably dissolved additional mineral matter from it. The nature of the dissolved minerals may also have been changed to some degree by base exchange. Wells farthest down the dip, or more precisely those farthest along the path of water movement, generally yield the most highly mineralized water.

The predominant anion in the water from these formations in the region is bicarbonate, concentrations being from 6 to 323 ppm and averaging 104 ppm. Average concentrations of sulfate, chloride, and nitrate are 15, 5, and 2 ppm, respectively. An exception is the water obtained from wells in the Salem-Woodstown area of Salem County where high chloride concentrations have been encountered, probably because of the proximity to the interface between salt and fresh waters in the aquifer. A chloride concentration of 137 ppm was found in water from a well in Woodstown, N. J.

Concentrations of fluoride exceeding 1 ppm have been encountered in the waters from a triangular area between Sewell, Glassboro, and Woodstown in Gloucester and Salem Counties, N. J. The maximum concentration, 2.6 ppm, was found in the sample from Woodstown.

In some areas of heavy pumping in or near the intake areas of the aquifers, the normal flow pattern has been reversed, so that induced recharge from bodies of surface water, mainly from the Delaware River, now supplies much of the water drawn from wells. In such areas, the quality of the surface water controls or strongly affects the quality of the water from the wells. The water in the Delaware River upstream from Camden has generally been of satisfactory quality for recharging the aquifers, and along this reach of the river, the quality of the ground water has not been affected adversely by induced recharge. In some places downstream from Camden, the river water is more highly mineralized due partly to pollution but mainly to the advance of salt water up the channel from the Atlantic Ocean. Induced recharge from the river in such places adversely affects the quality of the ground water.

In a few limited areas, the water in the aquifers of the Raritan and Magothy formations has been badly contaminated by the disposal of wastes or by a combination of waste disposal and induced recharge from highly mineralized sources (see figure 16). Such areas occur in Philadelphia County, Pa., and in Gloucester and Camden Counties, N. J. The highly mineralized area near Salem and Woodstown, N. J., is probably due to the proximity of the salt water that fills the lower part of the aquifer as already explained.

The serious contamination in areas of Gloucester County, N. J., is due partly to the intrusion of saline water from the channel of the Delaware River and partly to the dumping of industrial wastes on the land surface. Two aquifers are generally present in this area; the shallow one is contaminated from water percolating through the waste-disposal areas. The casings of some wells that tap the lower aquifer have been so badly corroded, where they pass through the upper sand, that highly mineralized water is admitted and conducted into the lower aquifer. Furthermore, the lower aquifer is generally exposed to induced recharge from the deeper parts of the river where salt water is usually present. Fortunately, the contamination in Gloucester County has thus far been prevented from spreading to other parts of the aquifers because of continued heavy local pumping. However, if the contamination should become so severe as to cause a shift of pumping to uncontaminated areas to the southeast, the area of highly mineralized water would be expanded in that direction and more distant wells would be increasingly affected by it.

The highly mineralized area in Philadelphia and Camden Counties is discussed in some detail in a later section on the movement of ground water in the region (see pp. 108 to 128).

Analyses of samples of water from the aquifers of the Raritan and Magothy formations are given in table 9. In this table, an effort was made to give representative analyses from wells in what may be called the different quality zones. It should be emphasized that most parts of the aquifers yield water of low mineralization. Analyses of other water samples from the Raritan formation are given in table 11 on page 122.

Recharge:—The aquifers of the Raritan and Magothy formations are recharged by precipitation on their intake areas, by induced infiltration from bodies of surface water that lie on their intake areas (mainly the Delaware River), and by leakage through the overlying or underlying aquicludes from the aquifers above or below. This last source of recharge is considered relatively unimportant because the head differentials are generally not large and the aquicludes are relatively impermeable. Nevertheless, the possibility of considerable recharge in this manner over many hundreds of square miles of aquifer should not be completely overlooked.

A major source of recharge for the aquifers of the Raritan and Magothy formations is precipitation on their outcrop areas. Within the 11-county region the intake area that probably can contribute recharge water from precipitation is approximately 285 square miles. Of this area, about 155 square miles lie in New Jersey, about 70 in Pennsylvania, and about 60 in Delaware. In arriving at this figure, it is assumed that water falling on clay members of the two formations migrates beyond their lateral limits and is absorbed by the underlying aquifers. Thus, the entire outcrop area of the formations may be considered as intake area. In view of the rather general covering of permeable Pleistocene deposits which would absorb water and funnel it to the aquifers, this assumption seems reasonable.

After the losses to evaporation and transpiration have been deducted, there remain about 20 or 21 inches of the average annual precipitation available for recharge. This is equivalent to about 1,000,000 gallons a day throughout the year for each square mile of intake area. On the basis of the figures and assumptions given above, the potential recharge of the aquifers from precipitation would average about 285 million gallons daily if conditions were such that none of the available recharge would be rejected. It is, however, seldom, if ever, feasible to establish a network of wells that will capture all the potential recharge that an aquifer can receive from precipitation so that none will be rejected. A yield based upon recharge from precipitation of 285 million gallons a day may not, therefore, be attainable. A more likely figure would be in the order of 200 million gallons a day.

Rejected recharge occurs when an aquifer is full of water in its intake area during a period of precipitation. One cause for this condition is the inability of the aquifer to transmit water away from the intake area fast enough under the hydraulic gradients that exist between the intake area and the points or areas of discharge. Because much of the intake areas of the aquifers of the Raritan and Magothy formations is at a considerable distance from the areas of discharge, the hydraulic gradients are gentle and the resulting low rate of water movement away from the intake area may not accommodate all of the water that is available for recharge.

The Delaware River, which flows over the outcrop area of the Raritan and Magothy formations from Trenton to Wilmington, is probably at least as important a potential source of recharge as precipitation on the dry land part of the outcrop area. Before this potential recharge can become effective, however, it is necessary to reverse the natural gradient, which is from the aquifer toward the river. This has been done in some areas by pumping from wells near the river. Where the river lies above an aquifer, the quantity of water that can enter the aquifer is not limited by the availability of water. The limit is either the infiltration capacity of the aquifer (or of the overlying silt, mud, or clay), or its capacity to transmit the water away from the intake area.

Infiltration capacity is a term developed to indicate the capacity of the land surface to admit water. Normally on land that is relatively dry or that was very recently wetted by precipitation or inundation there is a suction effect from dryer materials beneath the surface and perhaps resistance from entrapped air. These factors would not apply where the sediments are saturated from the land surface down. There would be no entrapped air, and the only force causing water to move away from the surface would be a gradient towards a discharge area. Thus, the usage of the term, infiltration capacity, in describing an aquifer under a body of surface water is somewhat different from the usage in describing similar material on dry land.

The infiltration capacity of aquifers in the Raritan probably is not the limiting factor in the amount of recharge from the river. The infiltration capacities of the river-bottom silts and muds are much lower, but probably still so large that they do not limit the potential recharge. A sand in the Raritan at the Perth Amboy water works accepted artificial recharge continuously at the rate of 600,000 gallons a day per acre (Barksdale and DeBuchananne, 1946). On this basis, a strip of aquifer 200 feet wide and 1 mile long on the bottom of the river could absorb about 15 mgd. At a dip of 60 feet per mile, an aquifer 60 feet thick would have an outcrop 1 mile wide. If such an aquifer should crop out entirely under the river for a distance of 1 mile, it would be exposed to the river water for a total of 640 acres or 1 square mile. If the infiltration capacity of this area were 600,000 gallons per day per acre, it could absorb nearly 400 mgd. Almost certainly, the aquifer could not transmit this much water away from the intake area unless large withdrawals were being made through wells situated in the river so that very high gradients were established. The magnitude of the figures indicates that the infiltration capacity of the aquifers in the Raritan is not the factor that limits recharge from the river.

Thus the factor that will probably govern the amount of recharge from the river to the aquifer is the transmissibility of the aquifer and the overlying silts, muds, or clays. For the purpose of estimating the potential recharge from the river, consider a section of an aquifer 1 mile wide along the strike and extending straight down the dip. Assume that the aquifer is 60 feet thick, has an average permeability of 1,000 gpd/ft^2, a dip of 60 feet per mile, and an exposure beneath the river adequate to absorb all the water that can be transmitted from the intake area to some point of discharge down the dip. Also assume that the aquifer is confined from the edge of its intake area under the river to the point of discharge. To avoid unwatering a part of the aquifer and thus decreasing its carrying capacity, the hydraulic gradient would be limited to the dip of the aquifer or to 60 feet per mile. The quantity of water that the assumed 1-mile section of the aquifer could transmit would be the product of its permeability, its saturated thickness, and the maximum hydraulic gradient in feet per mile, that is, 1,000 x 60 x 60 or 3.6 mgd. This is much less than the figures developed in the preceding paragraph for the quantities of water that might infiltrate the aquifer.

The hydraulic gradient might be increased under favorable conditions. For example, the river might be 30 feet deep over the outcrop area and a well field might be very near the river. This would increase proportionally the quantity of recharge that might be induced from the river. If a well field were on the southeast bank of the river and half a mile from the edge of the submerged part of the aquifer, the gradient would be approximately twice that in the example above. Under the favorable conditions suggested above, the aquifer might receive and transmit as much as 7 to 10 mgd of induced recharge from the river for each mile of its width along the river.

It must be emphasized that the estimated potential induced river recharge of 4 to 10 mgd per mile of aquifer was developed by assuming favorable conditions. Actual conditions that are less favorable would reduce the quantity of recharge. The potential induced recharge as computed is directly proportional to the permeability and thickness of the aquifer and to the hydraulic gradient established in it by pumping. The thickness of the assumed aquifer is typical of the aquifers in the Raritan formation, the permeability is fairly representative, and it would be difficult to maintain a hydraulic gradient as steep as 60 feet per mile, except where the wells are near the river.

The materials below the river bottom may limit significantly the quantity of recharge that can be drawn into an aquifer. Induced infiltration depends upon the aquifer having adequate exposure beneath the river to absorb as much water as it can transmit. If the sands and gravels of an average aquifer in the Raritan formation are directly exposed to river water, a fairly narrow strip (probably less than 100 feet wide) would accept as much water as the aquifer could transmit. If, however, a layer of river-bottom mud or silt lies between the aquifer materials and the river water, a larger area would be required to admit the same quantity of water into the aquifer. The distance and the difference in head between the river and the point of aquifer discharge are fixed. If the aquifer were exposed directly to the water in the river, a uniform hydraulic gradient would exist over the cited distance, and this would be the maximum gradient that could be established. Each unit length of aquifer between the river and the point of aquifer discharge would dissipate its proportionate share of the available head. If the aquifer is exposed beneath a layer of relatively impermeable material, a disproportionately large part of the available head would be dissipated as water moved through this material, and less head and a lower gradient would be available to induce flow through the remainder of the distance between the river and the point of aquifer discharge. For example, if the permeability of the river-bottom muds and silts should be one-thousandth of that of a good aquifer in the Raritan, its resistance to the flow of water foot per foot would be 1,000 times as great as that of the aquifer material. In other words, for a given rate of flow, 1 foot of river-bottom mud or silt would produce as much loss of head as 1,000 feet of aquifer material. Even if the permeability of the mud should be one-hundredth that of the aquifer, a few feet of mud or silt might greatly reduce the quantity of water that could be transmitted from an intake area on the bottom of the river to the aquifer discharge area for a given total difference in head.

There are, of course, many places on the river bottom where the aquifers are covered by clays of the Raritan formation rather than by river-bottom muds and silt. In such areas, recharge from the river is practically precluded. The problem may be analyzed in the same manner as for the river-bottom muds and silts. The clay will transmit some water from the river to the aquifer. However, its permeability is very low, probably no greater than 0.1 gpd/ft^2. This means that 1 foot of clay would produce as great a head loss as 10,000 feet (about 2 miles) of aquifer material for any given rate of flow. Thus, it is evident that the condition of the river bottom is a most important factor in determining the potential induced recharge from the river. Where the river flows on clay, little or no recharge can occur.

The quality of the river water is a factor to be considered in determining the usefulness and desirability of induced recharge; to a lesser degree it may bear upon the quantity of recharge that may be determined as feasible to induce. Detailed studies of the quality of the Delaware River water between Trenton and Marcus Hook have been made by the U. S. Geological Survey in cooperation with the City of Philadelphia since 1949 (Durfor and Keighton, 1954). The water in Delaware Bay is too salty for all ordinary uses except cooling. In the reach of river between Philadelphia and the bay the water is used by many industries for many purposes, but its utility decreases as its salinity increases. The salinity of the water in this part of the river fluctuates with the stream flow, with tide, and with other factors. At times of low flow salt water moves upstream, and at times of high flow it is forced downstream by the greater volume of fresh water.

At a sampling station opposite the Philadelphia Navy Yard on League Island, the highest chloride concentration observed in the period August 1949 to December 1952 was 196 ppm, and the highest specific conductance was 523 micromhos (Durfor and Keighton, 1954, p. 35). However, not much farther downstream, in periods of low flow the river water contains such a high content of salt that it is definitely undesirable as recharge for the aquifers. Farther downstream, but still within the limits of the 11-county region, the salinity of the river water is almost always too high for acceptable recharge water. It is fortunate, therefore, that conditions in this lower part of the river have generally been favorable to the deposition of thick layers of muddy and silty materials, which greatly minimize the opportunity for recharge from the river.

The quality of the river water upstream from the zone of salt water is generally satisfactory for recharging the aquifers, although industrial contamination and municipal pollution have occasioned some deterioration of the original quality. However, it is still usable both as recharge for the aquifers and as a surface-water supply with suitable treatment. Under the leadership and sponsorship of the Interstate Commission on the Delaware River Basin recent concerted action by the states along the river has greatly improved the water quality in this part of the river.

There is substantial evidence that induced recharge from the Delaware River is already occurring in the more heavily pumped parts of the aquifer near the river. This is particularly true in the Philadelphia-Camden area. The evidence may be arranged in three general categories —pumping-test results, temperature fluctuations, and changes in chemical quality. Pumping tests in Camden, at Beverly, and at Burlington have shown evidence of recharge boundaries beneath the river. A very thorough test on the Morro Phillips tract in Camden not only showed evidence of a recharge boundary under the river but indicated that after 2 years of operation, a new well near the river would be delivering about 90 per cent river water. Periodic observations of the water temperatures in a group of wells tapping aquifers in the Raritan formation in the Camden area show that the temperature of the water from wells near the river fluctuates seasonally in the same manner as the temperature of the river water (see figure 17, Beverly well). Wells drawing from the same aquifers a few miles away from the river maintain an essentially constant water temperature throughout the year (see figure 17, Haddon Heights well). The wells near the river are 70 feet or more deep and are thus below the depth at which seasonal changes of temperature of

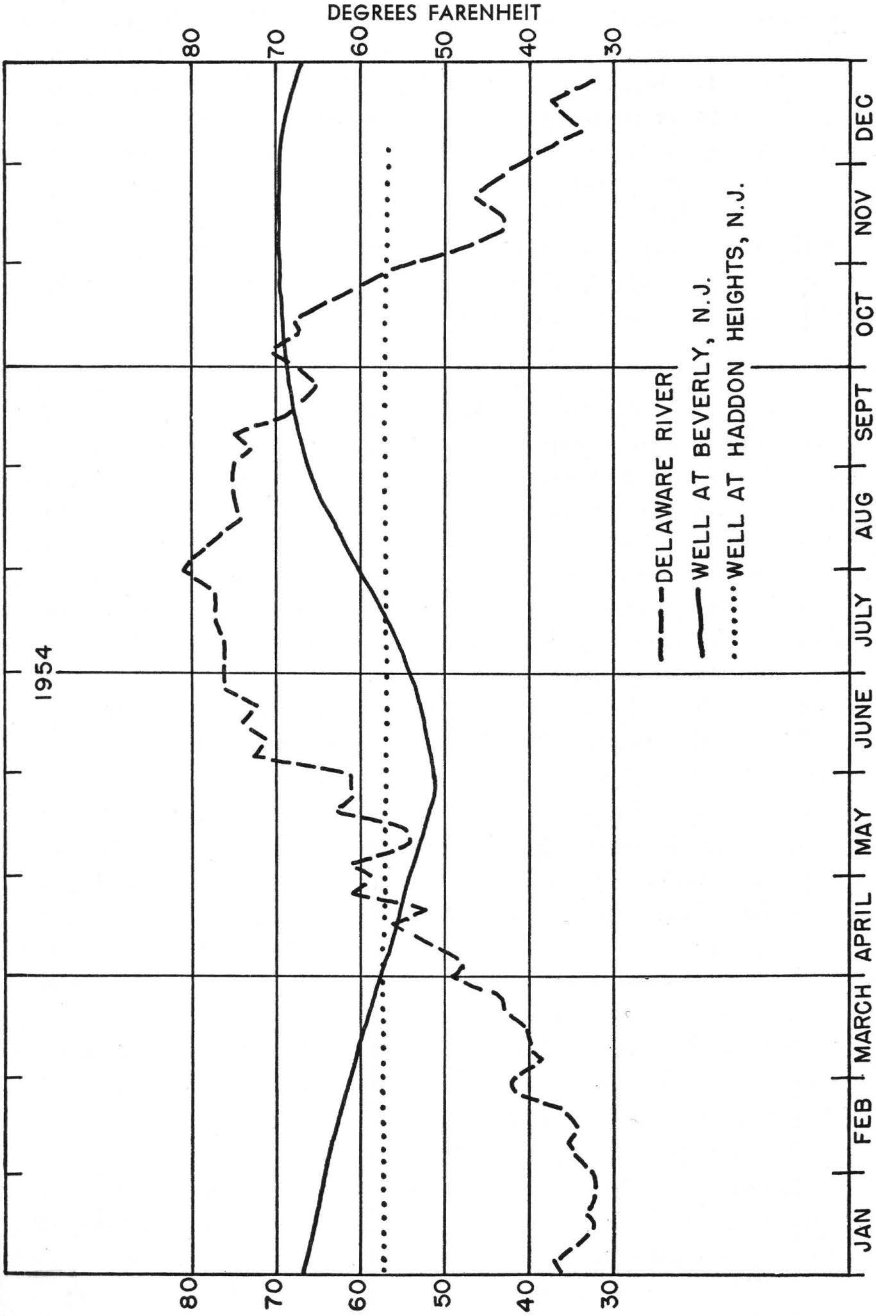

Figure 17.—Diagram showing temperatures of the Delaware River water and of ground water in wells at Beverly and Haddon Heights, N. J., 1954.

more than a degree or two would be expected. This seems to indicate clearly a movement of river water into the aquifer and to the wells near the river. The temperature in the well at Beverly lags about 4 months behind the river temperature. This is interpreted to indicate not only the time required for water to move from the river to the well, but also the time required to warm or cool the earth materials through which the water moves before reaching the well. Changes in the chemical quality of the water from wells near the river are discussed in a later section (see pp. 112 to 124). They provide some of the most convincing evidence of induced recharge from the river.

Movement of Ground Water:—

PATTERN OF MOVEMENT BEFORE DEVELOPMENT:—Before any water was withdrawn from aquifers in the Raritan and Magothy formations, through wells or other works of man, water flowed through the aquifers in them entirely in response to natural hydraulic gradients. These gradients reflect the difference in elevation and the distance between the intake and discharge areas, and the geology and physical properties of the water-bearing formations. The topography aids in identifying the location of the recharge and discharge areas; the geology aids in determining the routes by which the water moved from one area to the other. The detailed geology of the aquifers is complicated, and there is little doubt that some of the water followed devious paths around clay lenses on its way to discharge areas.

The intake areas were the higher parts of those areas where the aquifers were exposed either at the land surface or beneath bodies of water or deposits of permeable materials. The principal discharge areas were the similar exposures at lower altitudes. Movement through the confining clays overlying the Magothy formation was probably a larger portion of the total water movement than at present. However, it was probably a small part of the total movement because the head of the water in the Raritan and Magothy formations differed only slightly from that of the aquifers above the clay, and the resistance of the clays to the movement of water is very great.

Probably the largest part of the water that entered the aquifer from precipitation was discharged into streams nearby. The relatively high parts of the intake area are crossed by a number of small streams; the relatively low parts lie along such streams as the Delaware, Raritan, and South Rivers and along Raritan Bay. Most of the surficial material in the intake area is very permeable, and the slope of the land surface is generally gentle so that there was little overland runoff, and most of the water that fell as precipitation soaked into the ground. Much of it moved through the aquifer materials to the nearby streams.

A substantial part of the recharge, especially in the higher parts of the intake area, percolated down beneath confining clays and then through the aquifers to more distant points of discharge. The length and path of travel depended in part upon the extent of the confining clay and in part upon the locations of the particular intake and discharge areas involved.

There are two relatively high areas of recharge for aquifers in the Raritan and Magothy formations in the 11-county region. The head and flow of the water from the two areas and the density of the salt water in the lower parts of the aquifer determined the position of the contact between fresh water and salt water in the aquifers. It is, therefore, important to examine the probable flow pattern resulting from recharge in these two high-level intake areas.

Figure 18 shows the probable nature of the pattern of flow of water that entered the aquifers in the high-level intake areas and flowed beneath the confining clays above the Magothy to points of discharge. It does not purport to show the exact directions of flow within each aquifer or the precise location of the boundary between fresh water and salt water. Nevertheless, it is believed to show the general shape of the boundary and its approximate location and the general direction of flow within the aquifers of the Raritan and Magothy formations before any artificial withdrawals of water occurred.

The flow pattern shown in figure 18 is based upon certain facts and assumptions that should be examined in order to gain a better understanding of its significance and limitations. It was assumed that the Merchantville and Woodbury clays extend continuously over the Magothy formation throughout the area downdip from their outcrops and for a great distance out under the ocean, perhaps to a suboceanic outcrop along the Continental Shelf. Similar confinement beneath the lowest aquifer in the Raritan formation (or in the Patapsco formation in Delaware) was also assumed. Furthermore, it was assumed that the aquifers of the Raritan and Magothy formations are continuous and uniform and that they extend for a great distance out to sea beneath the confining clay layer. In detail, this assumption is one of the least tenable of those made in this analysis. The aquifers are not uniform, and they are known to be separated by layers of clay of considerable extent. Nevertheless, as has already been pointed out, it is believed that the sands are predominant and that all the important aquifers are connected with each other around the clay layers. Departures from the assumed uniformity explain such anomalies as two aquifers with different heads and perhaps with different

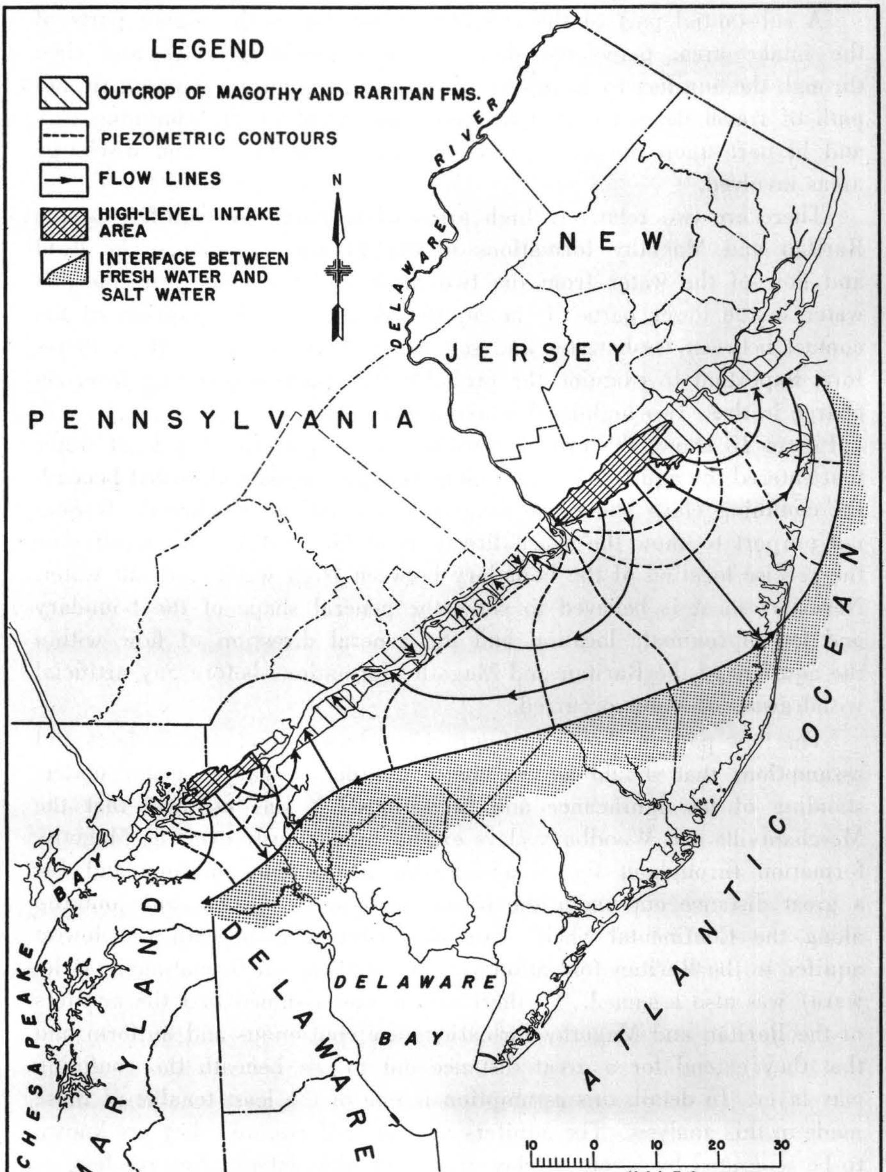

Figure 18.—Map showing the theoretical flow pattern and location of the interface between fresh water and salt water in the Raritan and Magothy formations before any artificial withdrawals of water.

directions of flow at the same place. They do not, it is believed, invalidate the overall analysis and the resulting general flow pattern.

Certain other assumptions which helped to simplify the construction of figure 18 bear primarily upon the details of the pattern such as the location of the boundary between salt water and fresh water and the points of origin of the flow lines. For example, it was assumed that the altitude of the high-level intake area in New Jersey was uniformly 70 feet above mean sea level and that the altitude of the Delaware high-level intake area was 50 feet. There are, of course, considerable variations of altitude in each area. It was assumed that the salinity of the salt water in the aquifers was approximately that of average sea water. The history and method of deposition of the two formations indicate that there may be variations from this value. Finally, in order to draw the limiting flow line, which coincides with the salt-water boundary, as a line rather than as a broad zone, it was assumed that the contact between salt water and fresh water was sharp and vertical. It was doubtless a zone of some thickness and more nearly horizontal than vertical so that the fresh water in the uppermost aquifer might extend several miles farther toward the sea than that in the lowermost aquifer.

Despite the limitations inherent in the assumptions discussed in the preceding paragraphs, the flow pattern shown on figure 18 is believed to be a valid and useful representation of the general conditions within the aquifers before any modifications were introduced by human activity. The water entering the aquifers in the high-level intake areas did not flow straight down the dip to some distant suboceanic outcrop as has been commonly supposed. This was due to the fact that the head of the fresh water was not great enough to overcome the greater weight of the heavier salt water and force it back to the suboceanic outcrop. Consequently, the salt water stood in the aquifer at a level determined by the head of the fresh water and the specific gravity of the salt water and acted as a barrier to the movement of fresh water farther downdip. The fresh water swept around through the parts of the aquifer updip from the salt-water barrier and was discharged into the Raritan River and Bay and into the Delaware River and into the Chesapeake Bay in areas where the aquifers were exposed at levels above that of the salt-water barrier. Theoretically, the limiting fresh-water flow line swept along the face of the salt-water barrier as indicated by the arrows on the figure.

To complete the prepumping flow pattern within the 11-county region, short arrows have been added along the Delaware River to show that the recharge in that part of the intake area was discharged directly to the river. Similar conditions existed in the low-level areas in Middlesex County, N. J., and along the Chesapeake Bay, but local conditions there are not shown because the aquifers are outside the 11-county region.

The validity of the theoretical flow pattern in figure 18 is confirmed by the shape of the piezometric contours on figure 19. These contours are based upon the earliest records of static water levels in each of the wells shown on the map. They are not, therefore, based upon simultaneous observations, but upon observations extending over a period of perhaps 50 years. Many of the water levels were affected by the pumping of earlier wells. Furthermore, no allowance could be made for the possibility that different aquifers in the same locality may have had different heads because the water may have had to travel by different paths or because of varying interference due to pumping. In spite of these limitations, there is an essential agreement between the general shape of the piezometric contours on figures 18 and 19.

PATTERN OF MOVEMENT AFTER DEVELOPMENT:—The artificial removal of large quantities of water from the aquifers of the Raritan and Magothy formations has no doubt altered considerably the pattern of movement in them. Increased development may be expected to cause additional changes. The removal of water from an aquifer by a well, or well field, lowers the head around the well enough to induce the flow of an equivalent quantity of water toward the well. The depression of head around the well is called the cone of depression. Before the beginning of the artificial withdrawal, the recharge of water to the aquifer was equal to the discharge. Therefore, the cone of depression of each new well must expand until it has induced additional recharge to the aquifer or intercepted discharge equal to the quantity of water removed by the well. This process may take a considerable period of time because large quantities of water may be removed from storage in the aquifer and in the adjacent aquicludes. When the process has been completed, however, new flow lines have been established or old ones have been diverted from their original courses as water moves toward the well.

Aquifers in the Raritan formation can generally be relied upon to yield a substantial quantity of water to wells, and many wells yielding a million gallons a day or more have been developed. For this reason, some of the deepest water wells in the 11-county region tap these aquifers. In the entire New Jersey Coastal Plain, probably more wells 1,000 feet or more in depth tap aquifers in the Raritan and Magothy than all other aquifers combined. Many wells pass through other good but less productive aquifers without drawing from them. Consequently, pumping from aquifers of the Raritan and Magothy formations is scattered widely between the outcrop areas and the zone where the aquifers lie 1,000 to 1,200 feet below the land surface. (See figure 20). How-

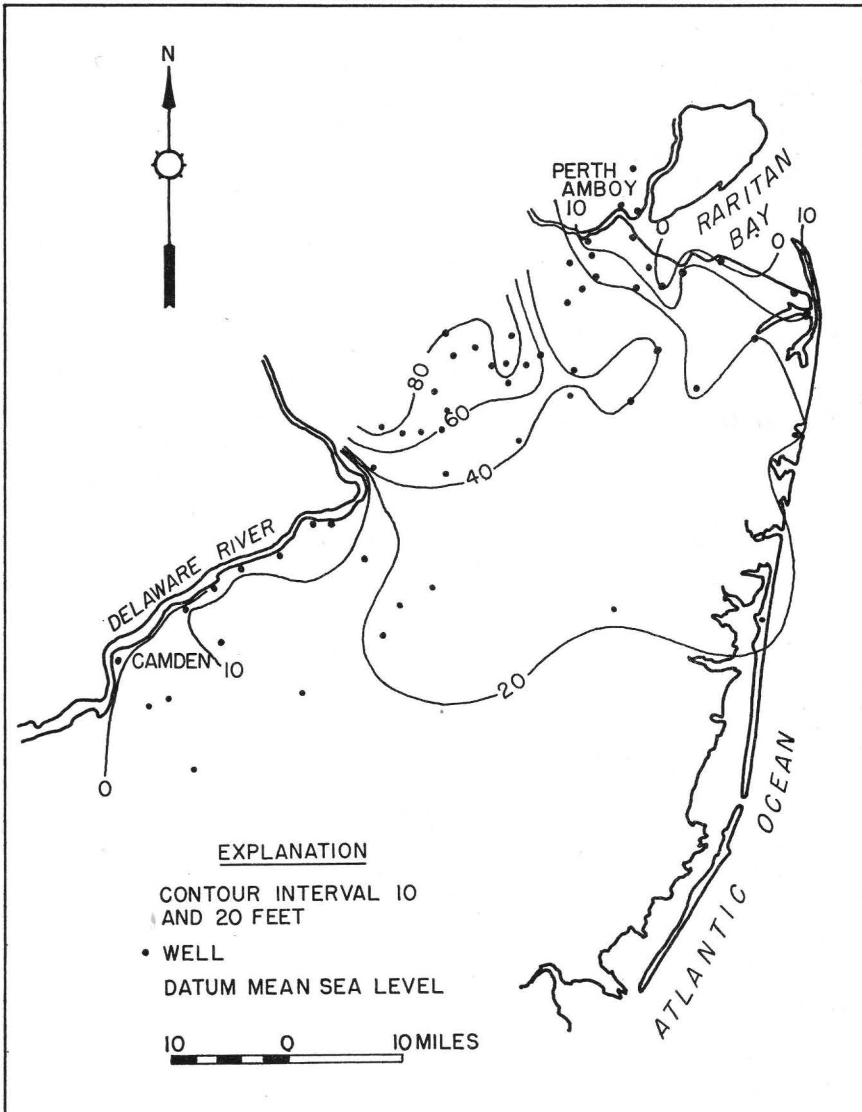

Figure 19.—Map showing piezometric contours for the aquifers in the Raritan and Magothy formations based upon the earliest records for each well shown.

ever, the major part of the pumping is concentrated in and near the intake area, where the depth to the aquifers does not exceed 300 or 400 feet.

Many wells tap the aquifers of the Raritan and Magothy formations northeast of the 11-county region. The heaviest pumping in this area

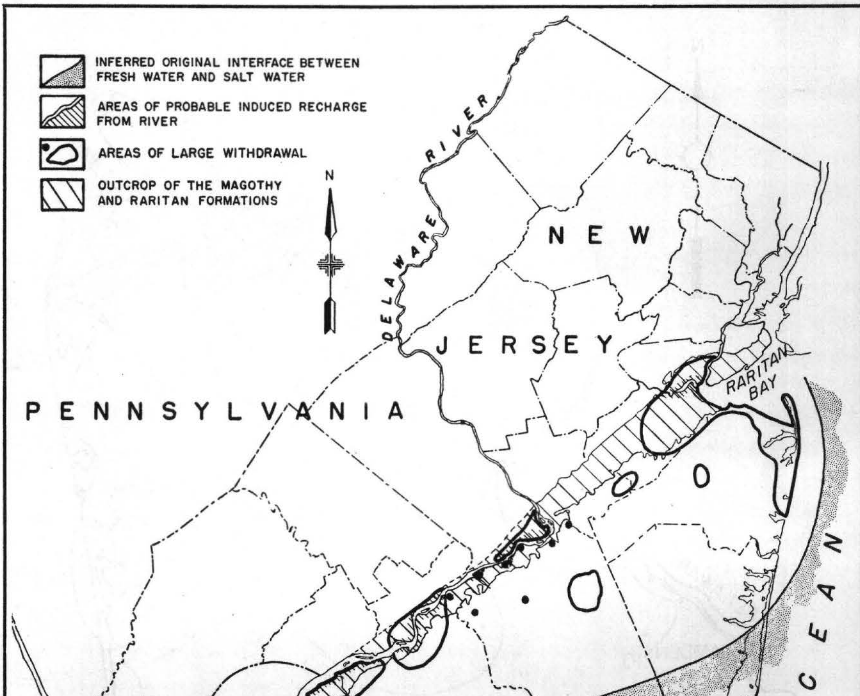

Figure 20.—Map showing areas of large withdrawals of water from the Raritan and Magothy formations and areas in which recharge is probably being induced from surface streams.

is concentrated near the intake area along the Raritan and South Rivers. Large quantities of recharge—some of it of very poor quality—have been induced from these streams.

The wells farther down the dip both within and without the 11-county region draw their recharge primarily from the high-level intake area northeast of Trenton, N. J. (See figure 18). To a lesser degree, they may induce recharge from other aquifers through the confining clays. Some of the recharge supplying these wells is probably water that formerly overflowed into streams in the intake area. The artificial discharge has brought about a steepening of the hydraulic gradients from the high-level intake areas, indicating some increase in flow from those areas. If it were possible to show quantitatively the original and the present flows of water from the high-level intake areas, the map showing present-day conditions would undoubtedly reveal greater flow from the intake area and less discharge into the Delaware River and into the Raritan River and Bay as a result of pumping.

Originally, as indicated on figure 18, the flow in the low-level intake area along the Delaware River was entirely toward the river. This applied to the movement of recharge from both the local as well as the distant high-level intake areas. The pumping of water from wells in the area along the river has intercepted all or a part of this flow. In many places pumping has reversed the normal flow and induced recharge from the river. It is probable that some recharge from the river has been induced wherever moderate or heavy pumping is occurring in areas very near the river. Where river recharge has been induced, the flow lines should now be drawn from the river to the wells or well fields. The flow lines are inherently perpendicular to the piezometric contours that depict the general configuration of the water table or of the piezometric surface of a confined aquifer. General directions of flow may therefore be inferred from a map showing piezometric contours. In general, in the 11-county region, the detailed water-level information needed for constructing such a map is not available and directions of flow must be inferred from other data such as the quality and temperature of the ground water, or changes in these properties.

In the Philadelphia-Camden area, the Delaware River departs from its general southwesterly course and flows almost south and then almost west, so that it swings across the outcrop area of the Raritan and Magothy formations almost to the area's southeastern limits. Both upstream and downstream from this area, the river flows over the lower aquifers of the Raritan formation, but in this area the river flows over higher beds. The lower aquifers in the Raritan lie beneath clay layers on the Philadelphia side of the river, and both the clays and the aquifers extend beneath the river into the Camden-Paulsboro area. Consequently, the lower aquifers in the Raritan formation are not directly exposed to river recharge in much of the area. The deeper of the two principal aquifers is probably not directly exposed beneath the Delaware River for 8 or 10 miles downstream from the point at which the river bends southward. The upper aquifer is probably shielded from direct river recharge by overlying clays for a much shorter distance.

The approximate northwestern boundary of the intermediate aquiclude that separates the two principal aquifers in the Raritan is shown on figure 21. This figure also shows water-level or piezometric contours in the lower aquifer of the Raritan in the Philadelphia-Camden area based upon all available water-level data. The depressions occur around the principal centers of pumping and indicate local flow into those centers from other parts of the area. The most pronounced depressions are those in the south-central part of Camden and at the Philadelphia Naval Base, in both of which the water levels are more than 50 feet below sea level. The higher contours tend to swing around the entire area, indicating a general flow of water into it from other parts of the aquifer.

The relation of the river to the principal aquifers in the area explains why some of the piezometric contours in figure 21 cross the river without being affected by it. Water moves through the aquifer under the clay unaffected by the position of the river. The relatively high water levels in the northeastern part of Camden, where the river flows over the intake area of the lower aquifer, reflect the availability of direct recharge from the river.

Confirmation of the flow pattern indicated by the contours on figure 21 may be found in the study of the quality of the ground water in the area. Figures 22 and 23 show that the highest concentrations of dissolved solids and of hardness are found in southeastern Philadelphia. These figures are based upon analyses that were made over a period of years rather than simultaneously. Consequently, they may not be as definitive as maps based upon nearly simultaneous analyses. Nevertheless, they are indicative of general conditions. A short tongue of mineralized water extends from the area of highest concentration south toward the low pressure area at the Philadelphia Naval Base. Another tongue of mineralized water appears to extend northeastward across the river into the low pressure area in the southern part of Camden. Early analyses of the ground water in southern Camden indicated that it was similar in character to that in the rest of the Camden area. When the increased mineralization of the water in that part of the city was first observed about 20 years ago, it was attributed to the induced infiltration of mineralized water from the river downstream from Camden or to leaking casings. The possibility of leaking casings in old wells cannot be ruled out entirely, but ground-water investigations on the Pennsylvania side of the river (Graham and Kammerer, 1954) demonstrated the exist-

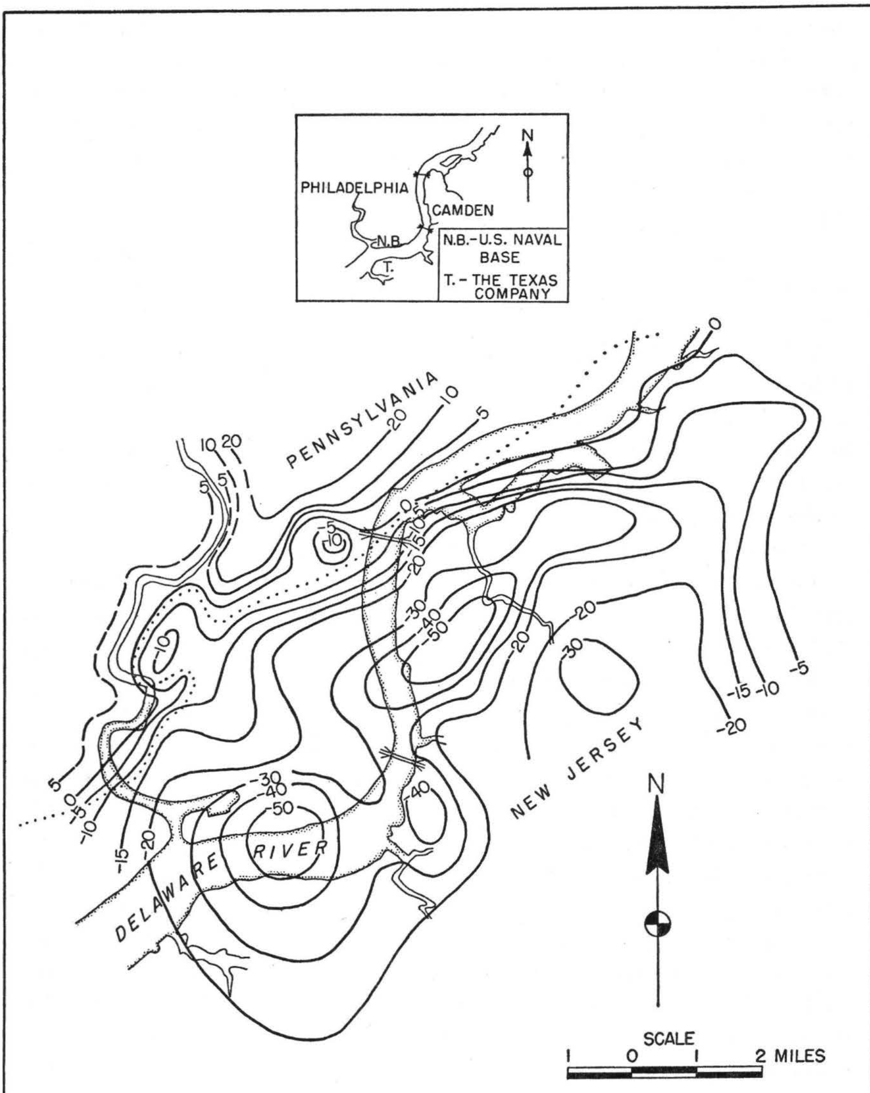

Figure 21.—Map showing piezometric contours in the lower aquifer of the Raritan formation in the Philadelphia-Camden area.

ence of a body of highly mineralized water in the aquifers in southern Philadelphia, obviously not derived from either the Delaware or the Schuylkill Rivers, because it was more highly mineralized than either of them. A continuation of these studies showed that the source of the mineralization was the disposal of wastes on dumps in the intake area and possibly directly into the ground through wells. Leaking casings of old wells and leaking sewers may also contribute to the contamination. The mineral content of the water from some wells in southern Camden is now also higher than that of the river waters or of any surrounding ground water except that in southeastern Philadelphia. These data seem to indicate that the highly mineralized water originating in southeastern Philadelphia may have spread to the areas of heavy pumping in southern Camden. They are, however, inadequate for a positive conclusion, and the question should receive further study. They do serve to emphasize the fact that it is possible to draw water under the river from one side to the other, depending upon the gradients created by pumping.

The zone of maximum concentration of mineralization and hardness in the lower aquifer of the Raritan formation as shown on figures 22 and 23 now lies some distance downdip from the edge of the aquiclude that overlies the aquifer. Thus it appears not to be directly connected with the highly mineralized water in the overlying Quaternary deposits. From this it is concluded either that liquid wastes were and perhaps are still being, introduced into this aquifer through wells; or that the concentration of contaminating materials in the intake area has decreased and the zone of maximum concentration in the aquifer has drifted away from the intake area. It is possible that both factors are working simultaneously. Data are not available currently to determine what is the true condition, but similar maps drawn on the basis of samples collected after the lapse of a few years may show whether or not the entire zone of maximum concentration is moving. If the mapping of subsequent analyses should demonstrate a shift of the zone of maximum concentration together with a decrease of concentration in the intake area, there would be hope that the contaminated area might ultimately be eliminated by continued pumping and continued improvement of conditions in the intake area.

The correct determination of the source of the contamination of the ground waters in southern Philadelphia was greatly facilitated by the availability of good information on the quality of the river water. This resulted from the investigation of the quality of the water in the Delaware River, conducted by the Quality of Water Branch of the U. S. Geological Survey in cooperation with the City of Philadelphia. The project included the detailed periodic sampling of the river water at

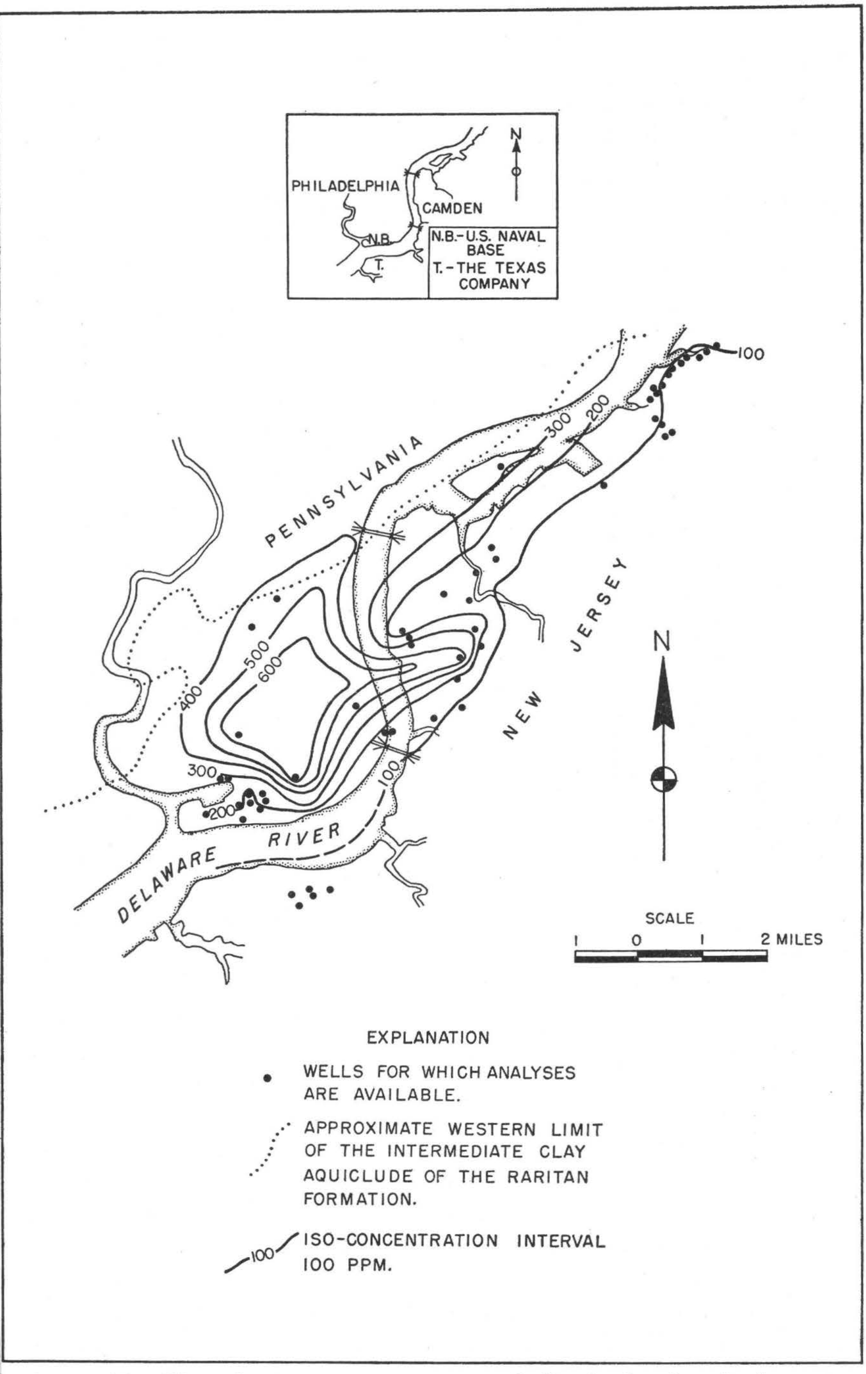

Figure 22.—Map showing concentrations of dissolved minerals in water from the lower aquifer of the Raritan formation in the Philadelphia-Camden area.

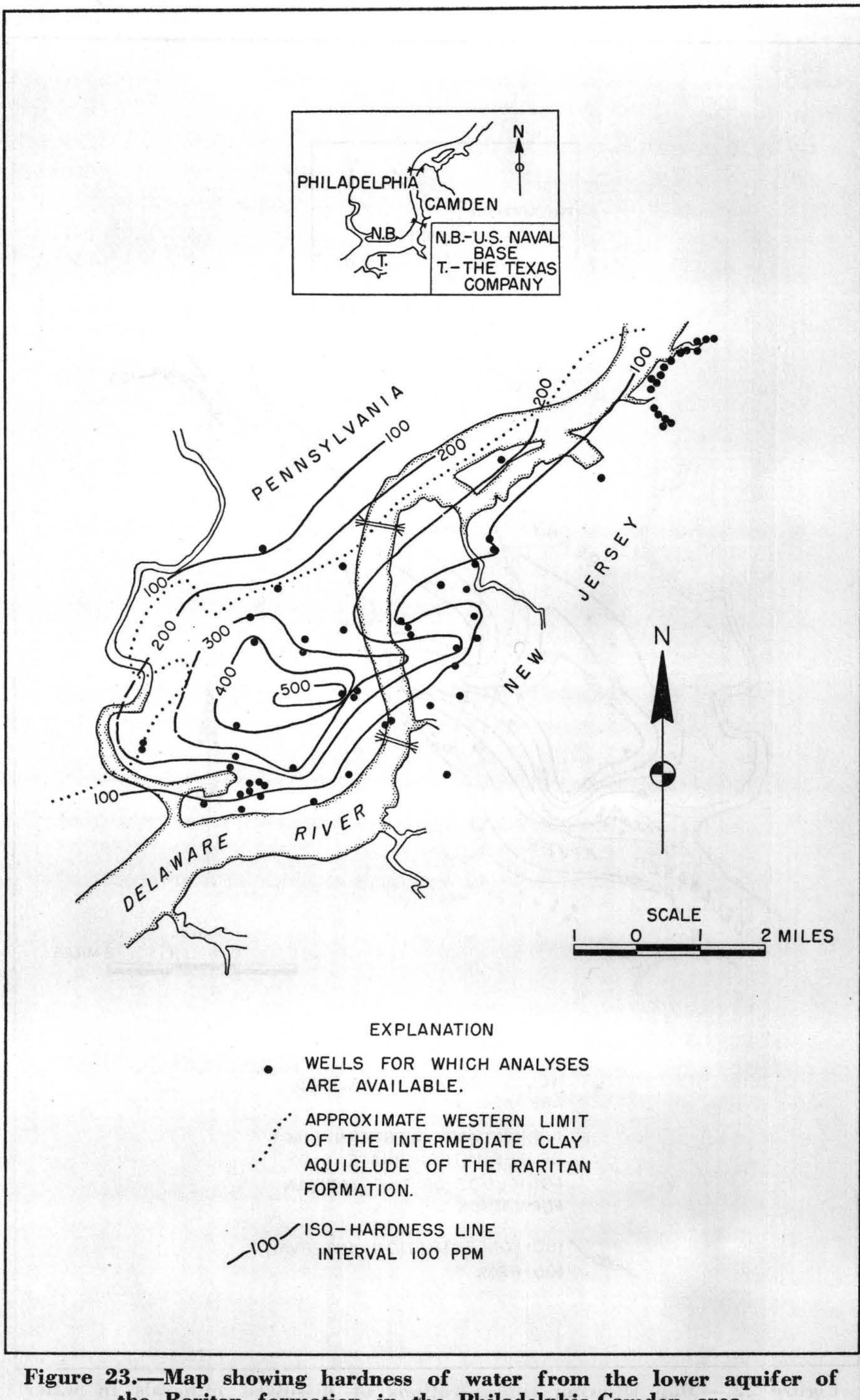

Figure 23.—Map showing hardness of water from the lower aquifer of the Raritan formation in the Philadelphia-Camden area.

selected sites from the beginning of the investigation to the present. It has resulted in the accumulation and interpretation of a vast amount of data on the quality of the river water and its relation to stream flow (Durfor & Keighton, 1954). The results have also been of great value in relating the quality of the ground water to that of the river water and in estimating the probable effect of induced recharge upon the quality of the ground water at other places along the tidal reaches of the river.

Conditions surrounding the piezometric low centering on the Philadelphia Naval Base are also of interest in connection with the movement of the mineralized water in southeastern Philadelphia. The wells of The Texas Co. are near the Deleware River opposite the Naval Base. Originally, the wells at the Naval Base yielded waters that were similar in chemical characteristics to that from the wells of The Texas Co. However, the water from the wells at the Naval Base has become progressively more mineralized as water from the mineralized area was drawn into them, while the water from the wells of The Texas Co. has remained fairly uniform in quality. In this case, the heaviest pumping and the lowest water levels or artesian pressures are on the Pennsylvania side of the river, and water of good quality is being drawn across the river from the New Jersey side, beneath the aquiclude. Thus, in effect, the heavy pumping at the Naval Base has shielded the wells on the New Jersey side of the river from the mineralized water. If the pumping at the Naval Base should be greatly curtailed, the highly mineralized waters would tend to move past the wells there and beneath the river to the wells in New Jersey, creating a situation similar to that now existing in southern Camden.

Another indication of the reversal of the natural ground-water flow toward the river and of induced recharge from the river may be found in the history of the chemical quality of the water from the wells at the Puchack Run well field of the Camden water works. Wells 1 to 4, inclusive, in this field are on a one-mile line perpendicular to the river, and well 1 is closest to the river. In 1924, soon after the wells were completed, water samples were taken from all of them and analyzed for mineral content. The sampling was repeated periodically thereafter. Results of analyses of water from wells 1 and 4 are shown in table 11. It is significant to note that although the total mineral content of the water from well 1 more than doubled between 1924 and 1953, the character of the water from well 4, which was shielded from river recharge by the other wells in the line, changed relatively little.

Analyses of water from the river directly opposite the Puchack Run wells are not available, but the Lehigh Avenue station operated by the Quality of Water Branch of the U. S. Geological Survey is only a short

Table 11.—Analyses of water from wells 1 and 4 at the Puchack Run station of the Camden Water Department
(Parts per million except pH and specific conductance)

Analyzed by the U. S. Geological Survey

Date Collected	*Silica* (SiO_2)	*Iron* (Fe)	*Manganese* (Mn)	*Calcium* (Ca)	*Magnesium* (Mg)	*Sodium* (Na)	*Potassium* (K)	*Bicarbonate* (HCO_3)	*Sulfate* (SO_4)	*Chloride* (Cl)	*Fluoride* (F)	*Nitrate* (NO_3)	*Hardness as* $CaCO_3$	*pH*	*Dissolved solids*	*Specific Conductance (Micromhos at 25°C)*
								WELL 1								
3/27/24	6.5	0.03		5.1	1.4	5.3		3.7	1.6	3.0		26	16		56	
12/ 8/26		.01						2	3	11		17	25			
11/21/32	7.3	.66	0	6.4	3.0	6.8	1.6	6.0	10	12		16	28		71	
11/21/33	7.6	.09		6.8	3.7	9.2	1.9	7.0	13	15		17	32		83	
2/ 6/34	6.7	.19	.24	7.0	3.6	8.8	1.8	6.0	13	14		15	32		73	
11/ 7/49	5.6	.17	.01	12	7.2	11	2.6	13	51	10	0.1	6.9	60	5.4	116	199
7/ 3/53	4.0	.00	.14	14	7.8	10	3.0	39	40	10	.0	7.5	67	6.5	128	198
								WELL 4								
5/10/24	7.0	0.03		3.3	1.0	3.0		3.7	1.1	2.5		16	12		47	
12/ 8/26		.01						5	1	1		7	14			
11/21/32	7.0	.48	0.3	6.2	2.8	4.1	1.2	15	7.1	7.0		13	27		57	
11/12/33	8.4	.08		5.0	2.0	3.6	1.0	12	1.7	5.0		12	21		44	
2/ 6/34	7.2	.49	.24	6.6	3.3	7.5	1.4	8.0	9.2	11		14	30		66	
11/12/35		.23	.12					13		6.2		10				
11/ 7/49	8.7	.07	.01	4.0	1.9	3.9	1.2	4	4.9	6.1	.0	13	18	5.3	49	69.8
7/ 3/53	7.9	.00	.41	5.2	1.8	3.5	2.1	4.0	10	7.2	.0	12	20	5.8	62	79.7

distance (2 mi.) downstream (Durfor and Keighton, 1954). The quality of the river water improves in an upstream direction, and the water at Lehigh Avenue may be too high in dissolved minerals for a direct comparison. On the other hand, the Puchack Run wells are shielded from recharge upstream from them by the wells in the Morris Station well field of the City of Camden. It seems likely that the major part of the river recharge reaching the Puchack Run wells comes from downstream. Probably a period of several weeks is required for the water from the river to reach well 1 by the most direct route, and a much longer period by more devious lines of flow.

The quality of the water from well 1 has tended to approach the average quality of the Delaware River. On November 7, 1949, the specific conductance of the water from well 1 at the Puchack Run station was 199 micromhos. From August 2 to November 1, 1949, the specific conductance of the water at the bottom of the river ranged from 276 to 400 micromhos (Durfor and Keighton, 1954, p. 78). Earlier figures are not available, but in each subsequent winter or spring the conductance of the river water has dropped to figures in the order of 100 to 150 micromhos. Although the water from this well is probably derived almost entirely from river recharge it should never reach as high a mineralization as the river water at low flow because the rate of recharge is affected by fluctuations in the rate of pumping and by the shifts in pumping from one well to another. Furthermore, even under uniform conditions, the water reaching the well at any time is probably a composite of water that left the river at various earlier times over a period of as much as several months, depending upon the length of flow paths over which individual particles of water traveled. At present the water of the Delaware River above Camden is not excessively mineralized and the utility of the water from well 1 has not, therefore, been significantly impaired.

Probably similar examples might be found in other parts of the region if detailed long-term records of chemical quality were available to demonstrate the changes. The major changes in the regimen of the river that are now being proposed, such as diversions from the basin and deepening of the channel, may have profound effects upon the quality of water. The quality of the ground water in heavily-pumped areas near the river will approach the quality of the river water wherever the aquifers are exposed to direct recharge from the river. It is imperative, therefore, that regular and detailed determinations be made of the future quality of the waters of both the aquifers and of the river and that the results be studied periodically for significant trends and interrelations, in the light of improved geologic knowledge.

The maintenance of a good quality of river water is, of course, desirable in itself. However, in view of the importance of the large quantities of ground water being taken from aquifers in the Raritan and Magothy formations and of the even greater quantities that can and will be taken in the future if the quality remains satisfactory, the maintenance of good water in the river becomes of the utmost importance.

Detailed evidence of the direction of movement of the water in the Raritan and Magothy formations in response to pumping is not as complete in other parts of the area as in the Philadelphia-Camden area. Nevertheless, as already indicated, there is substantial evidence of induced recharge from the Delaware River in several places. This necessarily implies a local reversal of the natural ground-water flow toward the river. Within the great area of the aquifer that is confined beneath the overlying clay, the flow is undoubtedly concentrated toward centers of pumping. Figure 20 shows the outcrop areas of the formations in outline, the hypothetical original margin of the salt water in the aquifer, the areas of probable induced infiltration, and the principal areas of heavy pumping. No attempt has been made to draw in the modified lines of flow, but the general nature of the flow pattern may be inferred by the preceding discussion and a comparison of figures 18 and 20.

SALT-WATER ENCROACHMENT:—The occurrence of ground water in the aquifers along the Delaware River are strikingly similar to those in the Farrington sand member of the Raritan formation along the Washington Canal near Parlin in Middlesex County, N. J. The quality of water in the Washington Canal is not satisfactory for recharging the contiguous aquifer, and thus the induced recharge is being called by another and more ominous name—salt-water encroachment. Salt-water encroachment in aquifers having hydraulic connection with salt-water bodies is generally accelerated by pumping fresh water from an aquifer, but under some conditions it might occur without any pumping. Along the Washington Canal, for example, salt water has entered the aquifer from updip intake areas. It is almost certain that the heavier salt water from the canal would ultimately flow down (encroach) into the lower parts of the aquifer even in the absence of any pumping. Actually, the encroachment has been accelerated by pumping to such an extent that some wells may soon have to be abandoned and the withdrawal of water from the aquifer probably must be reduced over a considerable area.

The geologic conditions along the Delaware River are essentially the same as those in the Parlin area on a vastly magnified scale. For many miles, the river lies on the outcrop areas of the aquifers and on essentially the highest parts of them. These aquifers have not yet been threatened by salt-water intrusion inasmuch as the river in these reaches has contained fresh water all or most of the time. In at least one locality along the lower part of the river, where the river water is generally salty, the first wells drilled to an aquifer were reported to yield salt water. It seems very probable that this was the result of the heavier salt water gradually flowing down the slope of the aquifer and thus encroaching without the aid of pumping. The danger of salt-water intrusion from the river is probably the most serious limitation to water-supply developments tapping aquifers in the Raritan and Magothy along the lower reaches of the Delaware River.

The importance of excluding salt water from the upper reaches of the Delaware River, which are now fresh and which are even now supplying substantial quantities of induced recharge to the adjacent aquifers, cannot be over-emphasized. The large and valuable ground-water supplies now being derived in considerable part from induced river recharge would be very seriously contaminated by salt water in the river. Future supplies, potentially at least as great as those already developed, could not be undertaken in the face of certain salt-water intrusion from the river. The fresh water that would reach the withdrawal area from the high-level intake area would not be adequate to cause significant dilution of the induced salt-water recharge. The advance of salt water up the Delaware River into reaches that are normally fresh would thus constitute a very serious threat to all the fresh ground-water supplies developed from aquifers in the Raritan and Magothy formations.

In those formations in direct contact with the ocean the advance of salt water up the dip also constitutes a danger that cannot be overlooked. The system of aquifers in the Raritan and Magothy contains salt water in its oceanward extensions. Thus on the one hand there is an essentially constant head of ocean water endeavoring to bring the salt water in the aquifers up to sea level, and on the other hand there is the opposing fresh-water head derived from the high-level outcrop (intake) areas. As more and more water supplies are developed from the aquifers, the fresh-water head is reduced and an opportunity may be created for the salt water to advance inland and fill a larger part of the aquifer. There can be little doubt that it is advancing in some places in response to the lowered fresh-water head.

This advance will occur gradually, perhaps over a period of many years, because the changes in head are gradual. Furthermore, there are very large quantities of fresh water in the aquifers between the original margin of the salt water and the position it would ultimately assume under the lowered fresh-water head. This water will be displaced gradually as it flows to areas of pumping and is discharged there. Thus it is probable that even in areas where the balance of heads may already favor salt-water encroachment from down the dip, many years may elapse before encroachment occurs.

It is evident from a study of figure 24 that the danger of salt-water encroachment directly from the ocean is not limited to the coastal areas where the aquifers are heavily pumped. Even before the development of ground-water supplies, it is believed that the margin of salt water cut across the coastal plain of New Jersey and Delaware, as shown in figure 24, gradually approaching the outcrop area toward the southwest until it was deflected by the influence of the high-level intake area in Delaware. Thus localities far from the coast may be near the margin of encroachment or even on the salt-water side of it. For example, it is possible that a well field in central Burlington County, N. J., may be as near to the original margin of salt-water encroachment as one along the coast of Monmouth County, N. J. The relative imminence of salt-water encroachment in the two localities would depend upon the intensity and distribution of pumping in the two areas and updip from them. A well in central Atlantic County, N. J., would almost surely produce salt water from the aquifers in the Raritan and Magothy formations. Even as far updip as the Camden area there is the danger of this type of salt-water encroachment, although it is possible that induced recharge from the Delaware River would supply all water withdrawn in excess of the normal flow from the intake area. If sufficient river recharge can be induced the cone of depression caused by pumping in the Camden area will not be well enough developed in the direction of the margin of salt water in the aquifer to cause significant additional encroachment. Conversely, if the induced recharge is substantially lower than the withdrawal, there will be greater development of the cone of depression toward the salt-water margin, causing its migration slowly toward the center of pumping. Actual arrival of salt water at the pumped wells would probably be a great many years after the over-pumping began.

The great value of the ground-water supplies from the Raritan and Magothy formations justifies all reasonable measures to prevent or delay the serious and lasting effects of salt-water encroachment. The maintenance of fresh water in the Delaware River is probably the most important preventive measure that can be taken. Next in importance would be the careful and intelligent areal distribution of pumpage in such a way as to take maximum advantage of induced fresh-water recharge and to avoid concentrated reductions of fresh-water head near the margin of the salt water in the aquifers. This would require detailed observations and careful study over many years. An aid in the planning and management of pumpage would be a system of outpost wells between known concentrations of pumping and the salt-water margin. Water levels in such wells

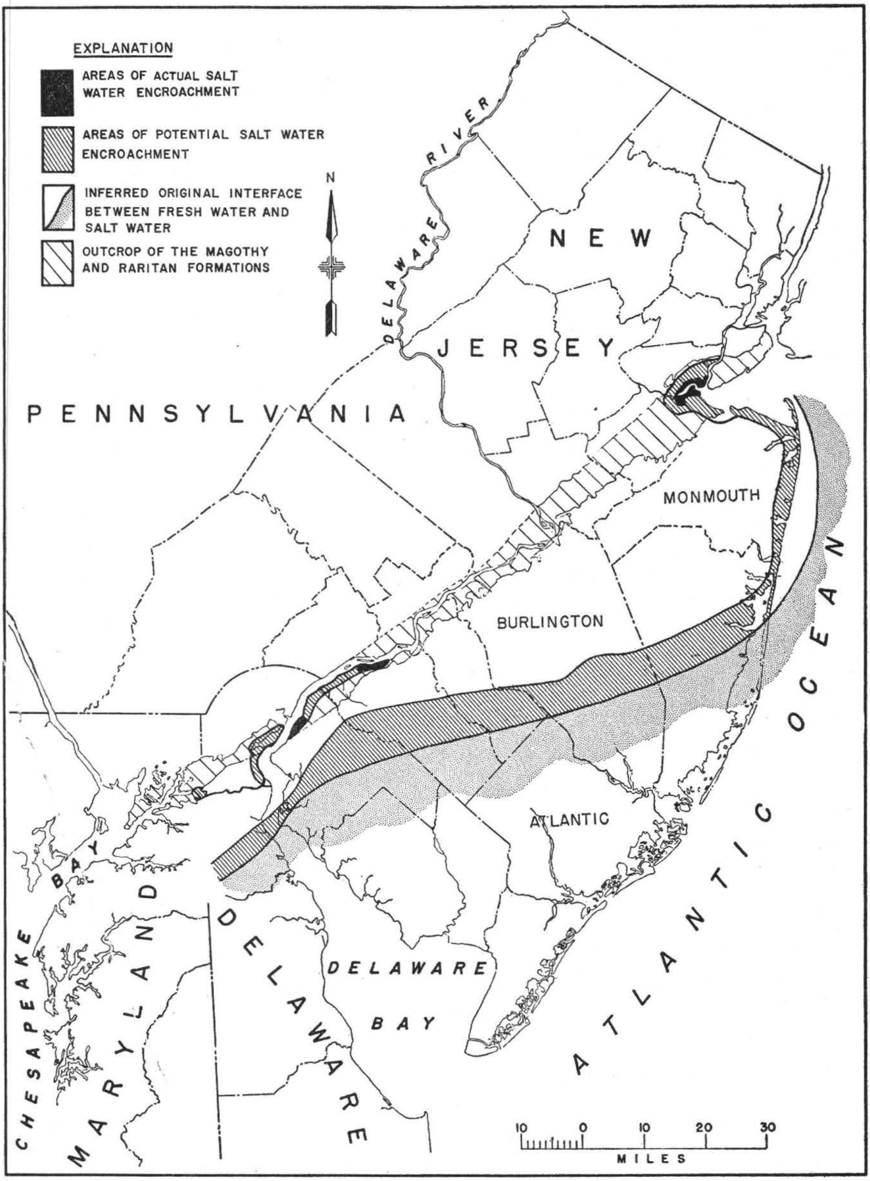

Figure 24.—Map showing areas of actual and potential salt-water encroachment into aquifers of the Raritan and Magothy formations in New Jersey and Delaware.

should be measured regularly to document the fresh-water head in that part of the aquifer, and water samples should be collected and analyzed periodically to detect any change in salinity. The data obtained from such wells would provide a means for intelligent management of the water supplies developed from the aquifers, assuring their maximum utility.

Discharge:—The natural discharge of water from the aquifers of the Raritan and Magothy formations has already been discussed to some extent in describing the movement of water through the aquifers. The general location of the discharge areas has, therefore, been established in the preceding section. The purpose of this section is to examine in detail the ways in which water is discharged from the aquifers and the effects of artificial withdrawals upon natural discharge.

The discharge of water from an aquifer under natural conditions occurs by flow out of the aquifer, by evaporation from a contiguous soil zone, or by the transpiration of plants whose roots penetrate to the aquifer. In places where the water table intersects the land surface, water is discharged; where it intersects a body of surface water the flow is either into or out of the aquifer, depending upon the respective heads. In humid areas, such as that of the 11-county region, the hydraulic gradient almost always favors the discharge of water from the aquifer. Where the water table is near the land surface, substantial quantities of ground water are discharged into the atmosphere by evaporation and transpiration.

Before artificial withdrawals began, the discharge from aquifers in the Raritan and Magothy formations occurred mainly in the outcrop areas of the formations, or in those areas where the aquifers are in contact with permeable beds of younger materials. Much the greater part of this discharge occurred within a few miles of the places at which the water entered the aquifers, because the greater part of the intake area is near discharge areas in the valleys of the Delaware and Raritan Rivers and their tributaries. Part of the water entering the aquifers in the high-level intake areas was also discharged into nearby streams. A small part of the total water entering the aquifers moved beneath the overlying clays, following the long paths to distant discharge areas as shown in figure 18.

There is little value in trying to develop any close estimate of the quantities of water that were discharged by the aquifers before any pumping began. These quantities were equal to the recharge, which did not approach the potential recharge because the low gradients limited the capacities of the aquifers to transmit water from intake areas to discharge areas. It is of interest, however, to consider the order of magnitude of the quantities involved. The high-level intake area northeast of Trenton is no more than 25 miles long. Assuming that all the aquifers in the two formations in that area have a total thickness of 200 feet and an average permeability of 1,000 gpd/ft^2, and assuming further that the average hydraulic gradient between the high-level intake area and the various areas of discharge was originally 2 feet per mile, the total flow beneath the confining clay would have been 10 million gallons a day. Recognizing that the high-level intake area is less than one-fifth of the total intake area, the total discharge from aquifers in the Raritan and Magothy formations in the region before pumping began may have been about 50 mgd.

The total pumpage from aquifers in the Raritan and Magothy formations in the 11-county region is now much more than the estimated natural discharge before pumping began. The development of such large quantities of water from these aquifers has decreased the natural discharge to some extent. However, it has increased the recharge to a still greater degree. Present indications are that induced river recharge is supplying much of the water withdrawn along the Delaware River, particularly in areas of heavy pumping. Probably natural discharge both into the river and into the air through evapotranspiration has been almost eliminated in areas of heavy pumping. Nevertheless, there are probably many parts of the low-level outcrop area where natural discharge is still occurring. There is little heavy pumping near the high-level intake area, and the hydraulic gradients from this area have been increased only moderately. It is probable, therefore, that in this area the natural discharge has been reduced perceptibly only in seasons when natural recharge is low.

Large yields may generally be obtained from individual wells tapping the aquifers of the Raritan and Magothy formations. The general availability of large quantities of good ground water from the aquifers of the Raritan and Magothy formations has contributed at least as much as any other factor to the wide distribution of industry within that part of the region where these aquifers are within a few hundred feet of the land surface. Most of the use of water from these aquifers is in the outcrop area of the formations or within 5 or 10 miles of it. Farther from the outcrop, the aquifers are so far below the surface that the cost of drilling tends to offset the value of large yields from individual wells and other sources are sought except in unusual circumstances.

In the 11-county region, more ground water is taken from wells tapping the Raritan and Magothy formations than from all other aquifers. In 1954, an average of about 120 million gallons of water was taken each day from the Raritan and Magothy formations in the region, compared with a total ground-water consumption of slightly more than 200 mgd. Aquifers in the Raritan and Magothy formations occur in 8 of the 11 counties in the region. In these 8 counties, the total ground-water use was about 165 mgd, of which more than 70 percent was derived from the aquifers in the Raritan and Magothy. The use of water from these aquifers in the 8 counties is shown in table 12. Both the total water use for the region as shown in table 8 (see page 56) and on figure 12 on page 57, and the water used for the Raritan and Magothy formations are partly estimated. However, substantially more than half the water use is documented by metered records, and the figures given in the table are believed to be essentially correct

Possibilities for Additional Development:—Although substantial additional quantities of ground water are available from the aquifers of the Raritan and Magothy formations, increased development should be undertaken with caution and only after careful study. Many variable factors affect the potential yield of these aquifers. Some of them relate to the structure and function of the aquifers themselves and some to the quality of the water in the Delaware River and in the aquifers downdip from the salt-water interface. All these factors should be continually inventoried, studied, and interpreted, not merely with a view toward increased development of the aquifers, but in order that much of the existing development may be continued with safety.

Table 12.—Use of ground water from the Raritan and Magothy formations in the 11-county region, 1954*

State	*County*	*Water use—MGD*
Delaware	New Castle	3
New Jersey	Burlington	14
	Camden	50
	Gloucester	17
	Mercer	4
	Salem	6
Pennsylvania	Bucks	11
	Philadelphia	15
	Total	120

*Partly estimated

In many places between Camden and Trenton, the aquifers of the Raritan and Magothy formations are probably still discharging water into the Delaware River and its tributaries. Most of this discharge can be diverted into a system of wells properly distributed along the river. Furthermore, by reversing the ground-water flow and inducing recharge from the river, much larger quantities of water can be withdrawn. As already indicated, the greatest quantities of induced recharge can be withdrawn from wells very near the river. Water from the high-level intake area and some water from the river or near it can probably be developed downdip from this reach of the river. However, precautions should be taken against salt-water intrusion from still farther down the dip of the aquifers. Assuming adequate exposure of the aquifers beneath this reach of the river, it may be conservatively estimated that something in the order of 100 mgd of additional ground-water withdrawals may be undertaken in this area assuming a properly planned and properly spaced system of wells. However, adequate exposure may not exist or be practical to create everywhere along this reach of the river, owing to the presence of overlying river-bottom deposits of low permeability or to the local thinning of the aquifers themselves. Ultimately, the major part (probably 80 or 90 percent) of the estimated additional ground-water withdrawal would come from induced recharge from the river. Its suitability for any given use would, therefore, depend upon the maintenance of a satisfactory quality of water in the river.

Downstream from the heavily-developed area in and around Camden and Philadelphia, the possibility of developing additional supplies of water from the aquifers of the Raritan and Magothy formations appears to be greatly restricted by the danger of inducing recharge of salty and otherwise unsatisfactory water from the river. In fact, additional development along the river in this part of the region should proceed with great caution, if at all. It seems quite possible that some of the presently developed supplies from these aquifers along this reach of the river may ultimately deteriorate because of the quality of the recharge being induced. Developments of additional water from these aquifers between this reach of the river and the salt-water zone downdip from it should also proceed with great caution, if at all, because of the danger of salt-water encroachment either from the river or from down the dip. In general, the water from this part of the aquifers is already more highly mineralized than that from many other areas (see figure 16).

South and southwest of Wilmington in New Castle County, Del., and to a much less extent in Salem County, N. J., aquifers in the hydrologic unit here considered probably have some undeveloped water-supply potential. In this part of the region, the aquifers in the Raritan and Magothy formations have not been clearly distinguished from underlying aquifers in the Patapsco formation. For the purpose of this estimate, both groups of aquifers are considered together. The high salinities of the lower Delaware River, of the Chesapeake Bay, and of the Chesapeake and Delaware Canal seem to preclude the assumption that any usable recharge may be induced from them. Consequently, the aquifers in this area must draw their usable recharge entirely from local inland and upland sources. New wells would have to be carefully placed and carefully operated in order to avoid induced salt-water recharge. In spite of these limitations, it seems probable that some additional supplies perhaps aggregating as much as 20 mgd may be withdrawn from these aquifers in this area. All new developments should be undertaken cautiously and somewhat tentatively in order not to exceed the combined optimum yield of the aquifers.

In summary, it may be said that aquifers in the Raritan and Magothy formations in the 11-county region, including the associated aquifers in the southern part of the region, are probably capable of yielding about twice as much water as is now being withdrawn from them. This conclusion should not be taken without two major qualifications. First, because the greater part of the estimated additional capacity is based upon induced river recharge above Camden, its utility necessarily depends upon the water in the river continuing to be of suitable quality for recharge. Second, in some areas, such as the center of the Camden-Philadelphia area, the aquifers appear to have been developed about to their capacity. In others, the present degree of development may even now be endangering the quality of the supply. Therefore, any substantial additional development should proceed carefully and cautiously, and the bulk of it should be located in relatively undeveloped parts of the aquifers. The complete and safe development of the water supplies from these aquifers cannot be accomplished on the basis of the existing knowledge of their geology and hydrology. As the development approaches its ultimate extent, the need for additional data and its interpretation will become imperative.

Effect of Deepening and Widening Delaware River Channel:—The proposed deepening and widening of the channel of the Delaware River between Philadelphia and Trenton would undoubtedly increase the opportunity for the interchange of water between the river and those aquifers of the Raritan and Magothy formations that would be intercepted by the proposed new channel. This would include all the aquifers that are now exposed beneath this reach of the river and possibly some that are not now exposed because of the presence of overlying clays. The nature of the effect upon the water supplies developed from these aquifers —whether an overall benefit or detriment—would depend upon the quality of the water in the river after the dredging is completed and for as long as the channel is maintained.

The quantity of water that could be withdrawn from the river as induced recharge would be increased by the construction of the new channel, both because the removal of relatively impermeable layers from the river bottom would increase the area of the aquifers exposed to river recharge and because the wider channel would bring the exposed areas closer to the producing wells. The amount of water transmitted through an aquifer is directly proportional to the hydraulic gradient, which in turn is the factor that most effectively limits the potential induced recharge of the aquifers from the river where, as in the Delaware River, an essentially unlimited quantity of recharge water is available. The removal of the silts, muds, and clays from the river bottom would increase the hydraulic gradient in the aquifer because less of the total available head difference would be dissipated in overcoming the resistance of relatively impermeable materials. This would tend to be offset to some extent by the deposition of fresh material in the bottom of the channel, but the new deposits would be removed periodically by maintenance work. The widening of the channel would shorten the distance between the exposed part of the aquifer and the producing wells and thus increase the potential hydraulic gradient and the potential flow through the aquifer to the wells.

On the other hand, the capacity of the aquifers to discharge water into the river, wherever the natural hydraulic gradient had not been reversed by pumping, would be increased by deepening the channel. This would be due primarily to the removal of the relatively impermeable materials on the river bottom and the consequent reduction in the loss of head throughout the areas of discharge. The distance from the intake areas of the aquifer to the river is generally much greater than the width of the channel so that the shortened distance caused by widening the channel would have a negligible effect upon the average hydraulic gradient. More of the recharge from precipitation on the high-level intake area northeast of Trenton (see figure 18) would then be discharged into the upper reaches of the river and less would be available to flow to the more remote parts of the aquifer. This loss would be relatively unimportant as long as the quality of the river water in the Philadelphia-Camden area remained suitable for recharging the aquifer. However, the loss might heighten the difficulty in that area if the river water there should ever become contaminated.

The industrialization of the Delaware River valley is proceeding at an accelerated rate, and the use of ground water is increasing rapidly. Probably in the relatively near future, all of the aquifers along the reach of river between Trenton and Philadelphia will be developed to such an extent that recharge will be induced wherever the aquifers are exposed beneath the river. The continued prosperity of the region may depend as much upon the continued availability of large quantities of good water from the Raritan and Magothy formations as upon the availability of cheap transportation by water. This statement is made in full cognizance of the fact that the water from the Raritan and Magothy formations could be replaced, if necessary, by water from the aquifers in the Cohansey sand and other sources farther inland. However, the total water supply of the region is limited, and the availability of water may well ultimately limit the development of the region. Furthermore, water from any distant source will be more expensive than that from sands in the Raritan and Magothy formations and this will place the water users at a competitive disadvantage. Constant vigilance and considerable expense would, therefore, be justified to maintain a good quality of river water and ensure resultant good quality of ground water.

Two general causes of contamination of the river water are to be guarded against. The first and more easily controlled is the discharge of inadequately treated municipal or industrial wastes into the river. The second is the advance of highly mineralized or salt waters upstream from the lower river and the Delaware Bay. Traces of such contamination have advanced almost to the head of the present deep channel in periods of sustained low flow. Model tests by the U. S. Army Corps of Engineers have indicated that salt water will probably not advance farther up the proposed new channel. However, this conclusion was conditional upon the maintenance of an adequate flow of good fresh water in the channel. Existing and future diversions of water from the Delaware River may make the maintenance of adequate low-water flow difficult.

If adequate low flows in the river should not be maintained, or if the results of the model tests are not verified by the performance of the river itself, salt water may advance up the new channel and threaten some or all of the existing and potential water supplies from the Raritan and Magothy formations. The greater part of the present development of ground water from the Raritan and Magothy formations within the 11-county region is near the downstream end of the proposed new channel and is thus most exposed to possible damage from salt water. If the choice must ever be made between a greater diversion of Delaware River water and the maintenance of the water supplies from the Raritan and Magothy formations, it should be made on the basis of broad regional or national interest and not on the basis of local interests. Ultimately this matter might well come within the province of the river master for the Delaware River appointed by the U. S. Supreme Court.

If, in spite of all attempts to maintain the low flows in the river, salt water should tend to advance up the new channel, it might be excluded by suitable locks in the channel. An alternate remedial measure might be the sealing of the top of the aquifer where it is exposed to river water. This might be accomplished by over-deepening the channel several feet and adding a permanent deposit of fine-grained materials to fill the excess depth. Such a procedure would lack any assurance of adequacy. Furthermore, sealing the river bottom by any means would be subject to the fundamental objection that it would cut off a substantial part of the total recharge available to the aquifers. Any effective remedial measure would probably be very costly.

Merchantville clay

Geology

The Merchantville clay is characteristically a green to black glauconitic and micaceous clay or a quartzose or glauconitic sandy clay. Indurated phases of this clay are often encountered. Marine fossils of Late Cretaceous age occur in the Merchantville clay. This formation ranges in thickness from 50 to 60 feet within the region and thins to a featheredge along the northwestern edge of its outcrop. It dips to the southeast at a rate of a little more than 40 feet per mile.

The Merchantville clay is overlain conformably by the Woodbury clay. If present in this region, the Magothy formation underlies the Merchantville conformably. However, throughout much of the region the underlying beds appear to possess a lithology very similar to that of the Raritan. If indeed these beds are Raritan, then they are overlain unconformably by the Merchantville clay.

Exposures of this formation may be seen at the pits of the Graham Brick Company at Maple Shade in Camden County, N. J.

Hydrology

The Merchantville clay is primarily an aquiclude or a confining layer. In combination with the Woodbury clay, it forms a very effective aquiclude between the aquifers in the Raritan and Magothy formations and the aquifers above. Because no acquiclude is completely impervious, it is probable that moderate or even considerable quantities of water would leak through this aquiclude if the necessary differential in head should exist over a wide area.

A few domestic wells tap the more sandy phases of the Merchantville clay for very small water supplies.

Woodbury clay

Geology

The Woodbury clay is composed of tough dark gray to black nonglauconitic blocky clay, which in outcrop weathers to a dove color or a light chocolate color. Whitish sand lentils several inches thick are found in this clay. Marine fossils of Late Cretaceous age have been found.

Within the 11-county region, the Woodbury clay is about 50 feet thick. It thins to a featheredge along the northwestern edge of its outcrop. It dips to the southeast at slighly more han 40 feet per mile.

The Woodbury clay is overlain conformably by the Englishtown sand. Where the Englishtown is absent, the Marshalltown formation may overlie the Woodbury unconformably. The Woodbury clay is underlain conformably by the Merchantville clay. In the vicinity of the Chesapeake and Delaware Canal the equivalents of the Merchantville and Woodbury clays are called the Crosswicks clay.

The Woodbury clay is well exposed along the Cooper River near Haddonfield in Camden County, N. J.

Hydrology

The principal hydrologic function of the Woodbury clay is that it serves in conjunction with the Merchantville clay as a confining layer or aquiclude between the aquifers of the Raritan and Magothy formations and the aquifers above. The Woodbury clay is probably the best aquiclude in the coastal plain of New Jersey because it retains its tough dense character wherever encountered. However, no clay is completely impermeable and therefore vertical leakage may occur through the Merchantville and Woodbury clays under suitable differences of head.

No wells are known to tap the Woodbury clay for water supplies.

Englishtown sand

Geology

The Englishtown sand derives its name from a type locality near Englishtown, Monmouth County, N. J. Typically it consists of a fine-grained to pebbly quartzose sand containing lenses and laminae of clay in some places. Subordinate amounts of mica, glauconite, and lignite are found in some outcrops. Shades of yellow, white, and brown characterize the Englishtown in the outcrop area, whereas the subsurface materials generally are a light gray. The Englishtown varies widely in both thickness and texture. It tends to become thicker and more fine-grained downdip from its outcrop. No fossils have been found in the outcrop area of the Englishtown sand, but shell fragments and microfossils have been recovered from subsurface samples. Where present, the Englishtown sand is conformably overlain by the Marshalltown formation and conformably underlain by the Woodbury clay.

The Englishtown sand is developed to its greatest extent to the northeast of the region covered by this report, in Monmouth and Ocean Counties, N. J. There it attains a maximum thickness of 140 feet at its outcrop and tends to be somewhat coarser in texture. The outcrop of the Englishtown sand thins toward the southwest until it disappears near the boundary between Gloucester and Salem Counties, N. J. The maximum thickness of the Englishtown sand in the 11-county region occurs in Burlington County, N. J., where it is 70 to 80 feet thick near the outcrop area. Although absent in outcrop in Salem County, N. J., and New Castle County, Del., it has been encountered in wells in Salem

County. In Delaware, the deposits that are assigned by the U. S. Geological Survey to the Englishtown are correlated by Groot, Organist, and Richards (1954) with the Wenonah sand.

The Englishtown sand dips very gently to the southeast at an average rate of about 40 feet per mile. It is generally wedge shaped with the thick end of the wedge lying down the dip toward the coast. Its outcrop extends from northeast to southwest, roughly paralleling the reach of the Delaware River between Bordentown, N. J., and Wilmington, Del.

Exposures of the Englishtown sand are most common outside the 11-county region in the areas where its outcrop is thickest. However, good exposures may be seen near Runnemede in Camden County, N. J., and Moorestown in Burlington County, N. J.

Hydrology

Importance as an Aquifer:—The Englishtown sand is an important aquifer in Monmouth and Ocean Counties, N. J. In the northeastern part of the 11-county area it is a moderately good aquifer, but its usefulness decreases toward the southwest as its thickness decreases. The Englishtown sand has not been heavily developed in the area covered by this report, but it has been tapped in many places for small to moderate supplies. The largest yield reported for a single well tapping this aquifer within the region is 200 gallons per minute, but it is probable that in some places, especially in Burlington County, N. J., carefully constructed and thoroughly developed wells will yield substantially more.

Quality of Water:—The water from the Englishtown sand is generally satisfactory for ordinary uses without treatment. Analyses of seven water samples collected from wells tapping the Englishtown sand indicate that the quality of the water in this aquifer is fairly uniform throughout its extent. The water is generally slightly alkaline and very moderately mineralized. The dissolved solids range from 101 to 156 ppm. The total hardness, ranges from 56 to 122 ppm. The iron content is normally low, in the order of 0.4 ppm, but one sample contained 3.0 ppm. These results indicate that although the water from the Englishtown sand may occasionally require treatment for the removal of iron or the reduction of hardness for some industrial processes, it is generally satisfactory for most uses without treatment. Two typical analyses of water from the Englishtown sand are given in table 9.

Recharge, Movement, and Discharge of Ground Water:—The Englishtown sand probably receives most of its recharge from precipitation on or near its outcrop area. The total outcrop area of this aquifer in New Jersey is about 130 square miles, of which about two-fifths lie in the 11-county region. The effective intake area is somewhat larger due to the effect of permeable Pleistocene deposits that overlie the outcrop of the aquifer and that of the adjoining aquicludes so that they may funnel water from precipitation into the Englishtown sand. It is probable that much potential recharge is currently rejected because the sand is full or nearly full of water when precipitation occurs.

The Englishtown sand lies above one of the most effective aquicludes in the region, the combined Merchantville and Woodbury clays, and is overlain by another good aquiclude, the Marshalltown formation. It seems unlikely, therefore, that it receives much recharge from adjacent aquifers through the intervening aquicludes. Nevertheless, it underlies many hundreds of square miles of the Coastal Plain and small differentials of head might produce substantial recharge to, or discharge from it by leakage through the aquicludes over such a large area. A study of the relative altitudes of the intake areas of the aquifers above and below the Englishtown indicates that there is probably discharge to the aquifer above, rather than recharge from it. The aquifers below, in the Raritan and Magothy formations, are now so heavily developed that any movement of water across the aquiclude is probably from the Englishtown rather than into it.

The intake area of the Englishtown sand is crossed by many small streams and a few large ones which are potential sources of additional recharge. It seems probable, however, that they are currently points of discharge rather than of recharge. Some of the more favorably situated of these streams may ultimately be sources of induced recharge if the aquifer should be heavily pumped near them.

The overall pattern of movement of water in the Englishtown sand prior to any pumping was probably somewhat similar to that in the aquifers of the Raritan and Magothy formations (see figure 18) except for the absence of a well-defined low-level discharge area at the southeastern end of the system where the aquifer thins out. Water moved from high-level intake areas in Middlesex and Monmouth Counties to the major discharge area along the Raritan Bay. Moderately heavy pumping northeast of the 11-county region has probably altered the original flow pattern considerably.

It is probable that the major part of the water that now enters the Englishtown sand within the 11-county region is discharged into nearby stream channels that cross the intake area. The gradients to the distant points of natural discharge along the Raritan Bay or to areas of pumping in adjacent counties are gentle so that water moves toward them at a slow rate. Discharge in those areas is probably supplied mainly from nearer intake areas northeast of the region. Probably some water that enters the intake area moves downdip and is discharged through the aquicludes into adjacent aquifers. Withdrawals from wells tapping the Englishtown sand within the region are probably only 1 or 2 million gallons daily. It would appear, therefore, that relatively little water is now discharged from the Englishtown sand within the 11-county region and that a relatively large part of the potential recharge is rejected in the intake area.

In Monmouth, Middlesex, and Ocean Counties, N. J., pumpage from the Englishtown sand probably totals almost 20 million gallons a day. Thus the total artificial withdrawal of water from this aquifer is of the same order of magnitude, that is, about 20 million gallons a day or more. Data are not available to estimate the quantities of water discharged naturally through the acquicludes and at the main low-level discharge area along Raritan Bay. It is believed, however, that the natural discharge through these outlets is now substantially less than the total pumpage from wells.

Possibilities for Additional Development:—It would appear on the basis of existing information that the Englishtown sand could probably yield substantially more water than is now withdrawn from it. On the basis of three-quarters to one million gallons a day for each of the 130 square miles of intake area, it might be estimated that the yield of the aquifer would be in the order of 100 to 130 million gallons a day. If the total discharge, both natural and artificial, is in the order of 50 million gallons a day, and if none of the natural discharge can be recovered, it might be estimated that about 50 to 80 million gallons a day of additional water could be withdrawn from the entire aquifer. These figures should be used only as an order of magnitude because of the many uncertainties involved in such an estimate. Of course, not all of the additional capacity would be available within the 11-county region.

The quantity of water that can be withdrawn at any point would depend to a considerable degree on the capacity of the aquifer to transmit water to that point from the intake area. This in turn would depend largely upon the hydraulic gradient that could be established from the intake area to the point of withdrawal. The steepest gradients could be established near the intake area; hence it may be concluded that the best place to develop additional water from the Englishtown sand would be in or within a few miles of its intake area. This would also be the area where the sand is nearest the surface, and in general it would be the area safest from salt-water intrusion.

A pattern of development that emphasized the area near the intake would mean that the yield in the 11-county region would be limited mainly to the intake potential within the region. It would also mean that the potential yield would tend to decrease as the water-bearing formation underlying the nearby intake areas became thinner. In view of the present small use of water from the Englishtown sand, it would seem that the potential yield in the region might be in the order of 30 to 50 million gallons a day. Most of this additional supply would be available in Burlington County, N. J., and the aquifer should not be expected to yield much water in Camden and Gloucester Counties, N. J., or farther to the south.

Within the 11-county region, the danger of salt-water intrusion would probably not seriously limit the optimum yield of the Englishtown sand. There is no major exposure of the aquifer to subsurface bodies of salt water because it seems to thin out before it reaches the Delaware Bay. Furthermore, if the pumping development is near the intake area and if the wells are appropriately spaced, there seems little likelihood of drawing in salt water from lower parts of the aquifer nearer the coast. Nevertheless, the possibility of an advance of salt water from that direction should be guarded against by the use of outpost wells if the aquifer should be developed extensively.

Marshalltown formation

Geology

In its outcrop area, the Marshalltown formation is composed of dark green or black clay or sandy clay, which is in some places highly glauconitic and micaceous. Quartz sand grains of medium size are found in the sandy portions of the formation. Downdip, in some wells, this formation does not retain its clayey character but grades into a sand more nearly resembling the Englishtown or Wenonah sands. Marine fossils of Late Cretaceous age have been found in the Marshalltown.

The Marshalltown formation ranges from 30 to 40 feet in thickness in or near its outcrop area. It dips to the southeast at a little more than 35 feet per mile. Where the Englishtown sand is present, it underlies the Marshalltown formation conformably. Where the Englishtown sand is absent as in much of Salem County, N. J., and New Castle County, Del., the Woodbury clay probably underlies the Marshalltown formation unconformably. The Marshalltown formation is overlain conformably by the Wenonah sand.

Exposures of Marshalltown formation may be seen in the banks of Oldmans Creek near Auburn in Salem County, N. J., and along the New Jersey Turnpike near Fellowship, in Burlington County, N. J.

Hydrology

The principal hydrologic significance of the Marshalltown formation is that it may serve as a confining layer or aquiclude above the Englishtown sand. Where the Englishtown sand is absent, the Marshalltown lies upon the Woodbury clay and thickens the aquiclude above the aquifers in the Raritan and Magothy formations. In those places down the dip where it is sandy in nature, the Marshalltown formation probably does not function effectively as an aquiclude. In such places, vertical leakage between the Englishtown sand and the Wenonah sand may occur if the necessary hydraulic gradients exist.

Domestic water supplies have been developed from sandy phases of the Marshalltown formation. Although yields as high as 40 gallons per minute have been reported in some places, little or no water is available from the clayey phases of the formation.

Wenonah and Mount Laurel sands

Geology

The Wenonah and Mount Laurel sands are discussed together because they function hydrologically as a single unit and because they cannot everywhere be separated into two distinct formations.

The Wenonah sand is mainly composed of fine-, to coarse-grained quartzose sands of white, yellow-red, rusty brown, and black hues. In places, it is highly ferruginous as shown by the presence of "ironstone" layers (iron-cemented sandstone). In other places, it is very fine-grained and micaceous. Near the contact with the underlying Marshalltown formation, a brown silty clay has been noted. The sand becomes finer grained down the dip. A sand similar in lithology to the Wenonah sand is found in New Castle County, Del. In New Jersey, the Mount Laurel sand is characteristically a medium-, to coarse-grained quartzose sand containing varying quantities of glauconite. In color it is generally a mixture of light grays and dark greens, giving a characteristic salt and pepper appearance. It thickens downdip and in some places appears to be coarser in that direction. In the New Jersey part of the region, lithology typical of the Mount Laurel appears to be more extensive than lithology typical of the Wenonah.

Marine fossils of Late Cretaceous age have been found in exposures of both sands.

The Wenonah and Mount Laurel sands crop out in a band a few miles wide extending across the region in a northeasterly direction. This band is roughly parallel to the predominant trend of the Delaware River in the region and is about 8 miles southeast of the river. After the river turns to the southeast, it crosses into Delaware. The sands are presumed to underlie all of the region southeast of this outcrop. The combined thickness of these two sands near their outcrop area ranges from 40 to 100 feet. The dip of the top of the Mount Laurel sand is about 35 feet to the mile to the southeast.

The Wenonah sand is underlain conformably by the Marshalltown formation. In parts of New Castle County, Del., it is thought that both the Woodbury clay and Marshalltown formation may be absent. If so, the Wenonah sand would rest uncomformably upon the Merchantville clay. The Mount Laurel sand lies conformably on the Wenonah sand and is conformably overlain by the Navesink marl.

Exposures of both the Wenonah and Mount Laurel sands can be seen near Auburn and Woodstown in Salem County, N. J.

Hydrology

Importance as an Aquifer:—The Wenonah and Mount Laurel sands function effectively together as one aquifer which has been developed more extensively in the 11-county region than the Englishtown sand. Its capacity to store and transmit water is less than that of the aquifers in the Raritan and Magothy formations or that of the Cohansey sand. However, in many places where aquifers like those in the Raritan are not as readily available for comparison, it would be considered an excellent aquifer. Unlike the Englishtown sand, the aquifer formed by the Wenonah and Mount Laurel sands tends to thicken somewhat toward the southwest. Wells yielding 300 or 400 gpm have been developed in this aquifer, and it is probable that even better wells might be developed under favorable conditions.

No pumping tests suitable for the determination of the coefficients of transmissibility and storage have been made on the aquifer composed of the Wenonah and Mount Laurel sands. However, sand samples from a well in Monmouth County, N. J., were tested for permeability and porosity (Thompson, 1930). The results showed coefficients of permeability of 566 and 887 gallons per day per square foot and porosities of 34 and 30 percent for the upper part and the lower part of the aquifer, respectively. Tests of samples collected in the course of the investigations that preceded this report indicated permeabilities of about 500 gpd/sq. ft. This compares with permeabilities in the order of 1,000 to 1,500 gpd/sq. ft. in the aquifers of the Raritan. Thus, the average permeability of the aquifer is believed to be in the order of 500 to 700 gpd/sq. ft., and an average section 70 feet thick would have a coefficient of transmissibility of less than 50,000 gpd per foot or about the same as some of the thinner aquifers in the Raritan.

Quality of Water:—The water from the Wenonah and Mount Laurel sands is fairly uniform in most of its chemical characteristics. It is generally noncorrosive, very moderately mineralized, and slightly hard. It may be used for most purposes without treatment except that it occasionally requires the removal of iron or the reduction of hardness. The pH ranged from 7.4 to 8.3 in 14 samples of water from wells tapping the Wenonah and Mount Laurel sands. Concentrations of dissolved solids ranged from 103 to 133 ppm. Concentrations of iron in the waters from these sands are not uniform; they vary not only between wells but also between samples from the same well. In the 14 water samples analyzed, the iron concentrations ranged from 0.07 to 5.6 ppm; however, they were generally about 0.3 ppm or less. Typical results of analyses of water from the Wenonah and Mount Laurel sands are given in table 9.

Recharge, Movement, and Discharge of Ground Water:—Currently very little water is being withdrawn from the Wenonah and Mount Laurel sands. The estimated withdrawal in the 11-county region is about 3 million gallons a day. Thus the natural equilibrium in the aquifer has probably been disturbed very little. The aquifer is being recharged from precipitation on its outcrop and is discharging water mainly at low points in its outcrop area. Probably a major part of the recharge moves relatively short distances through the aquifer and is discharged into streams crossing the outcrop area.

The aquifer crops out beneath Raritan Bay, the Delaware River, and the Chesapeake Bay. These are probably major areas of discharge. The aquifer is confined throughout most of its extent between the Marshalltown formation below and the Navesink marl above. Thus, it is probable that water is circulating through the confined part of the aquifer to sea level points of discharge in much the same manner that water circulated through the Raritan and Magothy aquifers before they were developed (see figure 18).

Neither the underlying Marshalltown formation nor the overlying Navesink marl are exceptionally tight aquicludes. Depending on the hydraulic gradient, there may be some movement of water into or out of the Wenonah and Mount Laurel sands, through the aquicludes, from adjacent aquifers or from sandy beds in the aquicludes themselves. Under existing conditions, such movement is probably of little consequence. If, under heavy development, the head in the aquifer should be substantially lowered, the adjacent aquifers might furnish moderate quantities of recharge.

Possibility for Additional Development:—The outcrop area of the Wenonah and Mount Laurel sands in the 11-county region covers about 160 square miles. At a rate of $3/4$ to 1 mgd per square mile of intake area, the potential yield of the aquifer would be in the order of 120 to 160 mgd. To this might be added recharge from other aquifers and induced recharge from the streams that cross the intake area. On the basis of an estimated coefficient of permeability of 700 gpd/ft^2. it seems probable that the aquifer could transmit 150 mgd or more from the intake area to nearby well fields. The available hydraulic gradients might limit the quantity of water that could be transmitted considerable distances from the intake area.

Another factor that is likely to limit the optimum yield of the Wenonah and Mount Laurel sands is the danger of salt-water intrusion. Throughout most of the region, the water level in the intake area of the Wenonah and Mount Laurel sands is not at a very high altitude so it is probable that the salt water in the aquifer is not very many miles downdip. If the head in or near the intake area should be lowered substantially by pumping, some of the wells that are closest to the salt-water front would probably be affected by salt-water intrusion.

A conservative estimate of the potential additional yield of the aquifer formed by the Wenonah and Mount Laurel sands would be in the order of 75 to 100 mgd. The estimate would be improved by more detailed and specific information on the geologic and hydraulic characteristics of the aquifer and on the position of the salt-water interface in it. Any large-scale developments of water from this aquifer should be preceded by careful and detailed study and by test drilling to determine the location of salt water and to provide a means for observing its movement.

Navesink marl

Geology

The Navesink marl crops out in a narrow band just southeast of the outcrop of the Mount Laurel sand. It is characterized by glauconitic sands and clays mixed with varying amounts of quartzose sands. The upper part of the formation is more clayey, whereas, the basal beds are often pebbly. In many localities where it is overlain directly by the Hornerstown marl, it is difficult to distinguish the two because they are very similar lithologically. Darker shades of green and a slightly higher clay content are typical of the Navesink. Marine fossils of Late Cretaceous age are found in exposures. The Navesink is estimated to range in thickness between 3 and 40 feet; it dips to the southeast at an average rate of a little less than 35 feet per mile. This marl is overlain unconformably by the Hornerstown marl or, where the Red Bank sand is present, the contact with it is conformable. Underlying the Navesink marl conformably is the Mount Laurel sand. In Delaware, the Mount Laurel and the Navesink are considered as a unit consisting of a very fine, to fine-grained quartz sand with some silt and clay (Groot, Organist, and Richards; 1954).

Exposures of this marl may be seen at Mullica Hill, Gloucester County, and near Runnemede, Camden County, in New Jersey.

Hydrology

Because the intervening Red Bank sand is absent throughout most of the region, it is thought that the Navesink and Hornerstown marls probably function as a single hydrologic unit. Their main hydrologic function is as a confining layer or aquiclude for the subjacent Wenonah and Mount Laurel sands.

It is possible that a few domestic supplies have been developed from the sandy layers in the Navesink marl.

Red Bank sand

Geology

In the 11-county region, the Red Bank sand crops out in extremely small areas in New Castle County, Del., and in northern Burlington County, N. J. It is, for the most part, a fairly coarse-grained yellow and reddish-brown quartz sand, locally cemented by iron oxide. Marine fossils of Late Cretaceous age have been found in the Red Bank sand. The Red Bank is estimated to be no more than 20 feet in thickness in the New Jersey section of the region. Not more than 10 feet of the Red Bank is exposed in New Castle County, Del. It dips at about 30 feet per mile to the southeast. The Red Bank is overlain unconformably by the Hornerstown marl and is underlain conformably by the Navesink marl.

Exposures of Red Bank may be seen near Sykesville, Burlington County, N. J., and along the Chesapeake and Delaware Canal near Delaware City, New Castle County, Del.

Hydrology

Within the region, the Red Bank sand is a very minor aquifer because it is generally thin or absent both in outcrop and in the subsurface. However, where present, this sand will yield adequate water for domestic supplies.

No permeability or porosity tests have been made of the Red Bank sand, but on the basis of appearance it is judged to be very similar in its physical properties to the Englishtown sand.

CENOZOIC SEQUENCE

TERTIARY SYSTEM

Eocene series

Hornerstown marl

Geology

The Hornerstown marl occurs in outcrop as a narrow band adjacent to the outcrops of the Navesink marl or to the Red Bank sand when present in New Jersey and Delaware. It is composed predominantly of glauconite with lesser proportions of clay and sand. The formation is generally dark green in color, due largely to the presence of glauconite which makes up as much as 90 percent of some samples.

Throughout most of the 11-county region, the Navesink and Hornerstown marls are difficult to separate because they are similar lithologically, and the Red Bank sand is not present between them. However, the Navesink tends to contain more clay and smaller percentages of glauconite than does the Hornerstown. Marine fossils of Eocene age have been found in the Hornerstown marl. In lower New Castle County, Del., the Hornerstown marl is not distinguishable lithologically from the overlying Vincentown sand, but it is separated from the Navesink marl by the Red Bank sand (Marine and Rasmussen, 1955). The combined thickness of these two formations within the region ranges from 35 to 70 feet. The top of the Hornerstown marl dips to the southeast at about 30 feet per mile. The Hornerstown marl is overlain conformably by the Vincentown sand whereas the underlying Navesink is considered to be unconformable with it. On the basis of recent paleontological studies, at least the lower part of the Hornerstown has been assigned to the Paleocene series by Richards (1956) and H. W. Miller, Jr. (1956).

Exposures of Hornerstown may be seen in the banks of Oldmans Creek near Woodstown, Salem County, N. J., and in pits near Medford, Burlington County and Sewell, Gloucester County, N. J.

Hydrology

The Navesink and Hornerstown marls probably function as a single hydrologic unit and serve as a confining layer or aquiclude above the aquifer formed by the Wenonah and Mount Laurel sands. However, they do not form a very tight aquiclude so that vertical leakage may occur through them into or out of the underlying aquifer, depending upon the hydraulic gradient.

In some localities, sandy phases of the Hornerstown may yield adequate quantities of water for domestic use.

Vincentown sand

Geology

The Vincentown sand probably underlies most of the Coastal Plain part of the region south and east of the outcrop of the Hornerstown marl. Throughout most of Camden and Gloucester Counties, N. J., and in the vicinity of Fort Dix in Burlington County, N. J., the Vincentown sand is overlapped by the Kirkwood formation so that it has no outcrop. It does, nevertheless, extend downdip to the southeast from this overlapped area and is encountered in wells there.

The Vincentown sand has two recognizable facies: (1) a sand of limy or calcareous nature composed of the remains of bryozoa, corals, echinoids, and other fossils with some quartz—this facies is sometimes indurated; (2) a quartzose sand that contains varying amounts of glauconite. The limy facies is predominant in Burlington and Salem Counties, N. J., and possibly in New Castle County, Del. The Vincentown appears to become more clayey and glauconitic towards the southeast. Thinning and, in many locations down the dip, complete disappearance of the permeable beds have been noted. Marine fossils of Eocene age are numerous in the lime-sand facies of the formation.

Like many formations of the Coastal Plain, this sand thickens to the southeast. In the outcrop area, the formation ranges in thickness from 25 to 100 feet. Subsurface thicknesses in excess of 100 feet have been reported from wells. This formation dips to the southeast at less than 30 feet per mile. Surface exposures of this sand cover approximately 90 square miles in New Jersey and Delaware. The Vincentown sand is probably, in large part, the equivalent of the Aquia formation of Maryland and Virginia.

The Vincentown is overlain conformably by the Manasquan marl, where the Manasquan is present, and unconformably by the Kirkwood formation where the Manasquan is absent. The Vincentown sand overlies conformably the Hornerstown marl; this contact is apparently gradational. Because the Hornerstown and Vincentown formations cannot be readily separated lithologically in Delaware, the position of the contact between them is inferred on the geologic map accompanying this report.

Typical exposures of the lime-sand facies of the Vincentown sand may be seen in an abandoned marl pit near Alloway, Salem County, N. J., and along the banks of Rancocas Creek near Vincentown, Burlington County, N. J. An exposure of the yellow quartz-sand facies, slightly glauconitic, may be seen along Oldmans Creek near Woodstown, Salem County, N. J.

Hydrology

Importance as an aquifer:—The Vincentown sand is a minor but relatively important source of water in New Jersey. Within the area of this report, it serves as one of the sources of supply for the City of Salem in Salem County, N. J., and is used elsewhere principally as a source of numerous domestic and farmstead water supplies and occasionally for a small industrial supply. The estimated total pumpage is more than 2 mgd.

Because of the variations in thickness, lithology, and in the amount of induration, which affects the permeability, it is not possible to estimate average values for such hydraulic constants as permeability, porosity, and specific yield. However, the unconsolidated limy and quartzose sands are often of a medium to coarse texture and will readily transmit water.

Wells in the Vincentown sand produce as much as 300 gallons per minute in the thicker portion of the aquifer around Salem, N. J. In the area between Woodstown and Grenloch, N. J., well yields are apparently much smaller. Here the yield will largely depend upon the thickness of permeable strata. From Grenloch to New Egypt in Burlington County, N. J., the yield may be as large as 50 to 100 gallons per minute. Northeast of this locality, little is known concerning the ability of the aquifer to yield water, but because the formation is predominantly sandy and relatively thick, good yields are probably available.

Quality of Water:—The water from the Vincentown sand is moderately mineralized, mildly alkaline, and hard. Comparatively high concentrations of calcium and bicarbonate are present. The concentration of dissolved solids is in the order of 250 ppm. The concentration of iron in the water from the Vincentown sand at Quinton, N. J. (see table 9) was 1.9 ppm, which is considerably above the allowable concentration for many uses. Except for hardness and occasional high iron, the water from the Vincentown sand is suitable for ordinary purposes.

Recharge, Movement, and Discharge of Ground Water:—Most of the outcrop area of the Vincentown sand, including that beneath the overlap of the Kirkwood formation, probably acts as an intake area. Natural discharge occurs at localities where the exposures are at lower altitudes. In general, the intake area is highest to the northeast in Monmouth County, and in the 11-county region it ranges from moderately high in Burlington County to low along the Delaware River. The lower portion of the outcrop near the river is probably a discharge area. However if ground water was discharging in the Quinton-Salem area under natural conditions, relatively heavy pumpage there may have reversed the ground-water gradient, causing it to become an intake area. Deposition of considerable thicknesses of silt and clay in the river channel probably retards the interchange of water between the river and the aquifer.

Possibilities for Additional Development:—The Vincentown sand probably has the smallest opportunity for recharge and the least ability to store and transmit water of any extensive aquifer of comparable thickness in the Coastal Plain. It is not everywhere a reliable source of water supply because in many places it is relatively impermeable. Its usefulness as a major source of ground water is, therefore, very limited. The water from the Vincentown is more mineralized than that from other aquifers generally available in the same area. Near the Delaware River and some distance downdip from the outcrop of the aquifer, the danger of salt-water encroachment may further limit the use of this aquifer. The future use of the Vincentown sand will probably continue to be restricted to farmstead and domestic supplies and to supplemental supplies for municipal and industrial uses.

Manasquan marl

Geology

In its outcrop area in New Jersey, this formation is composed of green and gray quartzose sand and clay, which may be very glauconitic. The sand is very fine-, to medium-grained. The Manasquan is exposed at the surface only in Burlington and Camden Counties. It has been identified from subsurface samples in other counties in New Jersey and may exist in New Castle County, Del. The lithology of the Manasquan is similar to that of the underlying Vincentown sand, and the two may grade gradually into each other.

The Manasquan ranges in thickness from a featheredge to 25 feet in the region. It dips at about 25 feet per mile to the southeast. The Manasquan is overlain unconformably by the Kirkwood formation and underlain conformably by the Vincentown sand. Marine fossils of Eocene age have been found in the formation. Exposures of typical Manasquan may be seen in a creek bank near Clementon in Camden County, N. J.

Hydrology

As far as is known, the Manasquan marl has not been utilized for any water supply in New Jersey or Delaware. Where present, its main hydrologic function is to confine water within the Vincentown sand. It is a poor aquiclude, and some ground water probably moves through it wherever there are head differentials across it.

Miocene Series

Kirkwood formation

Geology

The Kirkwood formation crops out over an area of about 165 square miles in the 11-county region. It underlies the coastal part of the region south and east of its outcrop area and extends to the coast and beyond, perhaps to the edge of the Continental Shelf. In outcrop the Kirkwood formation is composed predominantly of fine-grained micaceous quartzose sands, well sorted, and often delicately banded in shades of orange, yellow, white, and salmon pink. In Salem County, N. J., it is composed of light gray clay, a thin gray sand, and light gray clay. Farther down the dip, the clay layers account for an increasing proportion of the total thickness of the Kirkwood, and at Atlantic City, N. J., the clay layers account for at least four-fifths of the total. In spite of the increase in clay content downdip in the Kirkwood, the water-bearing characteristics of the sand appear to improve as the distance from the intake area increases. The sands coarsen and some of them yield large quantities of water to wells. Marine fossils of Miocene age have been found both in the clays and in the sands of the Kirkwood. Fossil evidence from subsurface sections indicates that the basal beds of the Kirkwood formation are the equivalent of part of the Calvert formation of Maryland. In Cape May and Atlantic Counties, N. J., the uppermost part of the Kirkwood contains fossils that have been correlated with the St. Marys formation of Maryland (Richards and Harbison, 1942, p. 235). The formation dips and thickens to the southeast. Near its outcrop area it is 65 to 190 feet thick, whereas it is as much as 1,000 feet thick in Atlantic and Cape May Counties. Basal beds in the Kirkwood dip about 25 feet per mile to the southeast whereas the average dip of the upper beds is a little more than 10 feet per mile to the southeast. Unconformably overlying the Kirkwood formation is the Cohansey sand. Unconformably underlying it within the region is the Manasquan marl, if present, or the Vincentown sand.

Apparently, at least two distinct aquifiers are present in some parts of the Kirkwood formation. In the vicinity of Seaside Park, Ocean County, two aquifiers have been recognized in the Kirkwood formation, one in the upper part of the formation and another in the very basal section, which is hydraulically connected with the upper part of the underlying Vincentown sand. At least two water-bearing sands within the Kirkwood have also been recognized at several localities in Atlantic and Cape May Counties.

Exposures of the Kirkwood formation may be seen in the stream banks of Oldmans Creek near Harrisonville, Gloucester County, and in a sand pit near Blackwood, Camden County.

Hydrology

Importance as an Aquifer:—The Kirkwood has been developed only for domestic and farmstead supplies within the 11-county region. Reliable yields to wells within the region are low, in the order of 5 to 200 gallons per minute. The water-bearing sands in the Kirkwood are much more productive in Atlantic, Cape May, Cumberland, and Ocean Counties, N. J., where more than 20 mgd are pumped from the aquifiers of the Kirkwood.

Physical Properties:—The permeabilities of several samples of sand from an aquifier of the Kirkwood, known as the Atlantic City 800-foot sand, were determined by laboratory methods. Their average coefficient of permeability was 864 gpd/ft^2 (Thompson, 1928). No other samples from acquifers of the Kirkwood have been tested in the laboratory for permeability. However, a few pumping tests have been made on aquifers of the Kirkwood at different places in the state. The results are as follows:

Locality and Aquifer	*Coefficient of permeability (gpd/ft^2)*	*Coefficient of storage (dimensionless)*
N. J. State Hospital at Ancora, Camden County	140	3×10^{-4}
August 18-22, 1952 an aquifer near middle of formation (2 tests; different wells)	210	4×10^{-4}
Seaside Park Water Dept. Ocean County March 20 and 22, 1951 basal sand of the Kirkwood formation	200	3×10^{-4}
Atlantic City Water Dept. Pleasantville, Atlantic County February 27, 1952 June 18, 1952 Atlantic City 800-foot sand	880	3×10^{-4}

Quality of Water:—Analyses of samples of water from three wells tapping aquifers in the Kirkwood formation are given in table 9. Analytical results indicate some difference in the chemical characteristics of the waters from different areas and probably from different aquifers in this formation. The geological data on the different aquifers are insufficient to correlate over great distances so the geochemical interpretation of changes in quality cannot proceed very far. The quality of water data do suggest, however, that at least two aquifers were sampled.

The waters from wells tapping an aquifer near the top of the formation in eastern Burlington County, N. J., as represented by the sample from Harrisville, resemble water from the Cohansey sand. This suggests a possible hydraulic connection between this aquifer and the Cohansey sand. This water is low in dissolved solids and hardness and its pH is in the acid range. Waters from wells on or near the outcrop of the aquifers at Hancock's Bridge in Salem County and at Fort Dix in Burlington County, N. J., resemble water obtained from the Atlantic City 800-foot sand. The sample from Fort Dix and one from Atlantic City are given in the table. These waters are fairly high in bicarbonate, in the alkaline range of pH, and moderately hard.

Iron concentrations in the waters from the Kirkwood formation vary, but are generally less than 0.3 ppm. In general, the water may be used for most purposes with little or no treatment. However, it may be necessary to adjust the pH of the water from some aquifers and to remove some of the hardness from water from others before use in some industrial processes.

Recharge, Movement, and Discharge of Ground Water:—The major sources of recharge to the aquifers of the Kirkwood formation are precipitation on the permeable parts of its outcrop and perhaps on parts of the outcrop of the overlying Cohansey sand. From this intake area, water moves toward areas of discharge. More often than not, the direction of the hydraulic gradient does not conform with the direction of the dip of the Kirkwood. At present, the major areas of discharge are probably also in the permeable parts of the outcrop area where stream channels and low swampy areas provide nearby relatively low-level discharge areas. The major part of the recharge thus probably moves only a short distance through the aquifer before it is discharged. Other generally more remote areas of large or potentially large natural discharge exist in low parts of the outcrop area at or near the localities where the aquifers pass beneath the ocean or its arms. Such areas occur where the formation passes under the ocean off Monmouth County, N. J., where it passes beneath the Delaware River between Salem County, N. J., and New Castle County, Del., and where it passes beneath the Chesapeake Bay. Water that enters the artesian parts of the aquifers in the Kirkwood may move many miles to distant points of discharge. Before pumping began, the pattern of flow was probably much the same as that shown for the Raritan and Magothy formations under similar circumstances (see figure 18). High-level intake areas to support this type of flow pattern occur along the outcrop of the formation from central Monmouth County to central Camden County, N. J.

A significant area of artificial discharge lies along the coast and centers on the Atlantic City, N. J. area. In the Atlantic City 800-foot sand, the flow lines now almost certainly converge on the Atlantic City area. The head of water in this aquifer has been lowered more than 100 feet in the center of the area and more than 20 feet over a wide surrounding area. It is believed that the lowering of head has extended as far as the intake area of this aquifer so that some of the recharge that occurs within the 11-county region is moving toward this major center of withdrawal.

Possibilities for Additional Development:—As already noted, the sands of the Kirkwood are fine-grained and therefore of relatively low permeability in and near their outcrop areas. Hence, they yield relatively small quantities of water to individual wells there. It is unlikely, therefore, that many large wells will be developed from the Kirkwood in the 11-county region. Nevertheless, it would probably be possible to withdraw a substantial quantity of water from the Kirkwood within the region by means of a system of many small-capacity wells, if that should become economically feasible.

There is insufficient geologic information available to determine how water moves from intake areas to areas downdip along the coast where some of the sands of the Kirkwood are more permeable. Probably the low permeabilities in and near the outcrop of the formation will limit the ultimate total withdrawals farther downdip. If so, the maximum development of the aquifers in the Kirkwood will necessarily include intensive development by means of small wells near the outcrop.

The areal extent of the Kirkwood outcrop, in the Coastal Plain of New Jersey and Delaware, is approximately 350 square miles. Of this area, about 250 square miles lie within the 11-county region. Except in Salem County, N. J., and New Castle County, Delaware, where the Kirkwood is predominantly clay in its outcrop area, the infiltration capacity of the outcrop area is probably high. The most permeable part of the outcrop area extends from Gloucester County to Monmouth County, N. J., and has an area of more than 200 square miles. If the structure of the formation and the available hydraulic gradients are such that water can move to areas of discharge, all this area would be potential intake area. The same would apply to the permeable parts of the outcrop in Salem and New Castle Counties. On the basis of ¾ to 1 mgd per square mile, which has been used for other aquifers in the Coastal Plain, it would appear that the potential recharge of the Kirkwood would be in the order of 150 to 200 mgd. A major part of this recharge would occur in the 11-county region.

The ultimate development of some of, if not all, the aquifers in the Kirkwood down the dip near the coast is limited not only by their capacity to transmit water from their intake areas, but by the danger of salt-water intrusion (Barksdale, 1936). It would seem that the greatest potential for additional developments of ground water from these aquifers might be in the area midway between the outcrop area and the interface between fresh water and salt water. This is the area in which the least is now known about these aquifers.

Miocene (?) series
Cohansey sand

Geology

Within the 11-county region, the Cohansey sand crops out in the eastern part of Burlington, Camden, Gloucester, and Salem Counties, N. J., covering approximately 750 square miles. Outside the region, it and equivalent aquifers crop out over a much greater area. It is composed chiefly of white or light-colored, medium-, to coarse-grained quartzose sand and occasional lenses of gravel. Locally, it contains clay laminae and lenses of light-colored clay that may be as much as 25 feet thick. Individual layers or beds within the formation generally dip or slope to the southeast at about 10 feet per mile. Plant remains from the Cohansey near Bridgeton and Millville, N. J., indicate a probable Late Miocene age.

A range in thickness from a featheredge to 200 feet has been reported for the Cohansey in the 11-county region. Owing to overlap and subsequent beveling by erosion, the Cohansey thins to a featheredge along its northwestern margin. Generally, the aquifer thickens to the east and south, the maximum rate of thickening occurring southeastward down the dip. The greatest observed thickness of the Cohansey (Richards, 1945, p. 896) is in the Young's Pier well at Atlantic City, where it attains a thickness of 264 feet.

The Cohansey sand overlies the Kirkwood formation unconformably. The contact can generally be detected by the appearance of the darker colored clays and sands of the Kirkwood formation. The Cohansey sand is the uppermost of the major formations of the Coastal Plain. Within the 11-county region, it is overlain unconformably by a generally thin veneer of various Pliocene (?) and Pleistocene formations. Along the coast in the vicinity of Cape May the overlying Pleistocene deposits attain a thickness of 100 or 200 feet.

The Cohansey sand is generally considered to be a river or estuarine-type deposit, although its materials may have been deposited under near-shore marine conditions. In support of this latter view, it is difficult to imagine that as extensive a formation as the Cohansey sand, composed of fairly well-sorted materials, could be deposited by stream action alone. It is possible that both stream and marine conditions are represented by the materials of the Cohansey.

Exposures of the Cohansey may be seen in sand pits near Berlin in Camden County.

Hydrology

Importance as an Aquifer:—The Cohansey sand is potentially by far the most productive aquifer in the New Jersey Coastal Plain. It is here considered as a single hydrologic unit, even though in some places it contains more than one distinct water-bearing bed. It is composed predominantly of highly permeable and generally well sorted sands and gravels and is thus able to store and transmit large quantities of water. It crops out either at the surface or beneath a veneer of permeable Pleistocene deposits over an area of 2350 square miles, more than the outcrop area of all the other aquifers in the Coastal Plain of the State. It is thus exposed to and able to absorb vast quantities of recharge from precipitation.

Within the 11-county region, however, the Cohansey sand probably ranks about equal to the aquifers of the Raritan and Magothy formations in potential yield of ground water. A major part of the outcrop area of the Cohansey within the region is near the featheredge of its outcrop where the sands are thin. Thus, although the outcrop area of the Cohansey in the region is almost one-third of its total outcrop area in New Jersey, its productivity is probably less than one-fourth that of the sand as a whole.

Nevertheless, the Cohansey sand, both within and without the region, is of great importance to the future economy of the region. After the waters of the Delaware River, the waters of the Cohansey sand are probably the most readily available major supply for the region. This applies primarily to water from the Cohansey sand in New Jersey. Sands equivalent to the Cohansey extend into southern Delaware but that area is so far from the centers of population and industry in the 11-county region that transmission of water from it would probably not be economical.

Physical Properties:—The sands of the Cohansey are commonly well sorted and highly porous. Hence a considerable part, 30 percent or more, of their total volume is void space capable of holding water. They are generally medium-, to coarse-grained and, therefore, capable of yielding a substantial portion of their stored water for human use. The weighted average specific yield of samples from this sand that have been tested in the laboratory is in the order of 23 percent. Several pumping tests on wells drawing from the Cohansey have been conducted in widely spaced localities in Atlantic, Cape May, and Cumberland Counties, N. J. In each place, the aquifer tested was only a part of the total formation and was locally confined or partially confined beneath clay layers. Thus the computed coefficients of storage represented artesian or semiartesian conditions and did not approach the magnitude of the specific yield. The coefficients ranged from 2.7×10^{-3} to 4×10^{-5}. The coefficients of transmissibility, which do not represent the total thickness of the Cohansey, ranged from 18,000 to 150,000 gpd/ft. The coefficients of permeability, as derived from these tests, are more representative than the coefficients of transmissibility because the various thicknesses of aquifers tested are eliminated. These coefficients range from 480 to 3300 gpd/ft^2 and average well over 1000 gpd/ft^2. The highest permeabilities were from tests at locations in Cumberland County; the lowest were from tests in Cape May County. Modern, large-diameter wells that tap substantial thicknesses of the Cohansey frequently yield as much as 1000 or 1500 gpm.

Quality of Water:—The quality of the water in the Cohansey sand is largely determined by local conditions at the land surface. Over most of its widespread outcrop area, the aquifer is recharged by the direct vertical percolation of precipitation. Hence, soluble materials in the soil or on the land surface may be leached and may contribute to the local mineralization of the water. Even where all or a part of the aquifer may be protected from direct vertical percolation by lenses of clay, such protection is no more widespread than the clay lens. Thus, the most productive aquifer of the region is also one that is most exposed to damage from human activity and most in need of protection.

Waters from the Cohansey sand are generally slightly mineralized and soft. The only constituents commonly present in objectionable quantities are iron and dissolved carbon dioxide. Objectionable quantities of nitrates are found in some samples of water from agricultural areas and are believed to be due mainly to the leaching of chemical and organic fertilizers. Treatment for the removal of iron and adjustment of pH may be required before use of the waters in certain industrial processes.

As much as 40 and 50 parts per million of free carbon dioxide and nitrate, respectively, have been found in samples of water from this formation. The water is generally slightly acid on the pH scale, the bicarbonate concentrations are very low, ranging from 10 to 14 ppm and averaging only 5 ppm for 16 samples, and the total hardness in the samples analyzed, range from 2 to 48 ppm. Almost all of the hardness is noncarbonate hardness that is due to the presence of calcium and magnesium sulfate and nitrate. Concentrations of dissolved solids ranged from 13 to 144 ppm and averaged 56 ppm. Iron concentrations ranged from 0 to 10 ppm, but objectionable quantities were present in only 4 of the 16 samples. Typical analyses of water from the Cohansey sand are given in table 9.

Recharge, Movement, and Discharge of Ground Water:—The ground water in the Cohansey sand is largely unconfined. However, the existence of rather continuous and impervious clay lenses in some localities causes the ground water to be locally confined under slight pressures, and semi-artesian to true artesian conditions prevail in many disconnected areas. There is probably no widespread regional pattern of movement of water in the Cohansey sand, such as that described in some of the artesian aquifers of the Coastal Plain. There is no single artesian system that would require such a pattern. Broadly speaking then, the behavior of water in the Cohansey sand is that characteristic of water-table aquifers. Recharge and discharge are generally local, and they are connected by a pattern of flow largely governed by topography.

Essentially all recharge to the Cohansey sand is derived from precipitation on the outcrop area. Generally, the topographic divide between those streams flowing directly to the Atlantic Ocean and those tributary to the Delaware River lies within the outcrop area of the Cohansey. There is, therefore, little opportunity for water falling on other formations to flow across the Cohansey and provide potential recharge. Consequently, most components of stream flow within its borders are related to the hydraulic characteristics of the Cohansey, as modified by the overlying discontinuous surficial materials, and the aquifer is an isolated hydrologic unit to an unusual degree. There may be some interchange of water between the Cohansey sand and aquifers of the Kirkwood formation, but this is believed to be a very small part of the total water movement in the Cohansey. Aquifers of the Kirkwood formation are in contact with the Cohansey sand near the outcrop of the Kirkwood from central Camden County northeastward and possibly in some areas downdip from this area.

The infiltration capacity of the Cohansey sand is very high, so high in fact that overland flow, except in established stream channels, seldom occurs even in the heaviest storms. Over extensive areas the iron and alumina materials have been leached out of the upper few feet of the formation, leaving a light textured highly pervious material at the surface. This material readily absorbs, stores, and transmits large quantities of water derived from precipitation.

There is little likelihood that the Cohansey sand rejects recharge from precipitation except where the water table is very near the surface.

As already indicated, its specific yield is more than 20 percent. Thus it will require approximately 2½ inches of precipitation to fill the voids in each foot of sand above the water table.

Water is discharged from the Cohansey sand mainly by seepage into stream channels and by evaporation and transpiration largely in the swampy areas that occur along the streams in many places. Water stored in the sand flows steadily into the areas of discharge with the result that the flow of streams originating on the Cohansey is the least variable of any in the region. Due to the high permeability of the sands, the hydraulic gradients toward areas of discharge are gentle and the distances between streams are greater than they would otherwise be in an area of generally low relief.

Only a small part of the total water moving through the Cohansey sand is withdrawn through wells. Major uses are for municipal and irrigation supplies largely in the southern part of the areal extent of the aquifer and near its thicker edge along the Atlantic coast. Relatively little industrial use is made of water from the Cohansey. Use of water from this aquifer in the 11-county region is not very great, partly because the formation is thin over much of the region, but also because the part of the region underlain by the Cohansey is generally sparsely settled. The total current use of water from the Cohansey in New Jersey is estimated to be in the order of 60 to 70 mgd.

Possibilities for Additional Development:—The Cohansey sand contains the last large essentially untapped reserve of water supply in the State of New Jersey. Its presence in and adjacent to the 11-county region is of great significance to the future of the region. Carefully laid plans for the protection and development of this resource should not be long delayed. The susceptibility of the water in the Cohansey sand to contamination from adjacent bodies of mineralized water and especially from human activities on the extensive outcrop area make such planning urgent. This great resource must not be spoiled by thoughtless action.

The Cohansey sand is capable of yielding at least 1 mgd from each square mile of its outcrop area. Thus, if it were possible to develop every square mile of the Cohansey for water supply, it would yield more than 2 billion gallons of water a day. Such full development of the aquifer is not possible for several reasons. The danger of salt-water encroachment around a large part of its margin and the thinness of the sands along most of the remaining marginal area limits development to the central part of the outcrop area. Part of the area must necessarily be devoted to other conflicting but necessary types of development, such as cities and industrial sites, and in such areas the waters will almost surely be contaminated. A small part of the outcrop area is impermeable.

The difficulties of fully developing many areas by a feasible network of wells would further limit the total water available. These and other factors will prevent the complete development of the entire outcrop area. However, even if these factors were to effectively eliminate half the outcrop area, the Cohansey sand, if wisely protected and developed, would still yield more than 1 billion gallons of water a day. Probably at least 400 million gallons of this could be developed in the 11-county region.

Plans and programs for the maximum development of this great resource should not be delayed until a haphazard pattern of other developments makes them difficult or impossible to execute. They should be based upon more detailed data than is now available. They should provide for zoning, or otherwise setting aside of large areas primarily for water-supply uses, or for a combination of water supply and other compatible uses such as forestry and various types of recreation. In this connection, the recent acquisition by the State of New Jersey of the Wharton Tract in Burlington and Atlantic Counties, N. J., as a water-supply reserve is a major step forward. This and other strategically located areas might well be held for the best quality of water while others could be planned to meet less rigorous requirements. Consideration should be given to zoning peripheral areas for the types of development that are most apt to affect the quality of the water supply adversely. The present rapid industrial and residential development of the 11-county region and its adjacent areas makes the planning for the use and protection of the water supplies from the Cohansey sand a matter of urgency.

Pliocene (?) series

Beacon Hill and Bryn Mawr gravels

Geology

The Beacon Hill gravel is characterized chiefly by white, yellow, and brown gravel and sand. Although originally deposited as a more or less continuous sheet, it now occurs only as isolated remnants (not shown on geologic map), capping hills in east central Burlington County, N. J., and possibly in Philadelphia, Montgomery, and Delaware Counties, Pa. Outcrops are generally found at altitudes higher than 180 feet above sea level. The reported thickness ranges from a featheredge to 20 feet. Apparently this gravel lies unconformably upon older rocks.

Exposures of the Beacon Hill may be seen at Apple Pie Hill in east central Burlington County, N. J.

In Pennsylvania, the Bryn Mawr gravel has been considered to be the equivalent of the Beacon Hill (Bascom, F., and others, 1909, columnar section). It occurs as a capping of hills in Chester, Delaware, Montgomery, and Philadelphia Counties, Pa., and in northern New Castle County, Del. Its lithology and thickness are similar to that of the Beacon Hill. Toward the west, it caps progressively higher hills. It lies unconformably upon the much older rocks of the Piedmont Province.

In New Castle County, Del., Pliocene(?) gravels occur as valley fill. These deposits have not been assigned to any formation but may be Bryn Mawr gravel.

The hydrology of the Beacon Hill and Bryn Mawr gravels is similar to that of the Pleistocene deposits and is discussed with them in a later section (see page 162).

QUATERNARY SYSTEM

Pleistocene series

Geology

The Bridgeton, Pensauken, and Cape May formations and the Wisconsin outwash comprise the Pleistocene beds in the 11-county region. These deposits generally form a thin veneer over the older rocks. They occur mainly in the Coastal Plain part of the region, but they also mantle large areas of the older rocks of the Appalachian Highlands. In a few areas in the region, they attain thicknesses as great as 80 feet or more.

The Pleistocene deposits are not shown on the geologic map accompanying this report. To do so would hopelessly confuse it. They are not shown on a separate geologic map because their hydrologic importance does not justify it.

The hydrology of the Pleistocene formations is similar, and to avoid unnecessary repetition, it is discussed in a single section after the geology of the several formations has been described.

Bridgeton formation

Fine-, to coase-grained quartzose sand and gravel are the main constituents of the Bridgeton formation in the 11-county region. The deposits are characterized by shades of white, yellow, and brown. The Bridgeton crops out in irregular and isolated patches at elevations ranging from 100 to 160 feet above sea level. It ranges in thickness from a featheredge to approximately 45 feet. Available evidence indicates that the Bridgeton, where present, rests unconformably upon rocks of Tertiary age or older.

Near Pittsgrove, Salem County, N. J., the Bridgeton is well exposed in an abandoned borrow pit.

Pensauken formation

The Pensauken formation occurs as irregular and disconnected patches, some of which are quite extensive, in each of the five counties in New Jersey and in Bucks, Philadelphia, and Delaware Counties, Pa. Within the region, the Pensauken formation is composed largely of medium-, to coarse-grained quartzose sand, although gravel and clay have been noted. The sand and gravel are characterized by shades of yellow, red, and brown. White, yellow, and brown clays have been found in exposures. In many localities, grains of sand and gravel are cemented together with ferruginous material. It is difficult to distinguish lithologically the Pensauken formation from the older Bridgeton formation. Deposits of the Pensauken are generally found at altitudes of 40 to 120 feet above sea level. Its thickness ranges from a featheredge to 60 feet. There are indications, however, that the Pensauken may be even thicker in northeastern Mercer County. The Pensauken formation, where present, rests unconformably upon rocks of Tertiary age or older. Plant remains have been found in an exposure at Dunham's Corner in Middlesex County, N. J., (Berry and Hawkins, 1935).

Good exposures of Pensauken may be seen at Auburn, Salem County, and near Runnemede, Camden County, N. J.

Cape May formation

Deposits of the Cape May formation crop out in irregular areas along the Delaware River and its tributary streams. They also occur along the Mullica River and its tributaries in Burlington County, N. J. They have been found at altitudes as high as 90 feet above sea level but generally occur at altitudes between 0 and 40 feet. In New Castle County, Del., the Talbot formation, as mapped by Bascom and Miller (1920) and Miller (1906) is the correlative of the Cape May formation.

This formation consists chiefly of medium-, to coarse-grained quartzose sand and gravel, although some clay is present. The sand and gravel are generally yellowish or brownish with shades of gray in some places. Yellow, brown, gray, and black clays have been reported. The reported thickness within the region ranges from a featheredge to 40 feet. Marine fossils have been found in the Cape May formation near the Atlantic coast.

Where present, this formation rests unconformably upon various formations which range in age from Precambrian to Pleistocene.

Outwash of Wisconsin age

Glacial outwash deposits are found in Bucks and Philadelphia Counties, Pa., and Burlington and Mercer Counties, N. J., in the proximity of the Delaware River.

Within the region, the outwash consists chiefly of stream-laid deposits of brown to gray colored coarse sand and gravel, with subordinate amounts of clay, silt, and fine-, to medium-grained sand. It is a mixture of coarse-textured and fine-textured sediments, some of which are of local origin and all of which were deposited by glacial melt-waters. Much of the material is poorly sorted, but even-textured beds do occur. Wide variations in the lithologic character of the outwash occur within short distances. The outwash ranges in thickness from a featheredge to 80 feet or more (in Bucks County) and lies unconformably on older rocks. It is difficult to distinguish the outwash from the Cape May formation or from the overlying Recent deposits.

Hydrology of the Pliocene (?) and Pleistocene deposits

Importance as Aquifers

The sands and gravels of the Pliocene(?) and Pleistocene formations in the 11-county region are not major aquifers. Nevertheless, they do yield moderate quantities of water to wells in some relatively small areas. They also yield small quanities of water to shallow wells for domestic and farmstead uses. Furthermore, they effectively increase the intake areas and the potential recharge of many of the aquifers on which they lie. The several formations discussed here do not form a single or a continuous aquifer. They are considered together because they function hydrologically in a similar manner.

Throughout most of the areal extent of these formations, they are too thin to yield much water to wells. They serve primarily to absorb and store temporarily the water from precipitation and transmit it to the underlying aquifers. In such areas, shallow wells draw directly from the Pliocene (?) and Pleistocene beds, for small domestic supplies, but large-capacity wells from these beds are not feasible. Where they overlie adjacent aquifers and aquicludes, these beds effectively increase the recharge area of the aquifers by absorbing precipitation that falls on them where they overlie the aquicludes and transmitting it laterally to the aquifers.

In certain limited areas in the 11-county region, the sands and gravels of the Pliocene(?) and Pleistocene series are thick enough to yield substantial quantities of water to wells. Near the Delaware River in southeastern Bucks County, Pa., about 15 mgd are being withdrawn from Pleistocene deposits, mainly from Wisconsin outwash. This is the most concentrated development of water from any of the Pleistocene aquifers here discussed. Other moderate withdrawals of water, ranging from 1 to 5 mgd are being made from Pleistocene beds near the Delaware River at localities in Burlington and Salem Counties, N. J., in Philadelphia

County, Pa., and in New Castle County, Del. Also in New Castle County, Del., moderate quantities of water in the order of 1 to 2 mgd are being pumped from Pliocene(?) beds. The total withdrawal from all these sources is not great.

Physical Properties

Most of the Pliocene(?) and Pleistocene deposits in the region are moderately permeable and have high porosities and specific yields. They weather to a loose highly pervious soil that readily absorbs water from precipitation.

Samples taken in Middlesex County, N. J., (Barksdale, 1943), had a specific yield of 38 percent and a coefficient of permeability of 450 gpd/ft^2 for the Cape May formation, and a specific yield of 30 percent and a coefficient of permeability of 170 gpd/ft^2 for the Pensauken formation. Similar tests are not available for the other aquifers here considered. Pumping tests in outwash materials in Bucks County, Pa., and in Burlington County, N. J., indicated very high coefficents of transmissibility, but precise determinations were hampered by nearby recharge boundaries in the Delaware River.

Quality of Water

The water in the aquifers of the Pliocene(?) and Pleistocene series in the 11-county region occurs under water-table conditions and is subject to contamination from soluble materials on the land surface. Normally it is derived from precipitation on uncontaminated outcrops and is only slightly mineralized. In a few instances, however, as in southern Philadelphia, and locally in Salem and Gloucester Counties, N. J., these aquifers yield comparatively highly mineralized water. Where these aquifers are being recharged from surface sources such as the Delaware River, the quality of the surface water tends to control that of the ground water.

With these various controlling factors, it is not surprising that the chemical quality of the water from this group of aquifers varies widely. This variation is fundamentally not from one formation to another, but, from one environment to another. On the basis of available analyses, the concentration of dissolved solids ranged from 63 to 1,140 ppm and the hardness from 18 to 856 ppm. In the industrialized areas where the highly mineralized samples were obtained, the hardness was largely noncarbonate hardness due to concentrations of calcium and magnesium sulfates and chlorides. In some agricultural areas, high concentrations of nitrate and sulfate, as much as 40 and 100 ppm respectively, were found. Usually the water from these aquifers is only slightly to moderately mineralized and the very high mineral concentrations are the exception.

Analyses of water from the Pliocene(?) and Pleistocene deposits are given in table 9.

Possibilities for Additional Development

Probably the major part of the water that the aquifers of the Pliocene(?) and Pleistocene series will yield has already been developed. Nevertheless, moderate additional quantities can probably be obtained. The possibility of developing substantial quantities of water from these aquifers depends largely upon their thickness—more precisely upon their saturated thickness—and upon their exposure to sources of recharge such as the Delaware River. The areal distribution of these deposits is well known, but much information as to their thickness and their saturated thickness is still needed. It seems probable that additional supplies can be developed from the thicker beds along the Delaware River, but it is unlikely that the new development will equal the quantities already being withdrawn from these beds in similar situations.

In upland areas away from streams, it is unlikely that these aquifers will ever yield more than household supplies. No doubt many additional small supplies can be obtained, but the total withdrawal of water will never be great. Even where a thickness of 40 or 50 feet of these materials is exposed on high ground only the lower few feet may be saturated because water is conducted so readily that the upper parts of the materials are soon drained. The high water table (i.e., close to the land surface) in low areas is the reason for the considerable saturated thicknesses where the beds themselves are thick. The larger yields in low lying areas are, therefore, partly the result of high water tables.

Recent series

Alluvium

Since the retreat of the last continental ice sheet, the land surface of the 11-county region has remained relatively static. The erosion of the land surface by wind and water has continued, and the materials thus removed have been and are still being deposited in tidal flats and along the more gently sloping reaches of streams. This recently deposited material is known as alluvium. It is composed of grayish silts, organic material, sand, and gravel. The alluvium is 50 feet thick (dark gray silt) in the vicinity of the Delaware Memorial Bridge at Deepwater, Salem County, N. J.

Where present, the alluvium lies unconformably upon older formations.

The coarser facies of the alluvium may contain ground water, usually under water-table conditions, but they are rarely thick or extensive enough to yield water to anything but domestic dug wells. They are generally found in localities where such supplies are not in demand. The fine-grained alluvial deposits in the bottom of the Delaware River and of the Delaware Bay tend to act as leaky aquicludes and to retard the movement of surface water into the underlying aquifers.

Eolian Deposits

Eolian or windblown deposits occur only in a few scattered localities in the 11-county region and are generally thin. Where present, they usually consist of light gray, well-sorted sands whose quartz grains have been highly polished by wind action. In some agricultural areas within the region, thin deposits of windblown soil may be found along the edges of fields that are clean cultivated before the crops attain sufficient growth to retard wind action. This material differs little from the soil upon which it is deposited. These deposits lie unconformably upon older formations. The coarser eolian deposits are generally highly pervious and may enhance the recharge of underlying aquifers. They are not important as aquifers.

GROUND WATER LAW

NEED FOR LEGAL CONTROL OF GROUND-WATER USE

In the humid eastern part of the United States, where water generally has been abundant in the past, there has been a widespread tendency toward development of ground-water reservoirs in an uncontrolled manner. Such development has led at times to problems of interference between wells and depletion or contamination of supplies. Such problems have been aggravated by lack of public knowledge and by a general impression that the supply of ground water is almost inexhaustible. Solution of the problems has been affected by existing laws which did not provide, or in some instances did not permit, control of the withdrawal of ground water, especially of that withdrawn for private and industrial uses. Communities have vied with one another for new industries and have freely given assurances that plentiful supplies of ground water were available, often in the absence of definite knowledge to justify such assurances.

In many areas, the withdrawal of water from certain aquifers has depleted their supply or endangered their chemical quality to the extent that the public interest now demands the impartial regulation of all withdrawals of ground water. Nevertheless, because so many developments have been successful in the past, the common assumption is still that more and more water can be drawn from the same aquifers in the same areas by the simple process of drilling more wells. The tremendous amount of water held in storage in the more productive aquifers make each new development appear successful and safe. Only after years of pumping may the effects of overdevelopment become evident.

If carefully developed and if protected against depletion and contamination, ground-water supplies can last indefinitely. On the other hand, if they are overdeveloped their usefulness may be impaired or destroyed altogether. Under the climatic and hydrologic conditions that prevail in the lower Delaware Basin, the maintenance of a rate of withdrawal that will assure the permanence of the supply generally is the first consideration in a decision as to the feasibility of any proposed large new ground-water supply. Conditions warranting progressive depletion of stored water followed by abandonment of the aquifer for large-scale development, sometimes popularly called "mining water," generally do not exist in the Delaware Basin as they do in some areas of the West. In the Delaware Basin a continuous, though limited, supply of ground water is considered by the responsible State agencies to be much more valuable than a larger supply that might be taken from the aquifer for a brief period of years after which it would no longer be available.

It is the purpose of this report not to suggest the form that the regulation or control of ground-water development in the 11-county region should take but simply to point out that means must be found for control in the interest of preservation and full, equitable development of the ground-water supply. It is essential to emphasize that the critical factor will be the perennial yield of whole aquifers rather than of small parts of them. The regulation of ground-water developments in one county, for example, might be helpful, but much of its value might be destroyed by unregulated development of the same aquifers in adjacent counties. To be effective, therefore, control will have to be statewide, and the protection of interstate aquifers will require interstate cooperation and broad vision on the part of those who administer the regulations. All major use of water of course will have to be regulated if control is to be effective. Restrictions applied to one class of water users and not to others would be futile, as well as subject to challenge on constitutional grounds. Where controls are necessary, neither industry, agriculture, nor public water supplies can safely be excluded from them. Domestic uses not exceeding certain small amounts can be exempted safely, as they are in many States, so long as adequate standards of construction and operation are maintained for the protection of both the user and the aquifer.

Most of the foregoing discussion deals with the need for legal actions designed to assure users of ground water a perennial supply. A factor of equal importance is the maintenance of the quality of the supply at a satisfactory level. The threat of salt-water encroachment from the tidal reaches of the Delaware River and its tributaries is a major problem that will require much constructive thought and action. The contamination of ground water by human activity also should be considered.

A possible alternative to governmental regulation would be cooperative action by some form of water users association. Such action would have to be based upon agreement by all users or potential users of ground water. The achievement of such unanimity might in itself require governmental action.

PRINCIPLES OF GROUND-WATER LAW

The principles of ground-water law have developed gradually with the needs for water and with the general understanding of ground-water hydrology. They are still being modified to fit modern conditions and current knowledge of the occurrence and movement of ground water. Ground-water law, like that on surface water, is generally based either upon the common-law doctrine of riparian rights or upon the doctrine of prior appropriation; in places both principles are applied to some extent.

Under the common-law English rule the landowner may withdraw all the ground water he can get from wells on his property for any purpose he desires. A modification of the English rule is the American rule of reasonable use, which restricts the landowner in his withdrawal of ground water to the extent that he must exercise his own rights reasonably in view of the similar rights of others. This rule has been modified further into the California doctrine, or doctrine of correlative rights, under which not only must one landowner's use be reasonable, in consideration of the similar rights of others, but it must be correlated with the uses of others in times of shortage (Thompson and Fiedler, 1938, p.1063). The use is restricted to the lands overlying the common supply at times when the supply is insufficient. When the supply is sufficient and no injury to others results, any amount reasonably needed may be taken for use either on lands overlying the common supply or elsewhere.

The doctrine of prior appropriation was developed in the Western States in areas where the total supply of water was insufficient for all beneficial uses. Under this doctrine, the first user in time had prior claim to the available water before later appropriators. The two most universally recognized features of an appropriative right are (1) that he who is first in time is first in right; in time of scarcity the later appropriators must cease their use in reverse order of priority; and (2) the use must be a beneficial one; no right is acquired to water that is not used beneficially (McGuinness, 1951, p. 4).

GROUND-WATER LAW IN THE 11-COUNTY REGION

Ground-water laws applicable in the 11-county region have taken two forms: the regulation of the drilling of water wells, and the control of the diversion of water from underground sources. The purposes of the first are mainly to provide adequate geologic information from drilling and to guard against the faulty construction of wells. The control of diversion is a direct means of conservation of ground water. Well drillers' licensing acts are in effect in New Jersey and Pennsylvania. The control of diversions is in effect only in New Jersey. Ground-water legislation is being studied in Delaware, but no laws have yet been passed.

The State of New Jersey has been a leader in the development of Eastern ground-water law. Areas where serious overdevelopment appears to be imminent are delineated as protected areas. Thereafter, no large diversions of ground water may be made in such areas without the consent of the State. In some cases, permits are issued for specified periods, and then renewed at the end of the period if conditions seem to warrant renewals. In some others, permits are issued for specific periods and thereafter are subject to modification or cancellation at any time if such action appears to be in the public interest. Much of the Coastal Plain part of the 11-county region within New Jersey has been delineated as a protected area.

SUMMARY AND CONCLUSIONS

The major objectives of the ground-water investigations in the 11-county region were the evaluation and appraisal of the ground-water resources of the region and the identification of conditions that now exist or may develop that would seriously interfere with the continued use of these resources. Each of these objectives has many ramifications and, once determined for a given set of conditions, cannot be considered final, because the factors that affect them are continually changing. The region is in a generally favorable position with respect to ground-water supplies. Nevertheless, some potentially serious hydrologic problems should be recognized in planning expanded ground-water developments.

The Appalachian Highlands part of the region lies north and northwest of the Fall Line, which lies near and roughly parallels the Delaware River from Trenton, N. J., to Wilmington, Del., and continues in the same general direction beyond these points. Ground water occurs in the cracks, crevices, and solution openings of the consolidated rocks in that part of the region. The yield of individual wells in this part of the region is generally small to moderate and not readily predictable. Ground water from the consolidated rocks generally contains low concentrations of dissolved minerals and may be used for most purposes without treatment.

In the Appalachian Highlands portion of the region, the limestone aquifers and those in the Triassic rocks are the principal ones capable of yielding large additional quantities of water. The investigations preceding this report were not detailed enough to justify a close estimate of their potential yield. However, on the basis of their wide extent and general productivity, it seems probable that they would yield a considerable additional quantity of water, perhaps of the order of 200 mgd.

Ground water occurs in the voids of the unconsolidated sediments in the Coastal Plain part of the 11-county region, which lies south and southeast of the Fall Line. Wells of large capacity are common, and sufficient quantities of water may be obtained for most uses anywhere within this part of the region. The chemical quality of the water is generally acceptable for most uses; however, objectionable concentrations of iron and other minerals are found in some places, and some waters have a low pH and are corrosive.

The aquifers from which the greatest quantity of water is being withdrawn are those in the Raritan and Magothy formations, which are readily available in the heart of the region. The principal source of large additional supplies of ground water for the region is the Cohansey sand. Only a part of the outcrop area of the Cohansey is in the 11-county region, but much of the remaining outcrop area is near enough that it would be physically feasible to divert water from it into the 11-county region.

At least 500 mgd can be developed from the Cohansey sand and made available in the region. Much smaller additional quantities of ground water may be withdrawn from the other aquifers in the region. The complete development of the aquifers of the Raritan and Magothy formations would yield at least an additional 100 mgd. The remaining aquifers of the Coastal Plain, those in the Patuxent formation and those between the Magothy formation and the Cohansey sand, would probably yield at least an additional 300 mgd of water within the region. In summary, it would seem that additional daily ground-water withdrawals totaling more than 1 billion gallons might be available for use within the 11-county region. Probably less than half this quantity could be collected and transmitted economically to the present centers of industrial activity along the Delaware River. The remaining quantity, owing to the potentially small yields of wells in many places and the necessity for spacing them widely, would require the development of small to moderate quantities at many scattered localities.

In a region as wide and as varied in its geology as the lower Delaware River basin, it must be recognized that the availability of ground water will vary widely from place to place. The consolidated rocks that occur in the Appalachian Highlands throughout most of Bucks, Montgomery, Philadelphia, Delaware, and Chester Counties and parts of Mercer and New Castle Counties differ greatly in their water-bearing characteristics from the sediments of the Coastal Plain in the remainder of the region.

In the consolidated rocks, the water-bearing openings are much more numerous and prominent in some places than in others. Consequently, wells tapping these rocks only a few feet apart may differ greatly in yield, and the depth of wells may show little relation to yield. An average expectancy can be derived from records of a large number of wells, but the yield of individual wells cannot be predicted with certainty prior to their completion. The application of geologic reasoning to this problem has resulted in the conclusion, which is confirmed by statistics of well yields, that moderately deep wells are apt to encounter more cracks and hence to yield more water per unit of depth than very deep wells. A further application of geologic and geophysical knowledge and techniques to these aquifers might yield valuable information on the areal distribution of systems of cracks and hence on the best locations for wells. This would be especially valuable in the more productive aquifers.

In sharp contrast are the relatively persistent and prolific sand and gravel layers to be found in the sediments of the Coastal Plain. Some of these extend more or less uniformly over large areas, but they dip gently toward the southeast and thus are encountered at different depths in different places. Even in the Coastal Plain, however, widespread, uniform aquifers are the exception rather than the rule. Many are of limited extent and variable in character. More detailed and precise geologic information would yield valuable returns in the future development of ground water from the sediments of the Coastal Plain. Basically, the information needed is a more accurate definition of the various aquifers and aquicludes as to position, thickness, extent, and lithologic character. For example, a better knowledge of the nature and extent of those aquifers of the Raritan and Magothy formations that are exposed beneath the Delaware River would be of great value in estimating the potential recharge and optimum yield of these aquifers. Changes in thickness and gradation in character are known to occur in all the major aquifers of the Coastal Plain, but much remains to be learned about them. Some, like the Vincentown sand, appear to grade into impermeable materials, whereas others, like the aquifers in the Kirkwood formation, seem to become more permeable down the dip.

The nature of some and possibly all of the aquicludes also changes from place to place. That formed by the Merchantville and Woodbury clays is believed to be widespread and generally impervious. The Marshalltown formation, on the other hand, grades from a highly impermeable layer in some places to a sandy material capable of yielding moderate quantities of water to wells in other places. A short distance downdip from the sandy part of the outcrop of the Kirkwood formation, clays of that formation appear to finger in and separate the sands of the Kirkwood from those of the Cohansey. Yet much farther down the dip, the results of chemical analyses of water suggest an interconnection between the sands of the two formations. Very little is known about the Kirkwood formation in a wide band between the coastal areas where it contains excellent aquifers and the areas near its outcrop where the Cohansey sand is not thick enough to yield water supplies adequate for all current needs. It seems possible that the clays of the Kirkwood may thin out in this intermediate area and permit interconnections between the aquifers of the Kirkwood and those of the Cohansey. Other examples of geologic problems that are also ground-water problems could be given, but these should suffice to illustrate their importance.

It is reasonable to assume that when ground water was first withdrawn from wells in the 11-county region, essentially all of it was potable and of accepted chemical character. The principal exceptions were scattered instances of high concentrations of iron and brackish water from some wells along that reach of the river that contains salt water. Consequent to the development of communities and industries, the disposal of wastes began to affect the quality of the ground waters from some aquifers. This problem is so serious in some areas that the ground-water supply is tending toward uselessness because of contamination. Examples of this type of problem in Camden and Gloucester Counties, N. J., and in Philadelphia County, Pa., have been described.

Contamination of this nature cannot be corrected quickly because the upper layers of the earth have been saturated with chemically inferior water. There is no quick and effective means of flushing them free of this contaminated water. Users of ground water in these localities must expect water of poor quality for a considerable period of time after the causes of contamination have been removed. Without remedial measures, it seems probable that the contamination will increase and reach levels that will render the water unfit for most uses even with treatment.

The waste disposal that accompanies the increasing urbanization and industrialization in the lower Delaware basin will increase the threat of contamination of both the surface and the ground-water supplies. State and interstate agencies such as "Incodel" have been waging a campaign to reduce this threat by requiring the construction of new or improved water-treatment plants and discouraging the discharge of wastes into wells. This campaign has had a gratifying measure of success in recent years, but it may be many years before the corrective measures can overtake the growing load of contamination. Constant and everlasting vigilance will be required to keep the present and potential water supplies of the region in a usable condition and as free as possible from contamination.

The maintenance and improvement of the quality of the water in the Delaware River is of the utmost importance for many reasons not related to ground water. The quality of the river water is also one of the most important factors relating to the quality of the ground waters of the region. Substantial recharge from the river has already been drawn into aquifers of the Raritan and Magothy formations and the associated aquifers of the Pleistocene deposits along the river. Substantially greater quantities of river water will be drawn into them as pumping continues and increases. The dredging of deeper and wider channels for navigation will tend to increase the proportion of river water drawn into nearby pumped wells. The quality of the water in the river is affected not only by manmade contamination but by the advance of salt water upstream from the ocean. The advance of salt water is controlled in varying degrees by the nature and depth of the channel and by the flow of fresh water into the tidal reaches of the river. The large quantities of water now drawn from the aquifers adjacent to the river and available from them for the future make it imperative that every reasonable step be taken to maintain a satisfactory quality of river water. The great value of these ground-water supplies would justify large expenditures to protect them from destruction.

When water is withdrawn from a well or well field the water levels or heads in the surrounding parts of the aquifer are lowered, indicating the induced water movement toward the well from points that may in time be as remote as an area of recharge. The greater the rate of withdrawal, the greater will be the lowering. In itself the lowering of water levels is not a cause for concern except as it is persistent year after year or as it is related to other factors.

Progressive lowering of water levels without increased pumping or disproportionally great lowering as a result of an increase in pumping may indicate that locally at least the aquifer is being overdeveloped.

Such conditions have not been observed in the region except in a few places where large supplies are being withdrawn from the hard-rock aquifers. Neverthless, it is important to maintain adequate and accurate records of pumpage and of water levels and to study their relation periodically. Records of water levels are valuable as an indicator of probable recharge from interconnected bodies of surface water. Adequate water-level records are therefore particularly important along the lower Delaware River where salt water moves upstream from the ocean.

Even though ground water is a renewable natural resource, the total quantity that may be withdrawn from an aquifer in a given area, either for a short period or long period, has certain limits, and the total quantity of usable water may be reduced markedly by deterioration of the chemical quality. Some regulation of ground-water use and of practices that tend to impair its quality would seem to be necessary. Recommendations as to the form that regulation of ground-water withdrawals should take in the 11-county region has no place in this report; however, failure to point out the need for regulation would be as great an omission as overlooking one or more of the major aquifers. There appears to be no better way to achieve maximum development of this essential resource for the good of the largest number of users than to devise some means of protecting the sources. The writers believe that the regulation of ground-water use can best be administered at the State level of government. However, wise development of interstate aquifers will necessarily involve close cooperation and broad vision on the part of the various State regulatory agencies. Whatever form the regulation of ground-water use may take, continuing basic geologic and hydrologic studies will be needed to provide the administrators of the regulations with an adequate basis for their enforcement.

The collection and interpretation of basic ground-water data is necessarily a continuing process. It is impossible to make more than qualitatives estimates of present and potential yields without adequate basic data. Because the development of new ground-water supplies and increasing demands on existing supplies create changing conditions, an adequate continuing program of basic-data collection *and interpretation* is essential to the maximum safe development of these resources. The geology of the region and the hydrologic characteristics of the water-bearing formations are known in a general way, but the collection of additional basic data is one of the major requirements for evaluating more closely the ground-water potential of the region. It is essential also for the protection of existing supplies. These data should include refinements of geologic information, where necessary; measurements of the fluctuation of water levels; the completion of the inventory of existing wells; records of the total withdrawal of ground water from each aquifer in each area; and further investigation of the hydraulic properties of the aquifers by means of field pumping tests and laboratory tests on selected samples of the water-bearing materials. In the area of consolidated rocks, methods should be developed by which the water-bearing beds and zones in apparently uniform rocks may be identified and the probable yields of wells may be predicted. The maximum safe utilization of the ground-water resources of the region can be made only on the basis of continued and accelerated investigation of the basic factors that control the occurrence, yield, and quality of ground water in the region.

BIBLIOGRAPHY

Anderson, J. L., 1951, Northeastern United States *in* Possible future petroleum provinces of North America: Am. Assoc. Petroleum Geologists Bull., v. 35, no. 2, p. 421-437.

Ashley, G. H., 1931, A syllabus of Pennsylvania geology and mineral resources: Pennsylvania Topog. and Geol. Survey Bull. G-1.

Ashley, G. H., and others, 1931, Geologic map of Pennsylvania: Pennsylvania Topog. and Geol. Survey.

Badon, Ghyben, W., 1889, Nota in verband met de voorgenomen put boring nabij Amsterdam: K. Inst. Ing. Tijdschr., 1888-1889, p. 21.

Barksdale, H. C., 1933, A 10-year record of water-table fluctuations near Runyon, N. J.: Am. Geophys. Union Trans., p. 466-471.

——————— 1936, Quantitative investigations of New Jersey ground waters: Water Works Eng., v. 89, no. 3, p. 150-153.

——————— 1937, Water supplies from the No. 1 sand in the vicinity of Parlin, New Jersey: New Jersey State Water Policy Comm. Special Rept. 7.

——————— 1952, Ground water in the New Jersey Pine Barrens area, *in* The Pine Barrens of New Jersey, a symposium; Bartonia, no. 26, p. 36-38.

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

Barksdale, H. C., Johnson, M. E., Schaefer, E. J., Baker, R. C., and De Buchananne, G. D., 1943, The ground-water supplies of Middlesex County, N. J.: New Jersey State Water Policy Comm., Special Rept. 8.

Barksdale, H. C., and De Buchananne, G. D., 1946, Artificial recharge of productive ground-water aquifers in New Jersey: Econ. Geology, v. 41, p. 726-737.

Barksdale, H. C., and Graham, J. B., 1952, Progress of the investigation of the ground-water resources of the Lower Delaware River valley: U. S. Geol. Survey open-file report.

Barksdale, H. C., and Jones, P. H., 1953, Availability of ground water in Lower Delaware basin: Pennsylvania Dept. Internal Affairs Bull., v. 21, no. 2, p. 3-10, 26.

Barksdale, H. C., and Lang, S. M., 1955, Ground water in the Delaware River valley: Am. Soc. Civil Eng. Proc., v. 81, Separate No. 593.

Barksdale, H. C., and Remson, Irwin, 1955, The effect of land-management practices on ground water: Internat. Union Geodosy and Geophysics, Internat. Assoc. Hydrology, 10th Gen. Assembly, Rome 1954, v. 2, Pub. 37, p. 521-525.

Bascom, Florence, 1904, Water resources of the Philadelphia district: U. S. Geol. Survey Water-Supply Paper 106.

Bascom, Florence, and others, 1909, Philadelphia folio, Pa.-N. J.-Del.: U. S. Geol. Survey Geologic Atlas, folio 162.

——————— 1909a, Trenton folio, N.J.-Pa.: U. S. Geol. Survey Geologic Atlas, folio 167.

Bascom, Florence, and Miller, B. L., 1920, Elkton-Wilmington folio, Md.-Del.- N. J.-Pa.: U. S. Geol. Survey Geologic Atlas, folio 211.

Bascom, Florence, and others, 1931, Geology and mineral resources of the Quakertown-Doylestown district, Pa.-N. J.: U. S. Geol. Survey Bull. 828.

Bascom, Florence, and Stose, G. W., 1932, Coatesville-West Chester folio, Pa.-Del.: U. S. Geol. Survey Geologic Atlas, folio 223.

——————— 1938, Geology and mineral resources of the Honeybrook and Phoenixville quadrangles, Pa.: U. S. Geol. Survey Bull. 891.

Bayley, W. S., 1941, Pre-Cambrian geology and mineral resources of the Delaware Water Gap and Easton quadrangles, N. J. and Pa.: U. S. Geol. Survey Bull. 920.

Beamer, N. H., 1953, Chemical character of surface water in Pennsylvania, 1949-1951: Pennsylvania State Planning Board.

Bennett, R. R., and Meyer, R. R., 1952, Geology and ground-water resources of the Baltimore area: Maryland Dept. Geology, Mines and Water Res. Bull. 4.

Berry, E. W., and Hawkins, A. C., 1935, Flora of the Pensauken formation: Geol. Soc. America Bull., v. 46, p. 245-252.

Bliss, E., and Jonas, A. I., 1916, Relation of the Wissahickon gneiss to the Shenendoah limestone and Octoraro schist of the Doe Run and Avondale Region, Chester County, Pennsylvania: U. S. Geol. Survey Prof. Paper 98, p. 9-34.

Bosch, H. M., and others, 1950, Methemoglobinemia and Minnesota well supplies: Am. Water Works Assoc. Jour., v. 42, no. 2, p. 161-170.
Brookhart, J. W., 1949, Ground-water resources, *in* The water resources of Anne Arundel County: Maryland Dept. Geology, Mines and Water Res. Bull. 5, p. 28-149.
Chamber of Commerce of Greater Philadelphia, 1956, Greater Philadelphia Facts.
Chamber of Commerce of Greater Philadelphia News, Feb. 1948 to date.
Clark, W. B., and Bibbins, A., 1897, The stratigraphy of the Potomac group in Maryland: Jour. Geology, v. V, p. 479-506.
Cloos, E., and Hietanen, A., 1941, Geology of the "Martic Overthrust" and the Glenarm Series in Pennsylvania and Maryland: Geol. Soc. America Special Paper 35.
Cooke, C. W., Gardner, Julia, and Woodring, W. P., 1943, Correlation of the Cenozoic formations of the Atlantic and Gulf Coastal Plain and the Caribbean region: Geol. Soc. America Bull., v. 54, no. 11, p. 1713-1722.
Darton, N. H., 1896, Artesian well prospects in the Atlantic Coastal Plain region: U. S. Geol. Survey Bull. 138.
Dorf, Erling, 1952, Critical analysis of the Cretaceous stratigraphy and paleobotany of Atlantic Coastal Plain: Am. Assoc. Petroleum Geologists Bull., v. 36, p. 2161-2184.
Durfor, C. N., and Keighton, W. B., 1954, Chemical characteristics of Delaware River Water, Trenton, N. J., to Marcus Hook, Pa.: U. S. Geol. Survey Water-Supply Paper 1262.
Faber, H. A., 1950, The Status of fluoridation in 1949: Public Health Eng. Abs. 30, no. 4-5.
Ferris, J. G., Ground water, *in* Wisler, C. O., and Brater, E. F., 1949, Hydrology: New York, John Wiley and Sons, Inc., p. 198-272.
Glass, H. D., 1955, Report on the clay mineral composition of the Cretaceous sediments in Delaware: Unpublished manus., on file with Delaware Geol. Survey, Newark, Del.
Graham, J. B., 1945, Occurence of ground water in the Triassic area of Pennsylvania as influenced by geology: Pennsylvania Water Works Oper. Assoc. Jour., v. 17, p. 86-98.
———————— 1950, Ground-water problems in the Philadelphia area: Econ. Geology, v. 45, no. 3, p. 210-221.
Graham, J. B., and Kammerer, J. C., 1954, Ground-water resources of the U. S. Naval Base, Philadelphia, Pa.: U. S. Geol. Survey open-file report.
Graham, J. B., Mangan, J. W., and White, W. F., Jr., 1951, Water resources of southeastern Bucks County, Pa.: U. S. Geol. Survey Circ. 104.
Greenman, D. W., 1955, Ground-water resources of Bucks County, Pa.: U. S. Geol. Survey open-file report.
Groot, J. J., Organist, D. M., and Richards, H. G., 1954, Marine Upper Cretaceous formations of the Chesapeake and Delaware Canal: Delaware Geol. Survey Bull. 3.
Groot, J. J., and Rasmussen, W. C., 1954, Geology and ground-water resources of the Newark area, Del., with a section on the surface-water resources, by Arthur E. Hulme: Delaware Geol. Survey Bull. 2.
Hall, G. M., 1934, Ground water in southeastern Pennsylvania: Pennsylvania Topog. and Geol. Survey, 4th ser., Bull. W-2.
Hartwell, O. W., 1929, Surface-water supply of New Jersey, to September 30, 1928: New Jersey Dept. Conserv. and Devel. Bull. 33.
———————— 1936, Surface-water supply of New Jersey, October 1, 1928, to September 30, 1934: New Jersey State Water Policy Comm. Special Rept. 5.
———————— 1944, Surface-water supply of New Jersey, October 1, 1934, to September 30, 1940: New Jersey State Water Policy Comm. Special Rept. 9.
———————— 1952, surface-water supply of New Jersey, October 1940, to September 1945: New Jersey Dept. of Conserv. and Econ. Devel., Div. Water Policy and Supply Special Rept. 12.
Hawkins, A. C., 1924, Alternative interpretation of some crystalline schists in southeastern Pennsylvania: Am. Jour. Sci., 5th ser., v. 7, p. 355-364.
Herpers, Henry, and Barksdale, H. C., 1951, Preliminary report of the geology and ground-water supply of the Newark, N. J., area: New Jersey Dept. Conserv. and Econ. Devel., Div. Water Policy and Supply Special Rept. 10.

Herzberg, Baurat, 1901, Die Wasserversorgung einiger Nordseebader: Gasbeleuchtung und Wasserversorgung, Jahrg. 44, Munich.

Howell, B. F., Roberts, Henry, and Willard, Bradford, 1950, Subdivision and dating of the Cambrian of eastern Pennsylvania: Geol. Soc. America Bull., v. 61, p. 1355-1368.

Hubbert, M. K., 1940, The theory of ground-water motion: Jour. Geology, v. 48, no. 8, pt. 1, p. 485-944.

——————— 1953, Entrapment of petroleum under hydrodynamic conditions: Am. Assoc. Petroleum Geologists Bull., v. 37, no. 8, p. 1954-2026.

Jacob, C. E., 1940, On the flow of water in an elastic artesian aquifer: Am. Geophys. Union Trans., v. 21, pt. 1, p. 574-586.

——————— 1944, Correlation of ground-water levels and precipitation on Long Island, N. Y.: Am. Geophys. Union Trans., v. 25, pt. 6, p. 928-939.

——————— 1946, Radial flow in a leaky aquifer: Am. Geophys. Union Trans., v. 27, p. 198-208.

Johnson, M. E., 1950, Revision of Lewis, J. V., and Kummel, H. B., 1912, Geologic map of New Jersey: New Jersey Dept. Conserv. and Develop. Atlas Sheet 40 (scale 1:250,000).

Johnson, M. E., and Richards, H. G., 1952, Stratigraphy of Coastal Plain of New Jersey: Am. Assoc. Petroleum Geologists Bull., v. 36, p. 2150-2160.

King, P. B., 1951, Tectonics of Middle North America: Princeton University Press, p. 132.

Knopf, E. B., and Jonas, A. I., 1929, Geology of the McCalls Ferry-Quarryville district, Pa.: U. S. Geol. Survey Bull. 799.

Kummel, H. B., 1898, Annual Report of the State Geologist: New Jersey Geol. Survey Ann. Rept. for 1897, Trenton, N. J.

——————— 1940, Revision of Lewis, J. V., and Kummel, H. B., 1914, The geology of New Jersey: New Jersey Dept. Conserv. and Devel. Bull. 50.

Lobeck, A. K., 1948, Physiographic provinces of North America: Columbia University, The Geographical Press (map, scale 1:12,000,000).

MacClintock, Paul, and Richards, H. G., 1936, Correlation of late Pleistocene marine and glacial deposits of New Jersey and New York: Geol. Soc. America Bull., v. 47, no. 3, p. 289-338.

McGuinness, C. L., 1951, Water law, with special reference to ground water: U. S. Geol. Survey Circ. 117.

Mackin, J. H., 1935, The problem of the Martic overthrust and the age of the Glenarm series in southeastern Pennsylvania: Jour. Geology, v. 43, p. 356-380.

McLaughlin, D. B., *in* "Geology and mineral resources of Bucks Co.": unpublished manus., on file with Pa. Geol. Survey, Harrisburg, Pa.

McLaughlin, D. B., and Willard, Bradford, 1949, Triassic facies in the Delaware Valley: Pennsylvania Acad. Sci. Proc., v. 23, p. 34-44.

Malcolm Pirnie, Engineers, and Albright & Friel, Inc., 1950, Report on the utilization of the waters of the Delaware River Basin for the Interstate Commission on the Delaware River Basin.

Marine, I. W., and Rasmussen, W. C., 1955, Preliminary report of the geology and ground-water resources of Delaware: Delaware Geological Survey Bull. 4.

Meinzer, O. E., 1923, The occurrence of ground water in the United States, with a discussion of principles: U. S. Geol. Survey Water-Supply Paper 489.

——————— 1923a, Outline of ground-water hydrology, with definitions: U. S. Geol. Survey Water-Supply Paper 494.

Meinzer, O. E., *in* Stearns, N. D., 1928, Laboratory tests on physical properties of water-bearing materials: U. S. Geol. Survey Water-Supply Paper 596, p. 148.

Merriam, C. F., 1948, Ground-water records in river-flow forecasting: Am. Geophys. Union Trans., v. 29, p. 384-386.

Miller, B. L., 1906, Dover folio, N. J.: U. S. Geol. Survey Geologic Atlas, folio 137.

——————— 1925, Mineral resources of the Allentown quadrangle: Pennsylvania Topog. and Geol. Survey, 4th ser., Topog. and Geol. Atlas 206.

——————— 1935, Age of the schists of the South Valley Hills: Geol. Soc. America Bull., v. 46, p. 715-756.

——————— 1939, Guidebook to places of geologic interest in the Lehigh Valley, Pa.: Pennsylvania Topog. and Geol. Survey Bull. G-16.

Miller, H. W., Jr., 1956, Paleocene and Eocene, and Cretaceous-Paleocene boundary in New Jersey: Am. Assoc. Petroleum Geologists Bull., v. 40, no. 4, p. 722-736.

New Jersey Dept. of Conserv. and Econ. Devel., Research and Statistics Sec., Population estimates.

Overbeck, R. M., 1951, Ground-water resources, *in* The water resources of Calvert County: Maryland Dept. Geology, Mines and Water Res. Bull. 8, p. 4-95.

Paulsen, C. G., and others, 1952, Quality of surface waters of the United States, 1948: U. S. Geol. Survey Water-Supply Paper 1133, p. 13.

Pennsylvania Water Supply Commission, 1917, Water resources inventory report, Part 3, Gazetteer of streams.

Philadelphia Inquirer, The, 1950, Water—A study of its hardness in the Philadelphia retail trading area: The Philadelphia Inquirer, Philadelphia Market Facts (report) 5.

Postel, A. W., 1940, Hydrothermal replacement of granodiorite near Philadelphia: Philadelphia Acad. Nat. Sci. Proc., v. 92, p. 123-152.

Rasmussen, W. C., and Slaughter, T. H., 1955, Geology and ground-water resources of Somerset, Wicomico, and Worcester Counties, Md.: Maryland Dept. Geology, Mines and Water Res. Bull. 16.

Rasmussen, W. C., and others, 1957, The water resources of northern Delaware: Delaware Geol. Survey Bull. 7 (in press).

Regional Planning Federation of the Philadelphia Tri-State District, 1932, Regional plan of the Philadelphia tri-state district.

Richards, H. G., 1943, Fauna of the Raritan formation of New Jersey: Philadelphia Acad. Nat. Sci. Proc., v. 95, p. 15-32.

——————— 1945, Correlation of Atlantic Coastal Plain Cenozoic formations, a discussion: Geol. Soc. America Bull., v. 56, p. 401-408.

——————— 1945a, Subsurface stratigraphy of Atlantic Coastal Plain between New Jersey and Georgia: Am. Assoc. Petroleum Geologists Bull., v. 29, no. 7, p. 885-955.

——————— 1948, Studies on the subsurface geology and paleontology of the Atlantic Coastal Plain: Philadelphia Acad. Nat. Sci. Proc., v. 100, p. 39-76.

——————— 1953, Record of the Rocks: New York, The Ronald Press Co.

——————— 1956, Geology of the Delaware Valley: Mineralog. Soc. Pennsylvania.

——————— 1956a, New investigations on the Cretaceous of New Jersey and Long Island: Abstracts: Internat. Geol. Congress, 20th, Mexico City, 1956.

Richards, H. G., and Harbison, Anne, 1942, Miocene invertebrate fauna of New Jersey: Philadelphia Acad. Nat. Sci. Proc., v. 94, p. 167-250.

Ries, H., Kummel, H. B., and Knapp, G. N., 1904, The clays and clay industry of New Jersey: New Jersey Geol. Survey.

Rima, D. R., 1955, Ground-water resources of the Lansdale area, Pa.: Pennsylvania Topog. and Geol. Survey Progress Rept. 146.

Schuchert, Charles, 1943, Stratigraphy of the eastern and central United States: New York, John Wiley & Sons, Inc.

Spangler, W. B., and Peterson, J. J., 1950, Geology of Atlantic Coastal Plain in New Jersey, Delaware, Maryland, and Virginia: Am. Assoc. Petroleum Geologists Bull., v. 34, no. 1, p. 1-99.

Stose, G. W., and Ljunjstedt, O. A., 1931, Geologic map of Pennsylvania: Pennsylvania Topog. and Geol. Survey (scale 1:380,160).

Stose, G. W., Jonas, A. I., and Ashley, G. H., 1932, Southern Pennsylvania and Maryland: Internat. Geol. Congress, 16th, Washington, 1932, Guidebook 10.

Theis, C. V., 1935, The relation between the lowering of a piezometric surface and the rate and duration of discharge of a well using ground-water storage: Am. Geophys. Union Trans., pt. 2, p. 519-524.

Thompson, D. G., 1928, Ground-water supplies of the Atlantic City region: New Jersey Dept. Conserv. and Devel. Bull. 30.

——————— 1930, Ground-water supplies in the vicinity of Asbury Park: New Jersey Dept. Conserv. and Devel. Bull. 35.

——————— 1932, Ground-water supplies of the Camden area, N. J.: New Jersey Dept. Conserv. and Devel. Bull. 39.

Thompson, D. G., and Fiedler, A. G., 1938, Some problems relating to legal control of use of ground waters: Am. Water Works Assoc. Jour., v. 30, no. 7, p. 1049-1091.

U. S. Dept. Agriculture, 1941, Climate and man: Yearbook of Agriculture, 1248 p.

U. S. Dept. Commerce, Weather Bureau, 1955, Local climatological data with comparative data, 4 p.

U. S. Geological Survey, 1936-54, issued annually (see below), Water levels and artesian pressure in observation wells in the United States (supplementary title since 1940—Part 1, Northeastern states): U. S. Geol. Survey Water-Supply Papers. (Offset.)

Year	*Water-Supply Paper No.*	*New Jersey part of area*	*Pennsylvania part of area*	*Delaware part of area*
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U. S. Geological Survey, 1956, Surface-water supply of the United States, 1930, Part 1-B, North Atlantic Slope basins, New York to York River: U. S. Geol. Survey Water-Supply Paper 1272, p. 220.

U. S. Public Health Service, 1946, Drinking water standards: Public Health reports, v. 61, no. 11, (Reprint no. 2697), p. 371-384.

Vermeule, C. C., 1899, Water supply from wells: New Jersey Geol. Survey Ann. Rept. for 1898, Pt. 4, p. 145-182.

Walton, Graham, 1951, Survey of the literature relating to methemoglobinemia due to nitrate contaminated water: Am. Jour. of Public Health, 1951; Public Health Engineering Abstract 31, Sept., 1951.

Ward, R. F., 1956, Geology of the Wissahickon formation in Delaware: U. S. Geol. Survey open-file report.

Watson, E. H., and Wyckoff, Dorothy, 1951, Guidebook illustrating the geology of the Philadelphia area (for Seventeenth Annual Conference of Pennsylvania Geologist), 34 p.

Webster's Collegiate Dictionary, 5th, 1946, p. 418 (Outline of Geology).

Weiss, Judith, 1949, Wissahickon schist at Philadelphia, Pa.: Geol. Soc. America Bull., v. 60, p. 1689-1726.

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

Wherry, E. T., 1909, Early Paleozoic of the Lehigh Valley district, Pa.: Science, N. S., v. 30, no. 769, p. 416.

White, W. F., Jr., 1947, Industrial utility of water in Pennsylvania, Chemical character of surface water, 1944-1946: Pennsylvania State Planning Board Pub. 17.

———————1951, Chemical character of surface water in Pennsylvania, 1946-1949: Pennsylvania State Planning Board Pub. 23.

Willard, Bradford, McLaughlin, D. B., Watson, E. H., and others, 1950, Geologic map of Bucks County, Pa.: Pennsylvania Topog. and Geol. Survey (to accompany forthcoming report on the geology of Bucks County).

Woolman, Lewis, 1899, Artesian wells in New Jersey: New Jersey Geol. Survey Ann. Rept. for 1898, Pt. 3, p. 59-144.

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